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Engineering Structures 30 (2008) 2101–2113

ENGINEERING STRUCTURES

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Seismic vulnerability of historic Dieh–Dou timber structures in Taiwan

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Available online 4 March 2008

Abstract

Dieh–Dou timber structures are commonly used as a traditional temple in Taiwan, which is located in a highly seismic area. In order to understand the not well-known behaviour of these historic timber buildings under earthquake, a preliminary FE linear analysis was performed showing that the stiffness of the timber joints is important in changing the magnitude of the overall displacement of the building. Ten laboratory tests on the set joints showed that their rotational stiffness depends on the vertical load applied to the joint while the translational stiffness is not affected by the vertical load applied, but the pull-out resistance is highly dependant on the accurateness of the connection. Inserting the appropriate values of stiffness into a refined FE model for three different frames, it is shown that the resulting displacements and stresses in the elements are in line with the failures observed after the 1999 Chi–Chi earthquake, confirming that a FE modelling can be used to assess the ultimate capacity of these historic buildings. As a further refinement, the use of a step-by-step nonlinear analysis will allow taking into account the global reduction of stiffness of the building due to the horizontal elements that reach the pull-out limit and ultimately lead to an accurate evaluation procedure for each typology.

Keywords: Historic timber structures; Seismic reliability; Finite element modelling; Timber joint; Joint stiffness

1. Introduction

Timber is a material widely used in historic building in Far East Asia. The traditional architecture of Taiwan is based on Minnan style (Fu, [1]), a style originated and relatively common in South Fujian, a southern region of mainland China, but still substantially distinguishable from it. Chang [2] classifies traditional Taiwanese timber buildings into two types from the structural point of view, the Dieh–Dou and the Chuan–Dou. Dieh–Dou structures, originated in Southern China and later modified and developed in Taiwan, are normally used for temples or wealthy residential buildings.

A temple compound typically includes several buildings and each building consists of two timber plane frames with the same layout supporting a system of purlins and connected to perimeter masonry walls laid in the direction normal to them. When used in temples, the main objective for the carpenters is to create a large free central space between the supporting columns. Figs. 1 and 2 show a schematic elevation and a real Dieh–Dou beam stack of the main space of a Dieh–Dou timber frame containing three layers of brackets. The weight of the roof is transferred from the purlins to the top of Dou–Gon sets. The load is then transferred to the columns (and then to ground) through three orders of beams connected with the Dou–Gon sets, as shown in the figures.

The small highly decorated timber elements stacked together to form the Dou–Gon (Fig. 3), are a characteristic feature of this typology, with the role of supporting the purlins and transfer their load to the timber beams and columns of the main frame. Beams and columns in the lower part of the structure are connected by mortise and tenon while the components of the Dou are shaped in double notch joints and connected to the out of plane members by way of shallow dove tails. The in plane bracket connects one Dou–Gon to the next in the plane of the frame, creating the slope of the roof, while in its concavity accommodates the round purlin. The system of transversal round purlins connecting the two adjacent frames provides out of plane stability and it is further stiffened by the out of plane brackets. Lateral forces, such as wind uplift or accidental impact, are counteracted by the substantial weight of the roof; however, this also represents a large mass that

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doi:10.1016/j.engstruct.2007.11.007

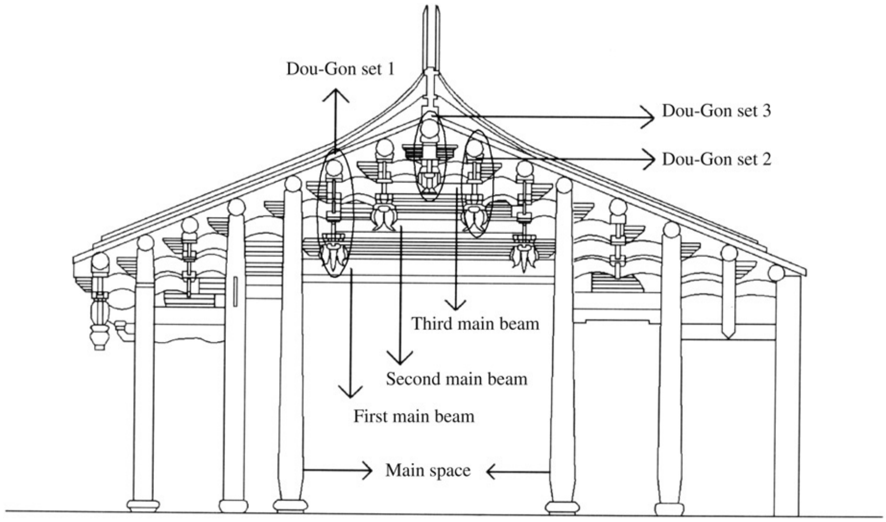

Fig. 1. Schematic illustration of a Dieh–Dou timber frame modified from [3].

Fig. 2. Timber frame of main space of Guan–Shi family temple.

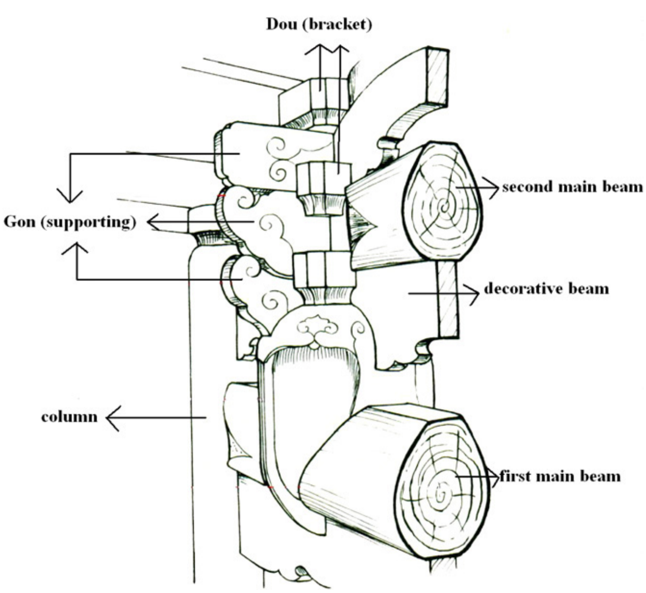

Fig. 3. Detail of Dou–Gon set modified from [4].

will produce large inertia forces in the event of an earthquake, causing substantial sway.

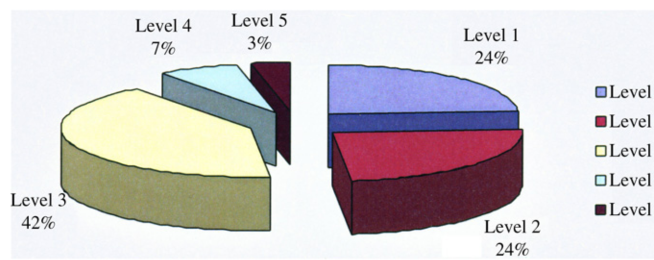

Fig. 4. Level of damage of Dieh–Dou buildings after Chi–Chi earthquake.

Such inherent seismic vulnerability was clearly highlighted by the widespread damage caused to this type of structures by the 1999 Chi–Chi earthquake of 7.3 Richter Scale. According to Chang [2], only 7% of timber buildings showed little damage, while most buildings were seriously damaged (45%) or collapsed (48%). However, these statistics did not classify the timber buildings by structural type. Further investigation carried out within the present project, identified at least 52 historical architecture compounds built as Dieh–Dou structures over the Chi–Chi earthquake stricken region; however, for 29 of them it was not possible to gather data about their condition after the event. For the remaining 23 Dieh–Dou compounds, Fig. 4 shows the level of damage that was identified. Level 1 means no damage. Buildings with elements pulling out from joints and roof decorated ridge damage are in level 2. Level 3 is the case of eaves rupture, masonry wall cracks and columns sliding from the original position, which are not considered an immediate threat to collapse. Finally, buildings leaning and collapsed are classified as damage level 4 and 5, respectively.

Given the crucial role that this architectural heritage has in testifying and illustrating the uniqueness of Taiwanese culture (Fu [1]), it is essential to thoroughly study and understand the structural behaviour of these buildings in order to repair and preserve them without reducing their significance and heritage value.

The remarkable difference between Far East Asian traditional architecture and modern western style timber joints