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Finite Element Modelling of Dieh-Dou Buildings in Taiwan

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ABSTRACT: Taiwan is in seismic zone and it is therefore necessary to perform structural analyses of Dieh-Dou historic timber buildings and assess their vulnerability under earthquake. The peculiarity of these structures lies on the existence of some unique bracket sets supporting the vertical load of the roof in correspondence of each transversal rafter and transferring the load to the to outer columns, which finally transfer the loads on the ground. In this particular structural system the modelling with finite element analysis (FEA) can bring several advantages, allowing a quick identification of the vulnerable areas. In the first stage, one single frame model was created in the finite element software "ALGOR" to simulate the response under horizontal load. The result shows that the according to the rotational stiffness of joints, the value of maximum displacement changes considerably, especially in the stiffness range 10^3 to 10^8 N.m/rad. Preliminary physical tests were undertaken in laboratory to find out the real rotational stiffness, which was found to be highly dependant on the magnitude of the vertical load applied on the joint, but in any case ranging from 10^4 to 5×10^4 N.m/rad, corresponding to the zone of high deformability of the structure.

1 INTRODUCTION

Timber is a common material for historic buildings in Far East Asia, which is an area of the globe where strong earthquakes happen frequently. In Taiwan, traditional buildings are classified into Dieh-Dou and Chuan-Dou buildings (Chang 2005). Dieh-Dou buildings are used for temples and wealthy houses while Chuan-Dou buildings are used for ordinary houses. As a result, Dieh-Dou timber structures are considered as highly representative of the traditional Taiwanese culture. Dieh-Dou buildings originated in the South of China and were later modified and developed in Taiwan. The characteristic features of these buildings are the small highly decorated timber elements stacked together to create bracket sets (Dou-Gon) that support the weight of the roof and transfer it to the main timber beams and columns.

Taiwan is located in a highly seismic zone where this kind of building is easily damaged under earthquake. According to Chang (2005), after the 1999 Chi-Chi earthquake (7.6 Magnitude), only 7 % of timber buildings had little damage, while most buildings were seriously damaged (45 %) or collapsed (48 %). In order to repair and preserve these historic buildings without reducing their significance and heritage value, it is necessary to find a way to analyse them properly as their structural behaviour is not fully comprehended. The advantages of a computer simulation for a structure whose characteristics are not well defined is the possibility of a parametric study to be compared with site surveys of damaged buildings, which will help to identify the overall behaviour and the vulnerable elements.

A program of numerical simulation of increasing complexity using the FE software ALGOR, together with a campaign of tests on some full-scale specimens of the Dou-Gon bracket set to identify accurate values of stiffness is undergoing at Bath University. In the present paper, the preliminary result of FE models and laboratory tests are discussed and compared after a brief description of Dieh-Dou construction.

2 PREVIOUS RESEARCH OF DIEH-DOU BUILDINGS

2.1 Brief summary of Dieh-Dou building

A Dieh-Dou building consists of two timber frames, which support the weight of the roof, and external masonry walls. The two timber frames have the same layout and are connected out of plane by several purlins, while the masonry walls provide the external enclosure. Because of their use as temples, the carpenters endeavoured to create a larger free internal space for ceremonial purpose. Fig. 1 is a schematic illustration of a Dieh-Dou timber frame, in which the bracket sets, Dou Gon are sitting on the main beams to increase the free central space.

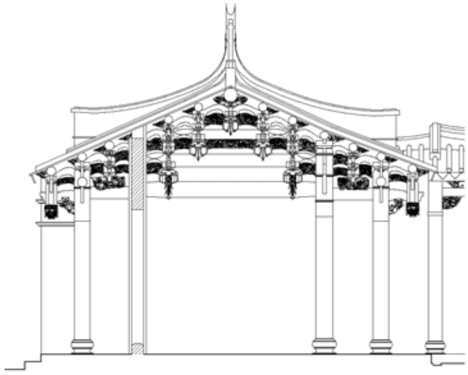


Figure 1 : Schematic illustration of Dieh-Dou timber frame (Hsu and Chang, 2005).

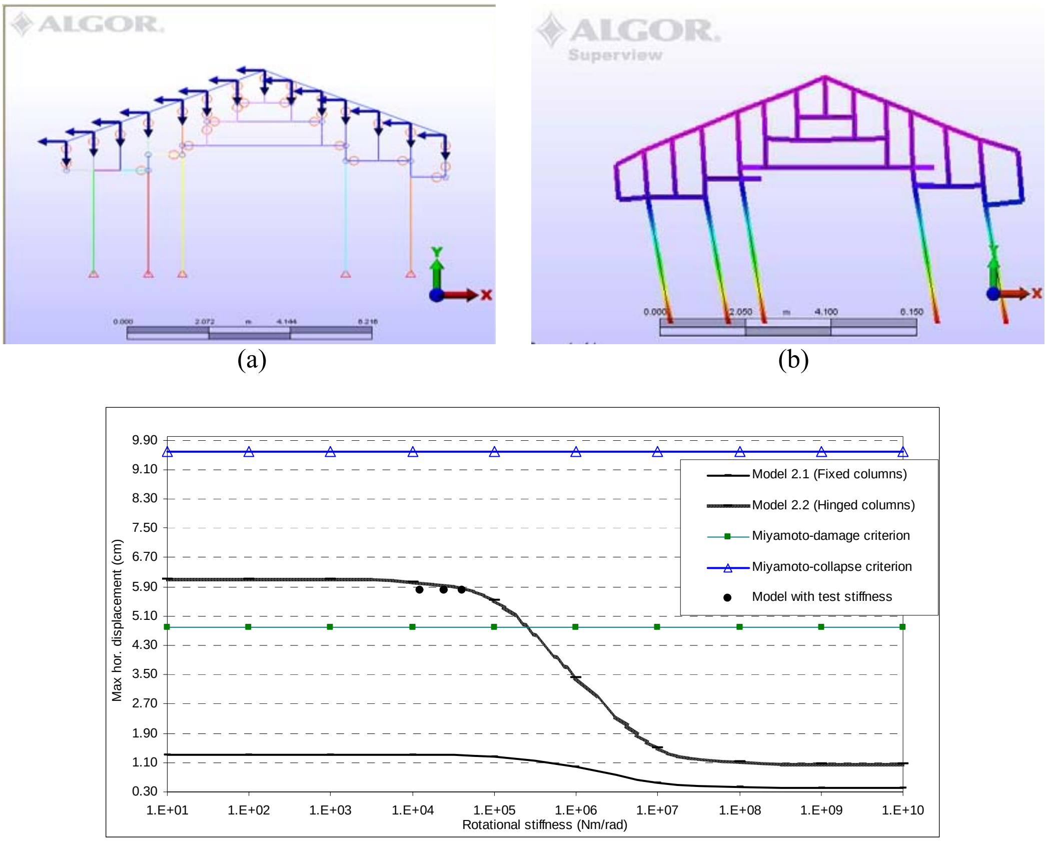
Figure 2 : Small structural components forming the upper part of Dieh-Dou structure by stacking and mortise tenon connections. (photo taken by Chow).

A Dieh-Dou building is built by several pieces of wood connected by mortise and tenon. The structure can be subdivided into a lower portion with two or four columns connected in mortise and tenon by a beam and an upper portion consisting of components assembled by brackets and double notch joint system and stacking. As illustrated in Fig. 2, the short columns are sitting as a saddle on a beam and stacked with other beams and short columns. A system of transversal round purlins connects the two adjacent frames and provides out of plane stability. The global lateral stability of the structure, as far as wind or accidental impact is concerned, is provided by the substantial weight of the roof, however this also represents a large mass that will produce large inertia forces in the event of an earthquake, causing substantial sway.

2.2 Previous frame modelling

Because the out of plane purlins that connect the frames are sitting on the top of the Dou (that is the upper part of Dieh-Dou set) without a tenon and mortise connection between them, they easily slide out of their seating under earthquake; several cases showed that once the purlins failed, the two frames of Dieh-Dou buildings move separately. In a previous paper by Tsai and D'Ayala (2005), a finite element simulation with ALGOR was performed modelling the plane frame of a Dieh-Dou building, in which only the main structural elements (as defined by Shu, 2000) were inserted. In this preliminary modelling, all the stiffness values of Dieh-Dou joints within a model were assumed the same, but different models were considered in which the stiffness value was changed from 10 to 10^{10} N.m/rad. The results showed that the value of stiffness of the Dieh-Dou set affects the maximum displacement of the building considerably.

Given the specificity of each of the temples, the frame of the main hall of Guan-Shi family Temple, which suffered serious global leaning under Chi-Chi earthquake, was chosen as case study Fig. 3a. The diagram of Fig. 3a shows the released joints and two cases were considered for the connection column-footpad, as either fixed (2.1) or hinged (2.2). The lateral load applied was equivalent to 0.3 g, lower than the maximum PGA recorded nearby. The deformed shape for model 2.2 (Fig. 3b) highlights the importance of the release of the joints at the top and bottom of the columns, and the failure of the cantilevering portion of the roof. This compare well with the heavy leaning and local failure for the temple as surveyed on site. The results in terms of lateral maximum displacement are shown in Fig. 3c and are compared with the maximum displacement of the damage limit criterion proposed by Miyamoto for historic timber structures in Japan (Miyamoto 2004), and with the corresponding collapse criterion, in which the damage limit value is doubled. This preliminary result indicates that the stiffness of Dieh-Dou joint set governs the structural behaviour and the actual value of stiffness dramatically changes the behaviour in terms of maximum displacement in the range 10^4 to 10^7.



(a) (b)

(c)

Figure 3 : (a) Finite element model indicating joints with release and finite stiffness, (b) deformed shape, (c) maximum lateral displacement as a function of joints stiffness.

2.3 *Discussion*

Besides the results of this preliminary simplified analysis, other works in literature show that numerical analyses with FE can be successfully employed to simulate Far East timber structures under earthquake loading (Fang 2001). While the preliminary modeling represents well the qualitative performance of the temple as observed on site, a more accurate value of the rotational stiffness of each joint needs to be determined, in order to have valid quantitative results. To this end, it was decided to perform a campaign of physical tests on the Dou Gon set.

3 DIEH-DOU JOINT TEST

3.1 *Introduction of Dieh-Dou joint test*

The bracket set of a Dieh-Dou building can be regarded as divided into different layers (see Fig. 4, that shows an example of a two-layer bracket set). A bracket set can have two or three layers according to its position along the height of the in-plane frame (Figs. 1, 2). Each layer consists of appositely cross shaped bracket timber pieces (parts 1, 5 and 9), continuous out-of-plane brackets (parts 2 and 6) that help to transfer the vertical loads from the purlin into the bracket set and discontinuous in-plane beams (parts 3, 4, 7 and 8), which connect adjacent bracket sets and columns and form the in-plane main frame of these structures. For the purpose of the experimental test, only one layer of Dieh-Dou set was reproduced at full scale. This is made of Part 5, the Dou, Part 6, the out of plane continuous bracket, and part 7 and 8, the in plane beams that connect to the other bracket sets and the far column.

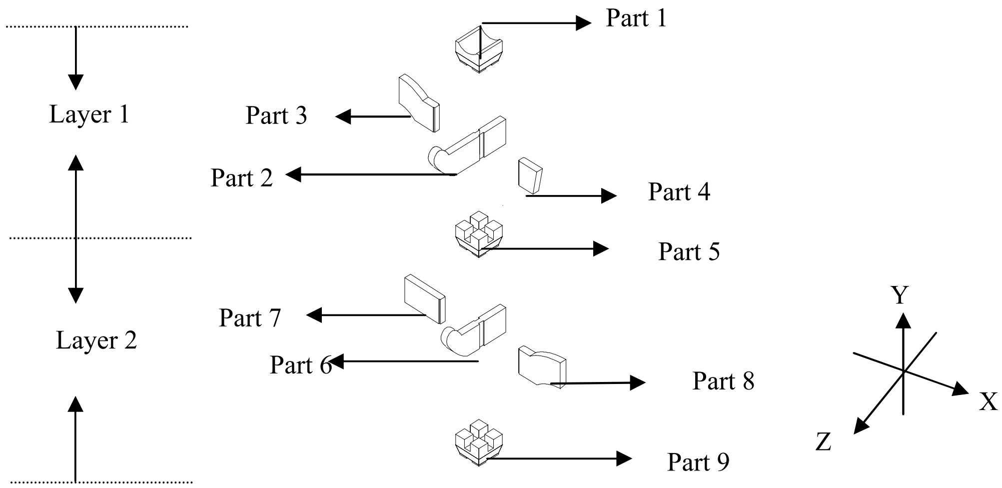


Figure 4 : Two layers of a Dieh-Dou joint.

3.2 Material properties

A major issue, when performing material tests related to historic buildings is the sourcing of correct material replica of the original on site, as, given the heritage value of the structure, components cannot be removed and tested to destruction. Tsai (1997) surveyed the timber types of historic buildings in Taiwan and found that several different kinds of softwood were used for the construction of these structures. Dieh-Dou buildings are heritage buildings, which mean that their timber is at least one hundred years old. In order to accurately account for the aging process, two timber beams reclaimed from a timber truss roof of a dismantled historic English church were used as the base material for the test specimen. The timber type is pine, a softwood specie.

Material properties test were performed in laboratory following the BS EN 408 and ASTM D198 codes. A moisture content of 10 % and average density of 400 kgf/m^3 were found. Compression tests and static bending tests were performed to evaluate the modulus of elasticity and strength of the material. According to the reference (Tsai 1997), the most commonly used timber for the main structural elements is cedar; a comparison between the properties of Asian Cedar (Wood Handbook, US department of Agriculture Forest) and the timber used for the specimens is summarized in Table 1, confirming the appropriateness of the choice made.

Table 1 : Material property.

	MOE parallel to grain (N/mm^2)	Compressive strength parallel to grain (N/mm^2)	MOR (Bending strength parallel to grain) (N/mm^2)
Specimen	6500	20	46
Cedar	6400	32	47

3.3 Test specimens and device

In Dieh-Dou buildings, some of the in-plane brackets are slightly curved (see part 8 in Fig. 4) but in order to simplify the test arrangement, all the test pieces were considered straight. The typical test specimens are shown in Fig. 5. The dimensions were taken as average values of a field survey carried out by the authors (Tsai & D'Ayala 2005) and according to Chao (2004).

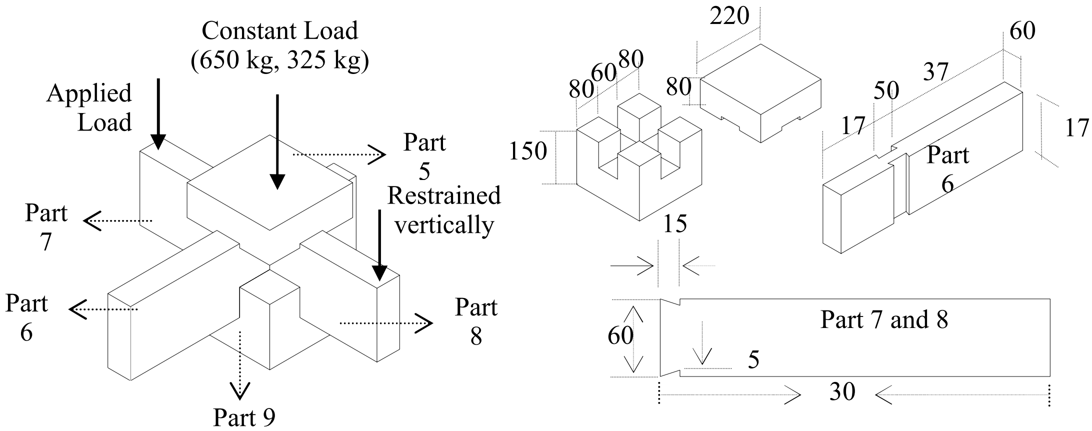


Figure 5 : Dieh-Dou joint specimen.

As mentioned before, the Dieh-Dou timber structures are made of several pieces of timber stacked together (Figs. 1 and 2); the load that acts on each different layer is different and one of the aim of the test is to verify to which extent this affects the stiffness of the joint. Two levels of loads were considered. Firstly, a constant load of 6.5 kN was applied on the upper Dou, which represents the dead weight of the roof and timber pieces above the lowest layer of a joint in the Dieh-Dou frame of Guan-Shi family temple and secondly a constant vertical load of 3.25 KN, representing a joint in the second layer. Test 1 and 2 refer to the first load level, Test 3 and 4 to the second.

A restraining jack was put on the top of part 8 (see Fig. 5) to prevent the joint to rotate during testing. In the real building, the further end of this beam (part 8) is restrained to prevent upward movement by the other Dieh-Dou set loaded vertically with the same value of the Dieh-Dou under testing. Finally a steel cylinder was inserted between jack and specimen to apply the point load, and two transducers were set on part 7 to record the displacements and calculate the beam rotation under loading. The apparatus is shown in Fig. 6 and 7.

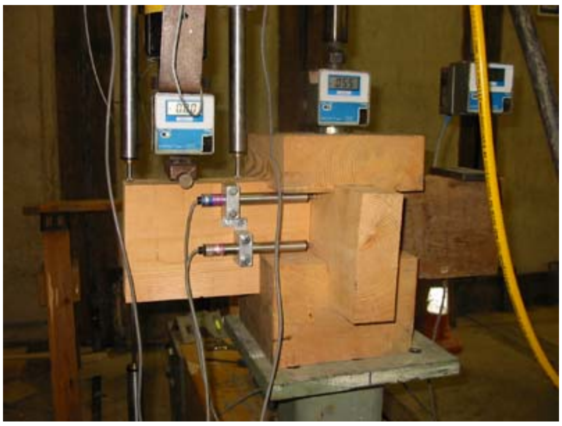


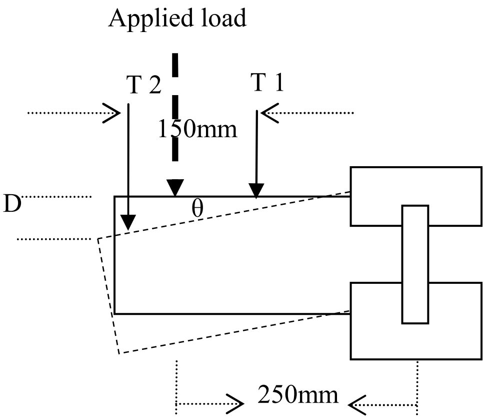
Figure 6 : Test apparatus.

Figure 7 : Applied load jack.

3.4 *Result of testing*

Transducers 1 and 2 were used to measure the displacements of the timber beam under loading. The difference of vertical displacement between transducer 1 and 2, divided by their distance, gives the rotation. The moment is calculated taking a lever arm from the centre of the load cell jack to the centre of the joint. The rotation and moment measurement are shown in Fig. 8.

The moment-rotation relationship for tests 1 and 2 are shown in Figs. 9 and 10.



$$\theta = \tan^{-1} \frac{D_{T2} - D_{T1}}{150}$$

$$M(N.m) = (\text{Applied Load}) \times 250(mm)$$

Figure 8 : Rotation and moment measurement.

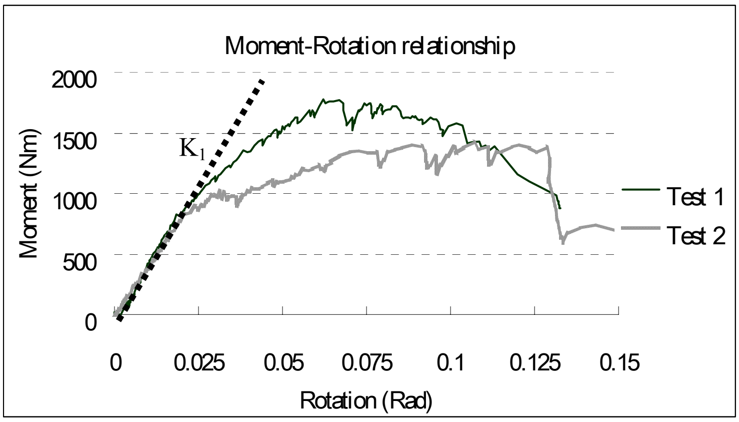


Figure 9 : Moment-rotation relationship for test 1 and test 2.

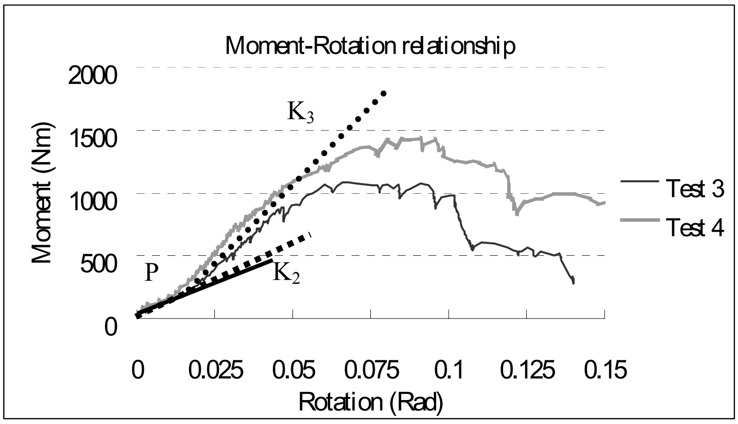


Figure 10 : Moment-rotation relationship for test 3 and test 4.

The rotational stiffness in the elastic stage in tests 1 and 2 is 4×10^4 and 4.09×10^4 N.m/rad (see Fig. 9), with an average value of 4.045×10^4 N.m/rad. In these tests the restraining jack on the top of part 8 (see Fig. 5) did not take any force, indicating that whit such vertical load magnitude the joint does not rotate, so the other portion of the beam does not affect the joint stiffness.

In tests 3 and 4 (see Fig. 10), where only 3.25 kN were applied on part 5, the moment-rotation relationship shows a different behaviour from the previous case, as two elastic stiffness can be defined in the plot. In the first stage, stiffness K2 is 1.16×10^4 and 1.3×10^4 N.m/rad for test 3 and 4 respectively. At point P, the stiffness changed to 2.3×10^4 and 2.5×10^4 N.m/rad respectively. Point P corresponds to the moment when the restraining jack on part 8 starts taking load, showing that in the case of reduced vertical load the joint can rotate and the stiffness changes according to the degree of restraining of the bracket set. The average elastic stiffness, in this case, is $K2 = 1.23 \times 10^4$ N.m/rad when the rest of the beam does not contribute and $K3 = 2.4 \times 10^4$ N.m/rad when it is activated. In both cases, the value of the stiffness is two to three times lower than in the previous case. The maximum value of load on the restraining jack is 1 kN.

3.5 Joint modeling

A 2D finite element was created on ALGOR to simulate part of the physical test. In this model, only half of part 5 and part 7 were considered, having assumed symmetry; the top surface of part 5 was restrained and a hinge was put on the point of part 7 corresponding to the edge of the lower supporting Dou (see Fig. 11). In this model a mechanical event simulation is performed with the two surfaces of part 5 and 7 separated by a 1 mm gap and a contact distance of 1 mm is defined, which means that they are in contact throughout the analysis, when the load is increased from zero until the maximum load reached in the tests. In this model the restraint provided by the dovetailing of part 7 in part 6 is ignored. The aim is to separate the effect of the vertical loading from the effect of the dovetailing, simulated in a second model.

Analyzing the maximum and minimum principal stresses in the model elements, it is found that, for values of load approaching the real failure load, tensile principal stresses of up to 6.5 N/mm^2 were acting along the top of part 7, while compression perpendicular to the grain reached values of 15 N/mm^2 leading to bearing failure of the top portion (see Fig. 12).

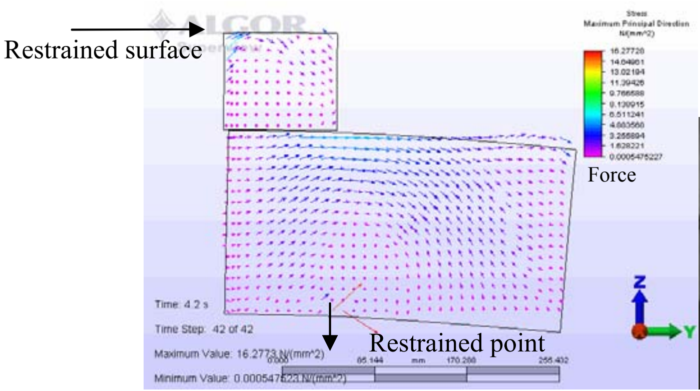


Figure 11 : FE model.


Figure 12 : Physical test failure.

4 CONCLUSIONS

Previous researches showed that numerical analyses with FE maybe successfully employed to simulate Far East timber structures under earthquake. In the first stage of this project it was found that a preliminary modeling with ALGOR can identify if the structure tends to have excessive permanent displacement under earthquake loading, when all the joints are considered with their appropriate stiffness and the columns are allowed to rotate, which seems reasonable given the actual connection typology with the stone pad.

The physical tests show that the stiffness of Dou Gon joints is always in the range of 1×10^4 to 5×10^4 N.m/rad; this corresponds to the range of values in Fig. 3c that gives higher displacement to the building. When the vertical load on the joint is 6.5 kN the elastic stiffness is constant, but when the load is reduced to half the stiffness decrease significantly and varies with the rotation and hence the level of restraint provided along the beam. This proves that the total weight acting on the top of Dou Gon joint governs the structural behavior. In many cases, the roof tile fell down at the early stage of a seismic event, hence leading to a great decrease of stiffness in the joints and increase of deformability of the structure. The average stiffness values obtained from tests were applied to the single frame model 2-2. In this analysis the stiffness of the joints located in the upper, medium and lower layers were put as $K1 = 1.23 \times 10^4$, $K2 = 2.4 \times 10^4$ and $K3 = 4.05 \times 10^4$ N.m/rad respectively. The maximum displacement is 5.88 cm, which still gives a storey drift higher than the Miyamoto criterion damage limit value (see Fig. 3c). The Guan-Shi family temple actually suffered serious global leaning after the Chi-Chi earthquake. This preliminary analysis shows that Dieh-Dou buildings may be prone to excessive displacements under earthquakes of such high magnitude. A fully nonlinear time step integration FE analysis considering the full three-dimensional structure will be necessary to accurately evaluate the behavior of these structures and give suggestion for their repair and structural conservation

The 2D finite element numerical model of the joint can explain the physics of the test failure and the maximum failure load if a yield criterion is adopted from the strength of the material. The conditions of computation modeling should be better refined to define other parameters of the test.

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