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Bilinear connection stiffness identification of heritage timber buildings with limited strain measurements

Mengning Lyu [a,b,c], Xinqun Zhu [c,*], Qingshan Yang [a,d]

[a] Beijing's Key Laboratory of Structural Wind Engineering and Urban Wind Environment, Beijing 100044, China
[b] School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China
[c] School of Computing, Engineering and Mathematics, Western Sydney University, Penrith, NSW 2751, Australia
[d] School of Civil Engineering, Chongqing University, Chongqing 400044, China

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ABSTRACT

'Que-Ti' is an important component connecting the beam and column in typical Tibetan historic timber buildings. It transfers shear, compression and bending moment by slippage and deformation of components as well as a limited joint rotation. A rigorous analytical model of 'Que-Ti' is needed for predicting the behaviour of a timber structure under loading. However, few researches have been conducted in this area, particularly on the effect of key parameters on the performance of the joint under loading. In this paper, a new method has been proposed to identify both the thermal load on the structure and the bilinear connection stiffness of the semi-rigid joint from limited measured strain responses by integrating the temperature-based response sensitivity analysis with the dual Kalman filter. A novel bilinear rotational spring model has been developed for the joint to take into account the friction slip at the interface, the shear in the tenon, and the gap between the tenon and the mortise of the 'Que-Ti' in typical heritage Tibetan buildings. The semi-rigid connection is modeled as two bilinear rotational springs and one compressive spring. The temperature is treated as the input of the structure and the thermal loading on the structure can be determined based on the proposed method. The numerical results show that the method is effective and reliable to identify the thermal loading, unknown boundary conditions and the connection stiffness of the 'Que-Ti' accurately even with 10% noise in measurements. A long-term monitoring system has also been installed in a typical heritage Tibetan building and the monitoring data have been used to further verify the method. The experimental results show that the identified stiffness by the proposed method with bilinear connection stiffness model can get better results than that with linear connection stiffness model.

1. Introduction

The 'Que-Ti' connection is commonly used as the beam-to-column joint in typical Tibetan heritage timber buildings that are over thousands of years old. This connection can withstand bending moment, compression and shear loads. The behaviour of the joint under loading is essential nonlinear [1,13,22]. As shown in Fig. 1, 'Que-Ti' is a key component of historic Tibetan timber buildings. For the safety of these buildings, it is important to assess the condition of this joint in the operational environment. However, little can be found in the literature on the stiffness parameters of this connection. In this paper, a temperature-based response sensitivity analysis is integrated with the dual Kalman filter to identify both the thermal load on the structure and the bilinear connection stiffness of the joint from limited measured strain responses.

Finite element model updating has widely been used to identify structural parameters from the field-measured responses [2,3,21]. There are significant discrepancies in the predicted and measured responses of an existing structure due to inaccurate modelling of the critical mechanisms in an a priori manner [26]. Dynamic response time histories of the structure have been adopted for structural identification in the last two decades [10]. Structural stiffness parameters of a multi-storey framework have been identified using the system identification approach in time domain [14]. Recently, the dynamic response sensitivity-based model updating method has been developed and used to identify structural parameters from the measured dynamic responses [16,17]. The validated finite element model of typical multi-tiered temples has been obtained to evaluate their seismic safety for future

* Corresponding author.
E-mail address: xinqun.zhu@westernsydney.edu.au (X. Zhu).

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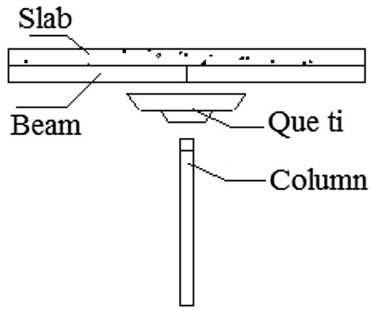

Fig. 1. The beam-column joints of typical Tibetan buildings.

earthquakes [4]. The method can provide highly accurate parameter identification with a few measurement points by taking advantage of the abundant time history data.

Structural parameter identification based on a reference set of measured data is usually subjected to the effect of the environmental temperature as it may be varied for two different sets of measurements. This effect is usually ignored in the subsequent model updating [23]. Temperature effects on structural health monitoring have been presented [24,9,5,7]. The variation of intrinsic forces due to thermal and other mechanisms can mask the effects from all other demands. Previous studies indicated the presence of large changes in the intrinsic forces over time but could not explain the exact mechanisms that give rise to these forces [8]. Recently, a few researchers have tried to identify structural parameters of bridges using the temperature-based approach. Kulprapha and Warnitchai [15] investigated the feasibility to monitor the structural health of multi-span pre-stressed concrete bridges using the ambient thermal loads and responses, such as strains, deflections and support reaction forces, etc. Yarnold and Moon [25] created the structural health monitoring baseline by utilizing the relationship between temperature changes and the strain/displacement responses.

In this paper, a temperature-based response sensitivity method has been developed to identify both the thermal load on the structure and the bilinear connection stiffness of the semi-rigid joint that takes into account the friction slip of the interface, the shearing of the tenon and the gap between the tenon and the mortise of the 'Que-Ti' in typical heritage Tibetan buildings from measured strain responses. The measured strain responses from the structure is the output of the system while the thermal load which is the excitation input and the stiffness of 'Que-Ti' can be determined accurately based on the dual Kalman Filter and temperature-based response sensitivity respectively. 'Que-Ti' is modeled as two bilinear rotational springs and one compressive spring. A two dimensional frame model is used to address the accuracy and reliability of the proposed method. A long-term monitoring system has been installed in a typical Tibetan heritage building and the collected data has been verified the method. The numerical results show that thermal load on the structure, unknown boundary conditions and the stiffness of the 'Que-Ti' can be identified accurately in the time domain even with 10% noise in strain measurements. The identified results from the field monitoring data using the proposed bilinear connection model can obtain a better accuracy in the identified results than using linear connection model [19].

2. Bilinear connection stiffness model for the 'Que-Ti'

One of the unique characteristics for typical Tibetan historic timber structures is the use of 'Que-Ti' as connections transferring the loading between the beam and column with an increase in the bearing area at the end of the beam, and a decrease of the beam span leading to an improved shear and bending resistance at the beam end. It seldom involves nails or pins in its construction [27]. The beam-column joint of a historic timber architecture, as shown in Fig. 1, is typically a planar structural component supporting column from the top and beams coming in from two horizontal directions with the beam discontinuous at the top of the column. The thickened parts of the connecting members close to the intersection form the 'Que-Ti'. The shear connector between beam and 'Que-Ti' is shown in Fig. 2. The deformation of the beam is limited by a wooden stick fit into a hole, which is shown with the rectangular mark in Fig. 2. The wooden stick and the hole in the connection are called the tenon and mortise respectively. Due to fabrication error and shrinkage distortion of wood, there will be a gap between the mortise and tenon, denote as s as shown in Fig. 3. The gap between the tenon and the 'Que-Ti' at the mortise will change under loading. The gap needs to be considered in the connection stiffness identification [6,12]. The stiffness parameters of 'Que-Ti' have been studied without considering the friction slip of the interface, the shearing of the tenon and the gap between the tenon and the mortise [19].

A two beams and one column frame model with 'Que-Ti' connection is adopted in ANSYS software, as an example, a one millimetre gap at both sides between the mortise and tenon is shown in Fig. 4. The contact between 'Que-Ti' and the beam, mortise and tenon are frictional contacts. Only thermal load and the self-weight of the structure are considered on the frame. Three temperature changes, from 0 °C to 5 °C, from 5 °C to 10 °C and from 10 °C to 20 °C, are studied to see how the friction and slip occur at the interface under loading. When the thermal load is small, it is a fully sticky stage and the frictional slip does not happen. The gap between the mortise and tenon has been changed, as shown in Fig. 5(b). As the thermal load increases, the frictional slip occurs as shown in Fig. 5(c). Fig. 5(d) reflects the mortise and tenon fully contact each other when the temperature variation reaches 20 °C. Considering the range of gap is mainly between 0 mm and 3 mm, the Moment-rotation curves with different gaps can be seen in Fig. 6. Based on the results in this figure, there are mainly two phases: the non-contact and contact between the mortise and tenon. The frictional slip and the relative longitudinal displacement at the contact surface between the beam and connection will occur under external loads. When the relative longitudinal displacement is larger than the gap s, the tenon will be subjected to the longitudinal shear which contributes to the load resistance of the layered beam. The location, range of slip and the distribution of the friction force vary with the external loading. Therefore, it is a typical nonlinear beam-column connection. A bilinear model is adopted in this study with the following assumptions for the beam-column connection system: