SEISMIC EVALUATION OF TRADITIONAL TIMBER STRUCTURES IN TAIWAN

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ABSTRACT :

The Taiwanese historic Dieh-Dou frames are prone to joint failures by element pull out or excessive rotation, during earthquake, as seen from reports and observations following the 1999 Chi-Chi earthquake. A series of laboratory tests were performed to obtain the actual value of rotational and translational stiffness and joint capacity, and a FE model of Dieh-Dou frame confirmed that these values fall within semi-rigid range very close to hinge behaviour. A parametric study indicates that rotational stiffness governs the overall displacements more than translational stiffness does. A non linear step by step analysis was performed to study the seismic response of these frames, where the model was updated at each step in accordance with the failure criteria. Results show that several elements pulled out or failed by exceeding rotational capacity in the early stage, especially in the corridor zone; this matches well with the observed failure mode of this building under the Chi-Chi earthquake confirming the accuracy of the methodology.

KEYWORDS: HISTORIC TIMBER FRAME, JOINT STIFFNESS, NUMERICAL ANALYSIS

1. INTRODUCTION

The island of Taiwan is populated by indigenous people and Hans from mainland China. Apart from these two races, in history, Taiwan has also seen the occupation of Spanish, Dutch and Japanese people. This multicultural environment reflects on the architecture in Taiwan. The Dieh-Dou buildings were mainly influenced by Chinese architecture (Fu 2005) but are a unique and typical Taiwanese traditional typology that differs from the Chinese Tailiang system in terms of construction and structure on the joints. The scheme of Dieh-Dou frame and Dou-Gon joints are illustrated in Figure 1. Dieh-Dou buildings are usually used as temples; these timber compounds include several buildings and each building consists of two identical timber frames connected to perimeter masonry walls laid in the direction normal to them and supporting a system of purlins.

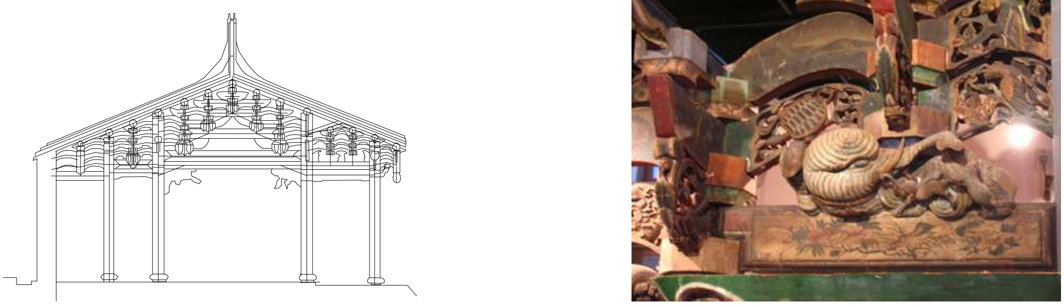


Figure 1 Schematic illustration of a Dieh-Dou timber frame and Dou-Gon joint

The main characteristic feature of Dieh-Dou buildings is the stack of small highly decorated timber elements forming the Dou-Gon joint set which sits on the main beam. This arrangement allows creating large spans between main columns and transfer the roof weight to the main beams and then to the ground. The Dou-Gon joint set consists in the Dou, which have the shape of double notch joints, and in plane members connected to the out of plane members (Gon) by means of shallow dovetail connections.

The construction of Dieh-Dou frames is complex and there is limited research on Dieh-Dou structures. The advantage of a computer simulation for a structure whose characteristics are not well defined is the possibility of parametric studies with corresponding identification of vulnerable areas and avoidance of extensive experimental work. However, to create a numerical model, the construction detail should be known. For timber structures, research has proved that the joints are not fixed nor pinned. The Dou Gon joint set takes an important role in Dieh-Dou buildings and there is no stiffness value that can be found in previous research as a reference.

In order to evaluate the Dieh-Dou buildings, first of all, the failure modes will be discussed and compared with FE model results. Secondly, a series of Dou-Gon joints tests are performed to obtain the actual value of stiffness. Finally, a refined finite element model is created to analyse and evaluate the failure of Dieh-Dou frames by increasing the loads in every step and performing a pushover analysis to be compared with the experimental observations.

2. FAILURE OF DIEH-DOU BUILDINGS

Taiwan is located between the Eurasian and Philippine Sea plates where the plate erupted from Philippine Sea pushes towards northwest into the Eurasian Plate: this is the cause of the frequent earthquakes in the island of Taiwan. On the 21st of September 1999 at 1:47 am, a devastating earthquake of magnitude Mw 7.6~7.7 happened in central Taiwan, with the epicentre located near Chi-Chi Town, Nan-Tou county, 7 kilometres below ground level. A review of post-earthquake damage reports 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 was not possible to gather data about their condition after the event. For the remaining 23 Dieh-Dou compounds, details of damage has been collected and classified into five levels of damage, according to structural failure. Level 1 being no structural damage, buildings with elements pulling out from joints and damage of the roof decorated ridge are categorised as level 2. As the bearing capacity of the structure as a whole is not impaired, damage level 3 includes eaves rupture, masonry wall cracks and columns sliding from the original position: these are not considered an immediate threat to collapse but may reduce the structural capacity. Finally, Dieh-Dou frames with overall in plane or out of plane leaning or collapse are classified as damage level 4 or 5, respectively.

From the surveys of Dieh-Dou building after the 1999 Ch-Chi earthquake, the most common local damage modes were found to be the elements pulling out, damage of the roof decorated ridge, eaves rupture, masonry wall cracks and columns sliding (table 1). The partial or global leaning or collapse are caused by several of these local damages concurring at the same time or by large quantity of same type of local damages, as for instance a large number of elements pulling out.

Table 1: Level of damage of Dieh-Dou buildings after the Chi-Chi earthquake

Damage level	Failure mode	Occurrence %
Level 1	No structural damage	24%
Level 2	Elements pulling out (10%) Damage of the roof decorated ridge (14%)	24%
Level 3	Eaves rupture (7%) Masonry wall cracks (21%) Columns sliding (14%)	42%
Level 4	Dieh-Dou frames with in plane or out of plane leaning	7%
Level 5	Dieh-Dou frames with in plane or out of plane collapse	3%

From the failure modes discussed before, the following conclusions can be drawn: 1)The two parallel timber Dieh-Dou frames are easy to separate (because purlins, linking two frames, sit on the top Dou without a proper connection, see Figure 2) and vibrate independently, 2)The bottom of columns can be considered as hinges; 3) horizontal elements easily pull out from joints; 4) There are several elements pulling out and rotating from joints(Figure 3) but few failing by material rupture; 5)The movement of the frames can be substantial before the frame collapses.

Figure 2 Upper Dou saddle to place purlin

Figure 3 Failure mode of Dou-Gon joint set

The damage factors and their causes highlight the importance of understanding the structural behaviour of heritage buildings. For the Dieh-Dou frames, in particular, a quantification of the bearing capacity and the load path among the members is necessary for further assessment and restoration where strictly necessary. An experimental campaign on Dieh-Dou joints (see D'Ayala, Tsai 2008), followed by an extensive sequence of numerical simulations were used to identify the structural behaviour.

3. JOINT STIFFNESS PARAMETRIC STUDY

3.1 Description of FE model

To create the finite element model analysed with the commercial Algor © package, the main hall of Guan-Shi family Temple was used as reference typology. This temple, built in 1849 (Hsu, 2002), According to Huang (2003), who categorised Dieh-Dou frame types by the number of columns and layers of beams, represents type B, one of the three most common types of Dieh-Dou construction. (see Figure 4). Due to the failure mode discussed above, a single planar frame was analysed, made of beam elements with cross sections according to the real building elements, with appropriate area and stiffness reductions for elements with holes. The load condition is represented by the self and imposed load of the frame and of equivalent horizontal forces representing an earthquake base acceleration of 0.3g (Su, 2003). Huang & Sheu (2001) stated that the failures of Dieh-Dou building were mainly caused by the heaviness of the roof weight compared with the lightness of the lower portion of building that led to large sway during horizontal earthquake. Hence, the tiny joint between wooden column and stone podium were modelled as hinge. Particular attention was paid to the accurate simulation of the internal joints of the timber frame, both for beam to columns, but also for the Dou Gon and the dove tails, by exploiting the complementarity of rigid elements and spring elements. Specifically, Figure 5 shows a joint simulation in the FE environment. On the left one layer of Dou-Gon joint set is reproduced, where node A is the centre of this joint layer. Next to node A is Line 1, whose length is from node A to the edge of Dou, while Line 2 is the beam element simulating the structural beam. Line 1 is located between node A and B, and is formed by three parallel elements, a rigid element, a DOF Spring element 1 and a DOF Spring element 2, respectively. For the Rigid Element, Tx and Ry are released while the other degrees of freedom are assigned the default rigid value. DOF Spring Elements 1 and 2 are assigned the appropriate translational or rotational stiffness respectively to simulate the finite stiffness of the joint for these two degrees of freedom as quantified in the test programme.

3.2 Effect Of Rotational and Translational Stiffness

Due to the limited number of laboratory test that could be realistically carried out during the project duration, the sensitivity of the model and the frame to variation in value of translational and rotational stiffness of the joints was studied by parametric analysis. First the translational stiffness was kept constant at a value of 1.8E+6 N/m, (as obtained by pull out tests for dove tail joints without imperfections) and the rotational stiffness was varied between 4E+0 to 4E+9 Nm/rad in the Dou joints, while a constant value is applied to all beam to bracket and beam to column joints. This allowed identifying the range of rotational stiffness for which the most substantial change in lateral displacement was obtained. The second part of the parametric study entailed keeping the rotational stiffness constant (at the extreme and median value of the range identified above) and varying the translational stiffness between 1E4 and 1E8 N/m. Table 2 illustrates the details for each of the groups of analysis.

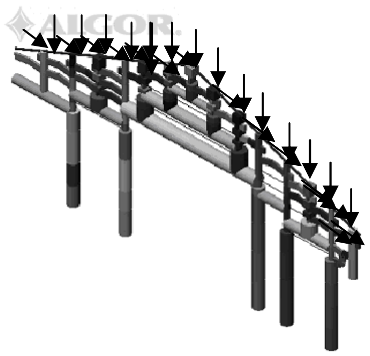


Figure 4: FE model

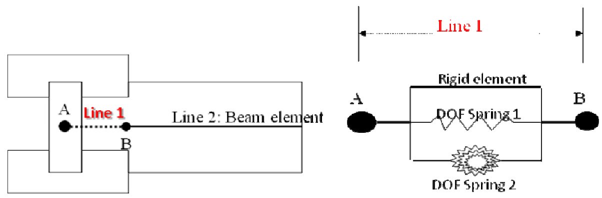


Figure 5: Joint simulation

Table 2: Rotational and translational stiffness value for each of the parametric analyses

	Rotational stiffness (Nm/rad)	Translational stiffness (N/m)
Group 1	4E+0 $<K_r<$4E+9	1.8E+6
Group 2	4E+4	1.8E+4 $<K_t<$ 1.8E+8
Group 3	4E+5	1.8E+4 $<K_t<$ 1.8E+8
Group 4	4E+6	1.8E+4 $<K_t<$ 1.8E+8

3.3 Results

As failure in Dieh-Dou building is brought about by lateral sway (Fang et al., 2001, Huang & Sheu, 2001), the influence of the stiffness is analysed in terms of roof apex lateral displacement and compared with a damage and failure criteria. Results are shown in Figure 6 for Group 1 and in Figure7 for Group 2 to 4. The result of Group 1 clearly shows that for constant translational stiffness is constant when the rotational stiffness is below 4E3 Nm/rad the structure tends to behave as if the joints are hinges while for stiffness value above 4E7 Nm/rad as if they are fixed, showing that this is the range of values for which the behaviour can be classified as semi-rigid joints. The rotational tests of Dou-Gon joints and the Chang's formula (Chang 2006) of beam to column joints are all in the range of 2E+4 and 3.8E+5 Nm/rad showing good correlation between tests and finite element modelling strategy. Moreover figures indicate that the joint stiffness is close to hinge behaviour.

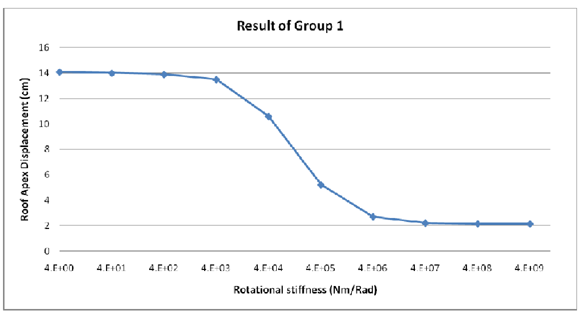


Figure 6: Results of Group 1 analysis

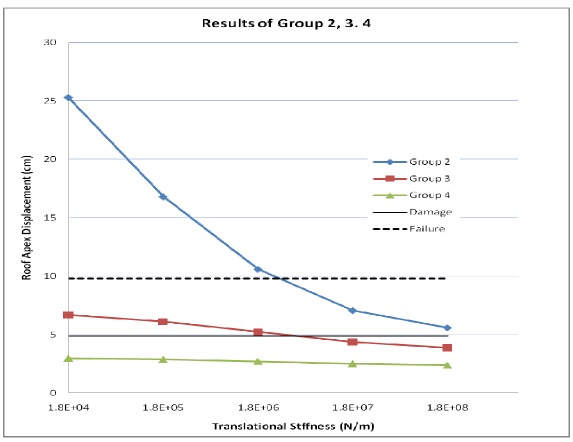


Figure 7: Results of Group 2 to 4 analyses

Comparing results of Group 2 to 4 in Figure 7, it is clear that the effects of variation in translational stiffness are amplified when reducing the rotational stiffness. It is particularly significant that the results comprised between rotational stiffness of 4E4 to 4E5 Nm/rad and translational stiffness of 1.8E6 to 1.8E8, (the range identified in the tests), are all contained between the damage and failure threshold for this structure. As proposed by Miyamoto et al (2004) for Asian historic timber structures. These are set as 1/120 storey drift for damage criterion and 1/60 storey drift for failure criterion.

4. EVALUATION ON DIEH-DOU FRAME

The parametric analyses discussed in the previous section were carried out in the linear range, assuming constant value for materials and connection and applying the maximum expected lateral load. The aim of the project is to define simplified modelling techniques for the vulnerability assessment of these structures and hence a linear approach would be ideal when many structures need to be assessed in a short time. Hence to validate results of the previous section a non linear pushover analysis of the same frame for a given set of initial value of stiffness of the joint was performed. For the rotational and translational stiffness of Dou-Gon joint set were applied the values obtained from tests. For the classic beam to column joint, the stiffness of these joints was assumed in relation to the connection geometry as proposed by Chang (2006) The translational stiffness was applied as for Dou-Gon joints, as the tests results shows there was no difference between different types of joints. Moreover a set of failure criteria were defined as introduced in the next section before discussing the final results.

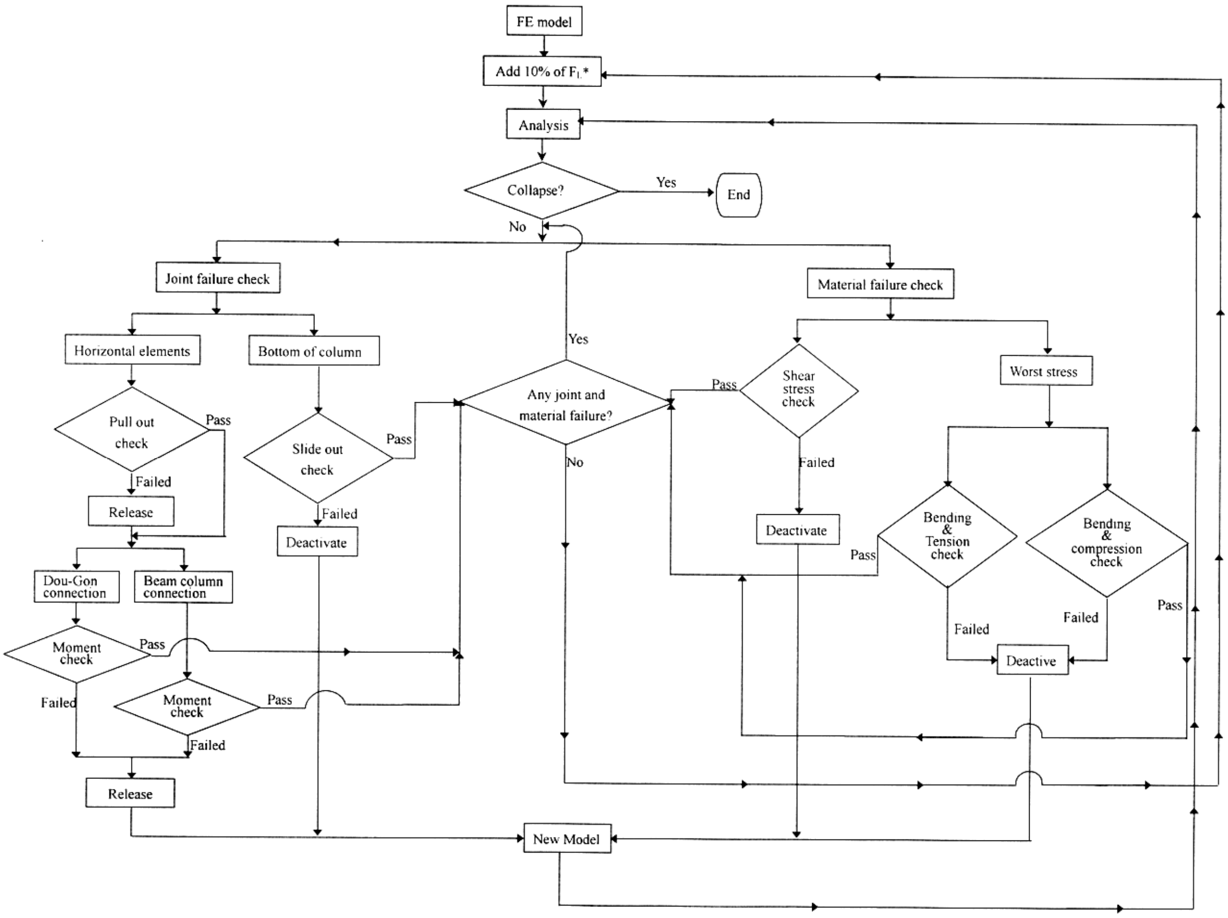


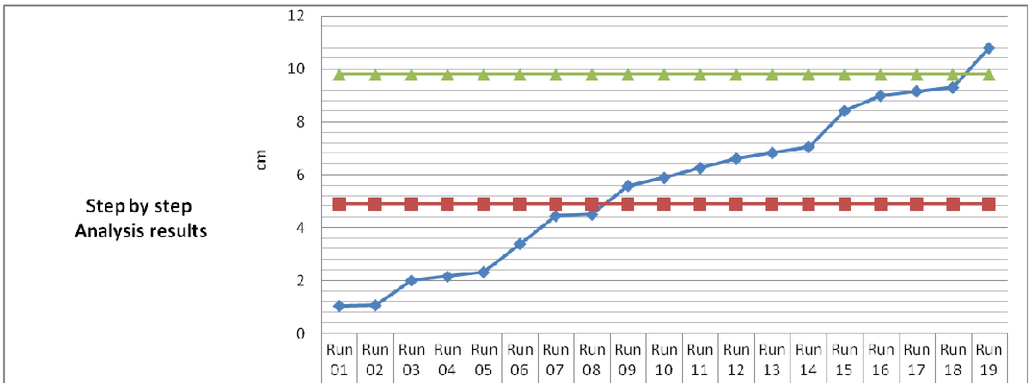
Figure 8: Flow chart of step by step analysis

4.1 Failure criteria

As stated previously failure modes for these structures can be grouped as joint failures and material failures. Joint failures can be further grouped as pull out and bending failure (applying to horizontal members) and column failure. For joint the failure criteria are set as the maximum associated stress resultant that the joint can take in tha particular failure mode. Following the results of the tests these were set as 1500N in pull out force and 1000Nm of joint bending capacity. As the foot of the column has a shallow pin into a stone base and relies on friction to resist lateral action, from tests a coefficient of friction of 0.55 was determined and the failure of the connection was defined by shear failure, beyond which the vertical and lateral capacity of the column is lost. For material failure, combined bending and tension, combined bending and compression and shear stress are examined. The ultimate material strength is taken from material tests compared with the Wood Handbook (1999). For the elements subject to axial compression and bending, the interaction formula of British Standard (BS 5268-2; 2002) adapted to consider ultimate values of strength. The failure criteria however are not independent and a hierarchy exist among them. Bending failure of a joint still allows axial forces to be transmitted through the joint and the connecting beam constraint change from semi rigid to pin, but the beam bearing capacity is not compromised. Pull out test at joints and material failure at cross sections away form the joints result in disconnecting and writing off the corresponding element. The push over analysis was run as shown by the flowchart in Figure 8, by first applying 100% of vertical loads and then applying lateral load in constant increments. After each increment the failure criteria were checked and once elements have failed they are treated accordingly and the same load level reapplied until no further element failure is attained before increasing the load again. The step by step analysis stops when the roof apex lateral displacement is over the collapse criterion proposed by Miyamoto et al 2004 for Asian timber structures.

4.2 Results of Push-over Analysis

In the step by step analysis, a total of 19 steps were performed until the failure criterion was reached. The lateral load at the thirteenth step was 70% of F_L. The columns did not reach the failure criterion and no material failure occurred. At the ninth step (50% of F_L), the roof apex has already met the damage criterion. The structure drifts results are shown in Figure 9, while Figure 10 shows the range of failed elements. The result shows that elements start to fail when the lateral load is still relatively low. When the roof apex meets failure criterion a total of 29 joints had failed and among these 11 failed by pull out and 18 failed by bending. However, up to Run 09, which is the first run at 50% of F_L, there are only pull out failures and this phenomenon highlights the importance of translational stiffness and pull out capacity in these timber buildings built by small pieces stacked and without metal nails. Traditionally the pull out capacity and translational stiffness are disregarded during analysis, but this study shows that for such buildings this feature needs to be considered for accurate modelling.



	Run 01	Run 02	Run 03	Run 04	Run 05	Run 06	Run 07	Run 08	Run 09	Run 10	Run 11	Run 12	Run 13	Run 14	Run 15	Run 16	Run 17	Run 18	Run 19
Results of step by step analysis	1.03	1.06	2.00	2.15	2.31	3.38	4.45	4.5	5.58	5.88	6.26	6.61	6.83	7.06	8.42	9.00	9.15	9.30	10.8
Damage criterion	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9
Failure criterion	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8

Figure 9 Structure drift of static and step by step analysis

According to Hsu (2002), the main hall of Guan-Shi family Temple suffered severe damage after the 1999 Chi-Chi earthquake. One frame collapsed and the other one was seriously damage. The results of FE model with the criteria can therefore match reality reasonably well. Furthermore, in the damaged frame, the main space of frame remained intact while the outer parts damaged with most elements pulling out of their original position, but no material rupture was found. This failure compared well with the FE model result, see Figure 10. This confirm that the strategy of using such numerical analysis coupled with modest number of full scale laboratory tests can successfully predict the structural behaviour of Dieh-Dou frames

5. CONCLUSION

The Taiwanese traditional architecture (Dieh-Dou building) has its own peculiar characteristics and also can represent the history and culture of Taiwan. It is necessary to establish a proper method to evaluate the structural behaviour of these buildings properly to resist decay and disaster. The Charters and Regulations of historic building conservation highlight the importance of keeping originality and not replace elements unnecessarily. Previous research shows that numerical analyses with FE can be successfully employed to simulate Far East timber complicated structures under earthquake. However, the numerical analyses need realistic input data to simulate the structure properly and compare it with the failure behaviour. First of all, failure reports after earthquake were collected and structural behaviours under earthquake were studied. The elements were found to be easily pulled out from the joints or suffer excessive rotations while very few cases of material failure occurred. The survey also shows that the two frames of the buildings often move apart during earthquake and act independently. Therefore a single frame was created and modelled with FE.

The joints play an important role in Dieh-Dou frames and also several researchers described the timber joints as semi-rigid. Full scale laboratory tests showed that the rotational stiffness of Dieh-Dou joints is around 2E4 to 4E4 Nm/rad and the translational stiffness is 1.8E6 N/m. A parametric study based on the FE model results confirmed these values are reasonable and that the joints are semi-rigid but tend to be close to hinges. The parametric analysis also found that changes in rotational and translational stiffness affect the overall movement of the structure substantially and that the range of values found experimentally corresponds to the range between damage and failure of the structure examined, which matched with the reality. A step by step analysis was performed to understand the failure sequence and give a more accurate picture of the vulnerability of the frame. Combining the series of laboratory tests results and survey of existing structures after the earthquake, a system of failure criteria was established to study the occurrence and effect of joints failure and material failure in Dieh-Dou buildings.

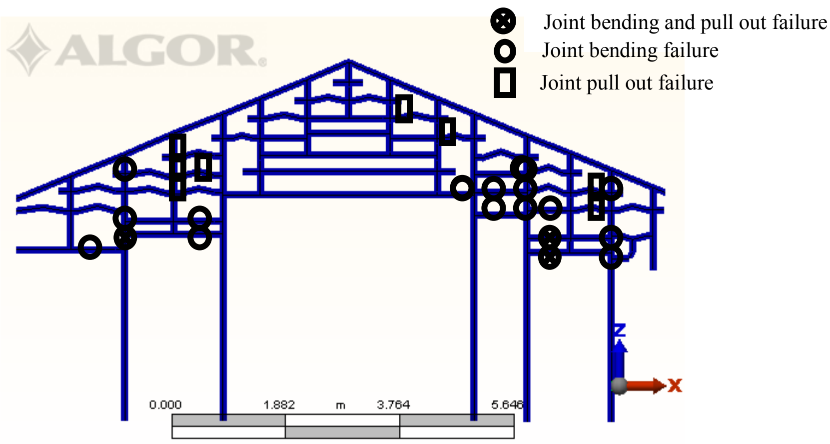


Figure 9 Element failure

The results of step by step analysis shows that the joints in the corridor and main beams are easy to fail at low levels of load and these are the critical elements to focus on first. This failure mode compared well with the observed failure of this frame and proved that the FE analysis is apt to assess Dieh-Dou buildings. Therefore, from the step by step FE analysis a preliminary result has been obtained which can help to identify the critical and vulnerable elements of the Dieh-Dou buildings. Different Dieh-Dou buildings, which have slightly different frame geometries, should be analysed to observe if the critical and vulnerable elements are similar and the structural behaviour follows the same trend. A parametric study on all results on different buildings can finally help to address the directions the conservation should take. Once the vulnerable and critical element has been defined, a strengthening strategy can be conveniently put into place.

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