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Connection stiffness identification of historic timber buildings using Temperature-based sensitivity analysis

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ABSTRACT

The beam-column connection, called 'Que Ti', is the key component of historic Tibetan timber buildings to transfer shear, compression and bending loads from one structural element to another. This kind of connections can reduce the internal forces and improve the structure's ability to resist earthquakes. Its structure is very complicated and there is little information about the behaviour of this kind of semi-rigid connections. In this paper, a temperature-based response sensitivity method is proposed to identify the connection stiffness of the 'Que-Ti' in typical historical Tibetan buildings from temperature and strain response measurements. The semi-rigid connection is modeled as two rotational springs and one compressive spring. The temperature is treated as a measurable input and the thermal loading on the structure can be determined from the temperature variation. The numerical results show the method is effective and reliable to identify both unknown boundary conditions and the connection stiffness of the structure accurately even with 10% noise in measurements. A long-term monitoring system has also been installed in a typical historical Tibetan building and the monitoring data are used to further verify the proposed method. The experimental results show that the identified stiffnesses by the proposed method are consistent with that by finite element model updating from ambient vibration measurements.

1. Introduction

Historic Tibetan buildings have an important role in the cultural heritage of society. These structures are subjected to earthquake, environmental and operational loading and they have experienced large environmental changes in last few centuries. There is an increasing interest to develop a rigorous and reliable approach for assessing the condition of these historic structures in operational environments. The historic timber architecture is a special kind of frame structures with the unique joint called 'Que-Ti', as shown in Fig. 1. 'Que-Ti' is a key component in historic Tibetan timber buildings and it is very important to assess the condition of this joint in the operational environment for structural safety.

During the past decade, many advanced analysis techniques such as finite element method have been applied to describe the various types of connections in the timber structures, e.g., Dou Gong [13,29], the mortise and tenon joint [8,5,32], the plug-slot [17], the glued in rod [36,33] and drift pins [35]. To authors' knowledge, there is a little research on modeling of 'Que-Ti'. Bjorhovde et al. [3] reported that the actual stiffness or restraint of connections lies between the two extremes of pinned and rigid, resulting in the development of connection stiffness models. Semi-rigid connections in frames have attracted attention of the researchers in last decades [1,16,14,34]. Particularly, the existence of semi-rigid joints in ancient timber architecture has become significant as it transfers shear, compression, and bending loads from one structural element to another. It can also reduce the internal forces and improve the structure's ability to resist earthquakes [11].

Past studies have illustrated the significance of structural identification by using the field measurements to validate and update analytical models [2,4,28]. Time histories of dynamic responses were adopted to identify the damage in the structure [7]. Structural stiffness parameters of a multi-storey framework were identified using the modal response in time domain with the genetic algorithm [18]. The dynamic response sensitivity based finite element model updating method has been developed to identify structural parameters [23,15,24,22]. The method only needs a few number of measurement points and it still can provide high accuracy for parameter identification as it takes advantage of the plentiful time history data. In fact, structural identification that is based on a reference set of measured data usually has the problem of different environmental temperatures in the two sets of measurements, and the effect of the temperature difference is normally ignored in the subsequent model updating [37]. Thermal effect may be more significant as the temperature generated by large

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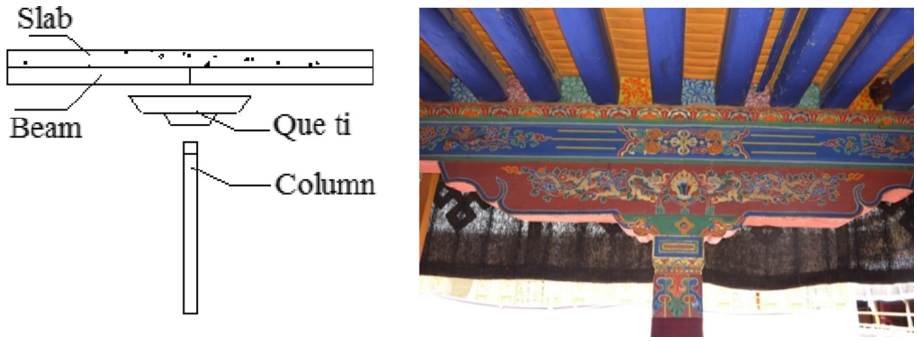

Fig. 1. Composition of beam-column joints.

ambient temperature variation may be larger than those produced by live load. The temperature effects have been considered in the structural health monitoring [26,40,9]. Previous measurements indicate large changes in intrinsic forces over time and the exact mechanisms that give rise to these forces are not known [6]. The research has revealed that discrepancies in the predicted versus measured responses of a constructed system are typically significant and it often results from an inability to accurately model all of the critical mechanisms in a priori manner. It is important to recognize that such errors are largely independent on any inherent shortcomings of available simulation tools, but rather, reflect a lack of knowledge or epistemic uncertainty [39].

Recently, a few researchers have tried to identify structural parameters of bridges using the temperature-based approach. Kulprapha and Warnitchai [19] 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. Yarnold and Moon [38] created the structural health monitoring baseline by utilizing the relationship between temperature changes and the strain/displacement responses. The thermal load is a slow-varying load compared with other dynamic loads. Lyu and Yang [25] developed a recursive least-squares method to extract the thermal load of a bridge structure from measured acceleration responses.

In this paper, a temperature-based response sensitivity method has been developed to identify the connection stiffness of the semi-rigid joint in typical historic Tibetan buildings from measured strain responses and temperatures. The structural temperature is monitored and then the thermal loading on the structure can be obtained from the temperature variation. This thermal loading is the excitation input of the structural system and the measured strain response is the output of the system. The structural parameters are determined using the temperature-based response sensitivity. 'Que-Ti' is modeled as two 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 both 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 method are consistent with that using the traditional dynamic method from ambient vibration measurements.

2. Numerical study

2.1. Model of the 'Que-Ti'

One of the unique characteristics for typical Tibetan historic timber structures is the use of the 'Que-Ti' as connections that transfer the loading between beam and column. The shear and bending resistance at the beam end can be improved by an increase in the bearing area at the end of the beam, and a decrease of the beam span. It seldom involves nails or pins in its construction [11]. 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 discontinued at the top of the column. The thickened parts of the connecting members close to the intersection form the 'Que-Ti'. With consideration of this arrangement, three linear springs are used to simulate the behaviour of a 'Que-Ti' in which two of them are rotational springs with stiffnesses K2 and K3 to simulate the behaviour of the rotating restraint on the beam, and the other one with stiffness K1 has vertical compressive stiffness to simulate the compression behaviour perpendicular to grain as shown in Fig. 2. In this study, all strain measurements in the time frame are much smaller than 300$\mu\varepsilon$. According to the GB/T 1931–2009 [27], the behaviour of time materials can be treated as linear elastic when the strain is less than 0.16% (about 1600$\mu\varepsilon$). Considering only thermal load was adopted in this study which cause strain are all small and in linear range, the three spring stiffness matrices are assumed linear and uncoupled.

2.2. A priori finite element model of a timber frame structure in typical Tibetan buildings

As shown in Fig. 3, a two dimensional frame structure with unknown parameters rotational spring stiffnesses K_2, K_3, K_5 and K_6 and vertical compressive spring stiffnesses K_1 and K_4 is adopted to illustrate the approach. This structure is modeled using two planar beam finite elements with three internal nodes in the vertical component (simulation of column components), and three planar beam finite elements with 10 internal nodes in the horizontal component. The structure is simply-supported at column bases and sliding-hinged at the end of beams. The cross-section of all beam members is 0.25 m $\times$ 0.5 m and the cross section of column is a variable cross-section from 0.25 m $\times$ 0.25 m to 0.4 m $\times$ 0.4 m. Beam and column members are of 4.150 m and 3.370 m long respectively. The material properties are assumed to be uniform along the length of the component. The mass density and the elastic modulus of material are 0.418 g/cm^3 and 6435 MPa respectively. No external static loading is considered on the frame other than the self-weight of the structure. This configuration will be adopted for all studies in this paper.

The response data used for this study was generated from a numerical modeling in which a measured temperature time history was applied and the response measurements include the strains at the beam and column. Unknown parameters can be identified using the temperature based response sensitivity analysis as shown below.

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