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Shaking table test of the Taiwanese traditional Dieh-Dou timber frame

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Earlier draft versions of this paper were presented at the 13th International Conference on structural repairs and maintenance of heritage architecture (Yeo *et al.*, 2013a) and the World conference on timber engineering (Yeo *et al.*, 2014). This paper adds detail explanatory on the literature review, experiment design and analysis background, and further revision of graphics and analysis results for all sections that originally appeared in the above two conference papers.

Shaking table test of the Taiwanese traditional Dieh-Dou timber frame

ABSTRACT (150 words)

This paper attempts to explore the dynamic behaviour of traditional Dieh-Dou timber structure under different combinations of structural forms and vertical loads. Using time-history record (TCU 084) from the Chi-Chi earthquake, two semi full-scale specimens (Symmetric and Asymmetric) were tested. Results showed that the Symmetric specimen tends to be damaged more easily and faster than the Asymmetric one. Damage pattern generally begins from the bottom Dou members and subsequently spreading upwards to the upper Dou, horizontal Gong members and adjoining Shu members. Friction force between the contact surfaces is crucial towards the maintenance of overall structure. Increase vertical loadings have significant effect on the natural frequencies and global stiffness of the structure. Using the Single-Degree-Of-Freedom (SDOF) system, the derived stiffness is generally in good agreement with the dynamic results of both forms. This study suggests that the effects of increasing vertical loadings should be taken into consideration for future evaluation.

KEYWORDS

Shaking table tests, full scale, traditional Dieh-Dou timber frame, bracket complex, stiffness, rocking behaviour

1 INTRODUCTION

Bracket system and heavy roof are unique characteristics of traditional oriental timber frame. Two main types of traditional Southern Han Chinese timber frames, namely the 'Chuan-Dou' frame and 'Dieh-Dou' frame are commonly found in Taiwan (Figure 1(a) and 1(b)). Chuan-Dou frame is usually used in the building of ordinary vernacular houses whilst Dieh-Dou frame is traditionally used in Temples, Ancestral Halls, and Residential Houses of rich people. Basically, Chuan-Dou timber frame is constructed by connecting both the horizontal and vertical members via the designated holes found on both sides of the vertical columns or post members. Whereas Dieh-Dou frame, in simple terms, refers to a series of bracket complexes (comprising of the 'Dou', 'Gong' and 'Shu' members) stacked one on top of the other starting from the post-like structures (Gua-Tong) that sit on the beams (Figure 1(c)).

During the 1999 Chi-Chi earthquake, many invaluable historic timber structures, were destroyed in Taiwan. Focusing on the damaged timber structures that were listed as historic buildings, post-earthquake reconnaissance damage assessments (CCA 2000a and 2000b) were conducted, whereby a total of 742 historic buildings around the seriously affected regions (including Taichung, Nantou, Changhua and Yunlin counties) were surveyed.

Findings from the above reports revealed that Chuan-Dou type accounted for 44% of the total number of damaged historic timber buildings; whilst the Dieh-Dou type was noted to have a lower damage percentage of 6%, comparatively (Figure 2). In view of the above, a series of research was initiated to investigate the seismic capacity of the Taiwanese traditional timber structures, placing priority on the Chuan-Dou type due to its higher damage counts.

After more than a decade of concerted efforts done for the study of traditional timber frames, limited studies were found on the Dieh-Dou timber frame. Considering the lack of concrete experimental data to assess its possible earthquake-induced damage, the seismic performance of existing historic Dieh-Dou timber buildings should be evaluated with urgency. Base on the reviews and photographic records of related post-earthquake reports and (ABRI, 1999; CCA, 2000a and 2000b; Hsu, Chung and Tseng, 2001; NCKURDF, 2001) gathered so far, it was observed that, most of the observed damage arised from vertical shear failure at the timber column–beam region and joint dislocation at both the timber column–beam region and timber column base–stone column/plinth connections, subsequently leading to a partial collapse of the global frame (Figure 3(a)). In the case of the bracket complexes, vertical and horizontal shear crack of adjoining members were commonly observed (Figure 3(b)). In addition, the corridor frame region (Figure 3(a)) of the Dieh-Dou frame was more prone to damage than the internal frame region (Figure 4). As the corridor frame is usually designed as the main entrance and exit zone of the entire building, hence in this paper, first priority is placed on the study of the damage behaviour of the corridor frame as this is the critical region in the safety design of escape route of the entire building, particularly when earthquake occurs.

By reviewing back on the limited literature reviews pertaining to Dieh-Dou timber frame study, it is noted that majority of the ancient oriental timber structural studies arise from Japan (Fujita *et al.,* 2000; Suzuki *et al.,* 2001; Suzuki and Maeno, 2006), followed by Taiwan (Chang *et al*., 2012; D'Ayala and Tsai, 2008; Hsu and Chang, 2011; Yeo *et al.* 2013a and 2013b; Yeo *et al.*, 2014) and China (Fang *et al.,* 2001a and 2001b; Chun, Yue and Pan, 2011; Yue, 2014). Also, most of the structural studies were mainly focused on the static aspects of specific groups of structure joint connections, dynamic studies of the global frame is still at its infantry.

Even though the structural forms and joinery systems of the Japanese and Chinese traditional timber frames are not quite similar to those of the Taiwanese traditional timber frames, some of the basic construction principles such as heavy roof loads, the 'Dou-stacking' property of bracket complex and the thick column-beam connection are essentially applicable for evaluating the structural performance of the oriental timber frames in general. Several critical points could be drawn from the above studies. Firstly, although an increase in dead load will magnify the inertia force, it can also increase the stiffness of the global structure on the whole (Fang *et al,*. 2001; Tsai and D'Ayala, 2008; Hsu and Chang, 2011; Chang *et al.,* 2012). This line of thought is also observed in the dynamic studies conducted by Fujita *et al.* (2000) whereby a series of bracket complexes with varied structural design and vertical loads were subjected to shaking table tests. Results from the above revealed that the stiffness of the bracket complexes has a tendency to increase as the vertical load increases. Hence the bracket complexes can be considered to have a positive role on the overall structural stability when subjected to earthquake force (Fujita *et al.,* 2000 and Suzuki *et al.,* 2001). The static tests conducted by D' Ayala and Tsai (2008), consisting mainly of a simplified modular unit of Dieh-Dou structures, showed that most of the joint connections found in Dieh-Dou timber frame are of dovetail type, and the strength of such connection, coupled with its geometry and material properties, will affect the overall bearing capacity of the inter-connected structures. It is noted in their tests that the two levels of vertical loads (6.5kN and 3.25kN) were applied onto the specimen. However, the rationale behind the choice of the above vertical loads is not clearly explained, hence the results obtained from the above studies is limited.

Despite the above-mentioned precedent works, questions concerning the structural performance of the Dieh-Dou timber frame, such as the various jointing designs found and their seismic performance, the actual damage mechanism of the corridor frame and internal main frame, and how the resultant damage of a particular region affects the global stability of the timber frame, the effects of structural forms and vertical loadings, adequacy of reinforcement for damaged parts and connections *etc*., are still not clearly answered, particularly from the dynamic point of view.. Furthermore, it is believed by the Master carpenters that among the two commonly-observed structure forms of Dieh-Dou timber frame, namely the Symmetric and Asymmetric form, the Symmetric form is said to be more stable than the Asymmetric one. But until now, no structural studies have been carried out to validate the above belief. As a result, the domestic conservation specialists can only rely on personal structural experience and post-seismic damage photographic records to evaluate the existing Dieh-Dou timber structures as an optimal gauge for the evaluation and maintenance of Dieh-Dou frame has yet come to a consensus. In view of the above, there is a critical need to properly study the Dieh-Dou timber frame so that more informed advice could be provided for heritage conservators in future.

To assess the dynamic seismic behaviour of the traditional Dieh-Dou timber frame, two different semi full-scale structural forms (Symmetric and Asymmetric specimens) were tested by the shaking table facilities of the Taipei National Centre for Research on Earthquake Engineering (NCREE). Under different combinations of roof dead loads and seismic inputs, the two specimens were tested uni-directionally. The observed damage patterns for both structural forms will be covered in details. By comparing the natural frequency and initial stiffness results derived from experiment results, the effect of vertical loading acting on both systems and also, their respective hysteresis loops behaviour and damping ratios, are presented. Following that, the maximum strength and deformation of both specimens are studied base on the hysteresis loop results and the maximum relative displacement measured. Finally, the rocking behaviour of the Dou members is examined to evaluate the seismic response of the Dieh-Dou frame.

2 SHAKING TABLE TESTS OF THE DIEH-DOU TIMBER FRAME

2.1 Specimen design

The design of the specimen mainly originates from an existing traditional Dieh-Dou timber frame that was once part of the Entrance Hall of the Chung Family Ancestral Hall at Ping-tung County in southern Taiwan. The Ancestral Hall was rebuilt in 1930 using Formosan red cypress (*Chamaecyparis formosensis* Mats.) as the main structural frame material and was completed in 1935. An overview of the timber frame of Entrance Hall is shown in Figure 3(a).

The geometric dimensions of individual members of the test specimens are based on the initial design of the Entrance Hall corridor frame section. As part of the corridor frame design (as demarcated by the boxed-up region in Figure 2(a)) is similar to the typical Dieh-Dou internal main frame design (Figure 3(b) and 3(c) in dashed line), Shu members along the dashed box region are shortened into simplified members so that the test results obtained from the revised test specimens could apply to a wider range of Dieh-Dou timber frames.

Two different structural forms, including the Symmetric and Asymmetric specimens, were fabricated based on the above-mentioned revised design (Figure 5). The specimens and the dowels were made of China Fir (*Cunninghamia lanceolata* (Lamb.) Hook. var. *lanceolata*). Basically, one complete set of Symmetric and Asymmetric specimen is composed of two sub-units of timber frame structure, as illustrated in Figure 5. The dimensions of one sub-unit of Symmetric and Asymmetric specimens are 69.5 x 106.4 x 89.4cm and 69.5 x 106.4 x 60.0cm, respectively. The main difference between the above two sub-units is that the Asymmetric set has roughly half the number of structural members as compared with the Symmetric one. Apart for the Gong members whose grain direction is perpendicular to the seismic force direction, the rest of the other members have grain direction parallel to the seismic force. The fundamental jointing design for single-level bracket complex members begins first by connecting the bracket complex (Shu-Gong complex and Shu-Jishe complex) via dovetail mortise-tenon joint (Figure 5(d), Table 3 and 4). After which, the bracket complex is then aligned within the designated mortise region of its adjoining lower Dou members, usually very little or no friction contact existed in between the member surfaces. The bracket complexes of each level are then subsequently stacked one on top of the other by means of wooden dowel, as shown in Figure 5(d).

2.2 Experiment program

The aim of this experiment is to understand the dynamic structural behaviour of traditional Dieh-Dou timber structure under different combination of structural forms and roof dead loads. Two different semi full-scale structural forms (Symmetric and Asymmetric specimens, Figure 5) were mounted on the shaking table of NCREE and tested under uni-directional excitation mode.

Base on the construction drawings of the existing Taiwanese research and restoration reports for Dieh-Dou type national monuments, the statistic data for span distance interval of 110 historic buildings were investigated and compiled by the first author (Figure 6(a)). It was found that the span width interval of Dieh-Dou timber frame could be broadly sorted into three main categories of 3m, 4.5m and 6m (Figure 6(b)). With reference to the calculation method proposed by Hsu, Chung and Tseng (2001) and Shih (2014), the estimated roof weights of 3m, 4.5m and 6m was estimated to be 17, 26, and 35kN, respectively (Table 1 and 2). Therefore, the above roof weights were set as the vertical loads of the test specimens. Both specimens were designed to undergo the same test schedules whereby only the 26kN roof load case was tested up to 100% and the remaining two cases (17kN and 35kN) were only tested up to 60% the seismic inputs. The reason for selecting the 26kN case to run the full test is due to the fact that nearly two-thirds of the Dieh-Dou timber frames in Taiwan fell within the span distance of 4.5m (Figure 6(b)).

The free-field record (TCU 084, East-West component) of the 1999 Taiwan Chi-Chi earthquake was used. Figure 7(a) shows the time-history and its corresponding acceleration response spectrum. The Peak Ground Acceleration (PGA) of the record reached 0.99g and the spectrum predominates at 0.9s. Due to the limitations of the shaking table, the amplitude was downscale to 0.16g, 0.34g, 0.48g, 0.64g and 0.80g, to represent the test levels of 20, 42, 60, 80 and 100%, respectively. The 42% intensity (0.34g) is used instead for the test as its intensity is close to the strong seismic zone intensity as stipulated under the Taiwan building regulations. White noise tests were carried out between every seismic test. The main objective of the dynamic identification tests was to evaluate the variation on the frequencies of the modes and, consequently, to keep track of any potential damage that may arise during the test. The test schedules for two specimens are listed in Figure 7(b), of which the Symmetric specimen was tested first.

A total of 34 channels of data were collected from the test, of which 27 displacement transducers and seven accelerometers were used. The displacement transducers were assigned to measure the vertical and horizontal deflection of the adjoining Dou-Gong members and relative displacement between each level. The accelerometers were placed at the front and back of the specimens to record the acceleration in single direction. Video cameras were used to record the global view and close-up views of all four sides of the test specimen. As the placement of all the measuring devices for Symmetric and Asymmetric specimens are the same, hence an overview of the positions of all the measuring devices, using the Symmetric specimen as an example, is presented in Figure 8. The parameters used for this study are mainly roof weight, acceleration, rotation and natural frequency.

2.3 Members restoration

During the test period, some of the fabricated members still underwent shrinkage over time. Deformation and seasonal cracks resulted, particularly on the Dou members. Epoxy repair was applied to those members with visible cracks prior to the execution of the experiment. Due to the limited resources, only one set of specimen was made for the two types of structural forms. Hence, when visible damage was observed during experiment, quick repair methods were often employed as the main aim was to reinstate the structural integrity of damaged member as close to its initial state as possible. Epoxy and conventional screw were commonly used. Overall structural evaluation of the specimen was assessed by comparing the white noise tests conducted before and after the repairs. In times when the damage of a particular member was far too severe for any kinds of repair, replacement using what was left from the previous test was selected. This situation only occurred for the last seismic testing (100%) of the Asymmetric specimen where the damage induced from the 80% test was far too great and that some of the Dou members had to be replaced with compatible and visibly good condition ones from the Symmetric specimen.

3 OBSERVED DAMAGE PATTERN FOR BOTH SYSTEMS

The damage pattern for both Symmetric and Asymmetric specimens when subjected to various levels of seismic loadings are summarised in the Table 3 and 4. Base on visual inspection, first sign of damage was observed when both specimens were tested under roof loads of 35kN and 42% intensity loading. In the case of Symmetric specimen 80% test, the specimen was already severely damaged during the first half of the input cycle, hence the experiment was terminated due to safety reason. The large seismic intensity caused damages on both specimens with a dead load of 35kN, which corresponds to the span distance of 6m. Fracture pattern of the experiments begins from the bottom Dou members and subsequently spreading from the front section and extending upwards to the upper Dou, horizontal Gong members and traverse tie members (Shu). Detachment of Dou dowel, shear failure of Dou and joint detachment between bracket complex and wood crushing were observed in both specimens. Figure 9(a) shows the damage pattern of a Dieh-Dou timber frame during Chi-Chi earthquake. The damage patterns obtained from the experiments are similar to the damage seen from the Chi-Chi earthquake (Figure 9(b) and 9(c)).

Being the critical linker between each level, the Dou member is found to be the first structural member to be damaged in both systems. This could be due to the fact that most of the force is often been channelled in and out of the Dou member. At times when high seismic force happens, the overall magnified force might cause the Dou member to be fractured more easily during the course (Figure 10).

When the two back-end mortises of the Dou were fractured severely, the widen mortise region might offer more room for plane rotation of the Shu-Gong complex, and subsequently, causing the front-end mortise to shear horizontally in the direction perpendicular to the seismic force.

Dovetail connection damage of the Shu-Gong complex for both systems was generally observed from high seismic tests of 80% onwards. Such phenomenon occurred when the cruciform mortise area of the Dou member was severely damaged, subsequently losing its restraint. From the video footages, differential uplift between the Shu-Gong complex tends to happen when the complex is constantly subjected to back and forth rocking force (perpendicular to the grain direction of the Gong member) and strong impact vertical forces. As a result of this strong rocking force, the Gong member was eventually ripped apart particularly at the dovetail connection. Hence the above observation suggests the structural importance of the bottom Dou member towards the maintenance of overall structural stability. As long as the general cruciform mortise area of the Dou is intact, the Dou member will be able to hold its adjoining Shu-Gong complex and rest of the upper members together to a certain extent.

4 EFFECTS OF VERTICAL LOADING ON NATURAL FREQUENCY AND INITIAL STIFFNESS

4.1 Frequency and stiffness prior to the tests

White noise inputs were applied prior to the main test. Base on the assumption proposed by Chang *et al.* (2012) and Fujita *et al.* (2000) of setting the entire bracket set as a Single-degree-of freedom (SDOF) system. The approximated weight of timber members for both specimens is around 0.90kN. As the weight contribution of the timber members with respect to the total weight of the specimen generally ranges between 2% and 5% for the three vertical loads, hence decision was set to assume the weight of bracket set to be negligible. Base on above assumption, the roof loads become the main mass contributor responsible for the global structural stiffness. By applying the free vibration theory, the theoretical global stiffness prediction, *K* was obtained.

In Figure 11, a normalized relationship between the natural frequency and stiffness of the two specimens when subjected to different roof loads. The natural frequencies of both specimens were generally found to decrease as vertical loads increase (Figure 11(a)). As for the case of structural stiffness comparison, the stiffness of Symmetric specimen increases as the vertical loads increases (Figure 11(b)). The increment between roof loads of 26kN and 35kN becomes gentle. Stiffness increment recorded between each subsequent loading is only found to be 11% (from 17kN to 26kN) and 4% (from 26kN to 35kN). Similar situation is also seen in the Asymmetric case whereby an 18% stiffness increment was achieved when vertical load was increased from 17kN to 26kN. However, stiffness of the Asymmetric set starts to decline by 4% when it is further loaded to 35kN. As mentioned in previous section that the increase in vertical loads represents a wider span interval of the Dieh-Dou timber frames, the above observation also suggests that as the span interval increase from 4.5m (26kN) to 6m (35kN), the global stiffness of both structure forms will tend to decline.

Generally, assuming the structure is isotropic with stiffness remain unchanged, the increase of mass is inversely related to the frequency of the structure. However, the wood specimen used in this study is anisotropic in nature, hence stiffness characteristic might vary between structural members. Furthermore, the connection between structural members is basically not rigidly fixed, thus to imply a particular stiffness value derived from one particular roof mass onto the other roof masses might not truly reflect the actual situation. As illustrated in Fig. 11, the increase of roof mass not only helps to improve the stiffness of timber connections and increase the global frequencies of the structures, the dynamic behaviour of the structure is also influenced consequently by the decrease of mode frequencies. Similar trend was also observed in the dynamic identification tests conducted by Chang et al. (2012), whereby one Asymmetric Dieh-Dou specimen was subjected to three different vertical loads of 5, 10 and 15kN tests. These results are in agreement with the results obtained from the dynamic identification tests carried out in this study

4.2 Frequency and stiffness after the tests

Figure 12 illustrates the effects of vertical loads on the measured natural frequency and initial stiffness of both systems. Under the natural frequency versus vertical load graphs, the two data points that are found under each seismic loading column (coloured in grey) refer to the frequency value measured from white noise tests conducted before and after each loading test. Although the natural frequencies of both specimens decline under the effects of increasing vertical load and seismic loadings, the initial stiffness of both structures generally showed an increasing trend (Figure12). In the case of 60% seismic intensity input, the Symmetric specimen shows a distinct drop in natural frequency for all three dead loads as compared with the 20% and 42% tests. Also, the frequency drop among the three dead loads becomes less sharp as dead loads increase. Having cross-referenced with the Table 3 results, the above scenario is consistent with the increasing damage areas observed during the 60% tests. For the Asymmetric specimen, the changes in frequency are similar under different intensity inputs, including the 60% seismic test. No visible fracture was observed after the test (Table 4). Hence, the widely distributed damages observed significantly affects the natural frequency and stiffness of the Symmetric specimen, thus making it more prone to damage at an earlier stage than the Asymmetric case.

From the natural frequency data gathered in Figure 12, the percentage change in natural frequency measured before and after each test for both systems can be traced (Figure 13). Although we can see from Figure 12 and 13 that a distinct frequency drop of 8.2% for Symmetric specimen occurred at 26kN/42% test, no visible damage was observed after that test. Furthermore, full dismantling for inspection of individual member was not conducted after each seismic loading test unless visible damage arise and active restoration was required, the lowered natural frequency value obtained after the 26kN/42% test might be due to some hidden damage, such as internal deformation or embedment, that could have already affected the overall stiffness.

First sign of visible damage began from 35kN/42% seismic tests for both systems, where the front upper Dou member of Symmetric specimen and back bottom Dou members of Asymmetric specimen were found damaged and repaired subsequently. Despite the repair done for the Symmetric specimen, the natural frequency measured before the start of 17kN/60% test was comparatively lower than the initial frequency measured before the start of 17kN/20% test. This suggests that some hidden deformation might still exist in other parts of the structure that is not easily detected via visual inspection. In the case Asymmetric specimen, when the bottom Dou members were repaired, the natural frequencies measured before the start of 60% test returned close to their initial frequencies measured before the start of the experiment. Thus, the above suggests the possibility of lesser hidden deformation occurring in the Asymmetric case.

Although the restoration work did on the specimens have, to a certain degree, caused some impact on the natural frequency results, the overall declination trend and damage distribution area are generally not affected. In spite of the restoration works done prior to 60% loading tests, the damage trend and distribution area of the Symmetric specimen continued to increase as vertical load increases. However, if active restoration was not employed, the damage might accelerate at a faster pace. Due to the limited experiment data on-hand, the results are insufficient for a quantitative discussion of the Symmetric and Asymmetric specimens. Hence, at this moment, only qualitative comparison of the maximum deformation behaviour between both systems can be carried out.

5 THE HYSTERESIS LOOPS AND DAMPING RATIO

Next, the natural frequencies (*f*) and derived stiffness values (*K*) (obtained from white noise tests conducted before and after each seismic test) and the damping ratios (obtained by using the half-power bandwidth method) of both structural forms were summarized in Table 5. As the two *K* values are mainly derived from the *f* values obtained from the white noise tests, *K1* will refer to the initial stiffness (measured before seismic test), and *K2* will be regarded as the stiffness measured after seismic test. The damping ratios of the two specimens are about 2.8%.

Figure 14 shows the hysteresis loops of the specimens under vertical loads of 26kN and 35kN. The shear force (Q) was obtained by the multiplication of the roof load and average acceleration (from accelerometer A3, A4, A5 and A7 as shown in Figure 7). As the weight contribution of the timber members generally decreases as roof loads increase, the inertia force of the timber members was considered negligible in this study. Apart from the inertia force of timber members, the damping forces and restoring forces were also not included in the calculation of total horizontal forces. The relative displacement (Δu) was simply the difference between the table displacement value and the value measured from device number 27 (Figure 8).

Signs of yielding for both specimens, in the form of shear damage of the Dou members, began when the loops start to loosen in the 35kN/42% test (Figure 14, Table 3 and 4). By cross-referencing the above observed damage patterns with the Table 5 values, it is noted that the damage in Dou led to a distinct drop in the *K2* values of both specimens, as seen in the Symmetric cases of 35kN/42% (*K* value drops from 1.59 to 1.50) and Asymmetric case of 35kN/42% (*K* value drops from 1.56 to 1.47). However, their respective damping ratios did not change significantly, this might be due to the fact that most of the damage is mainly localized in small regions. The corresponding hysteresis loops show slight plastic deformations.

Significant difference in loop behavior for two specimens starts from 60% test onwards. Larger deflection, in the form of wider external loops flanking on both sides, was observed more prominently in the Symmetric specimen than in the Asymmetric case. Under the same seismic condition, the increase of the vertical load leads to the development of wider loops, and hence more deflection is resulted. Table 5 also shows similar results. The Symmetric specimen starts to show signs of a lowered *K2* values at the beginning 60% test. Due to a weaker *K2* value, the Symmetric specimen tends to exhibit larger response earlier during dynamic test, and consequently more deformation, in the form of increasing damage distributions was resulted as vertical load increases.

6 MAXIMUM STRENGTH AND DEFORMATION

Base on the maximum deflection values and maximum shear force values measured from the hysteresis loops, a chart comparison between both structural forms was made to examine the effects caused by the two mechanisms. Figure 15 shows that the Symmetric specimen generally tends to deflect around two times more than the Asymmetric set. The maximum deflection of each vertical load will generally increase exponentially with increasing seismic intensities. Although the combine effect of heavier dead load and high seismic input will magnify the inertia force, the Asymmetric specimen does not deflect as much as the Symmetric set. For the intensity of maximum shear force, both structural forms is relatively similar under low seismic test range. Significant shear force difference is commonly observed in both systems during the 60% test, the shear force intensity of Asymmetric specimen is comparatively lower than the Symmetric set.

From the above observations, the reduction of nearly half of the structural members in the Asymmetric specimen clearly deflects lesser than the Symmetric one as the damages encountered in the Asymmetric set is mainly focused on the two back bottom Dou members. Whilst in the case of Symmetric specimen, more damages are observed during the tests and the damage areas are more widely distributed to different parts of the members on the bottom and second level (Table 3 and 4).

Such observation is also found in Figure 15 where a comparative study between both specimens was made to find out if the effect of different structural forms has any influence on the maximum deflection at each level of the structure. By simply taking the difference between the peak table displacement value and the maximum relative displacement value measured from each level of the transducer (Figure 8), the values were plotted against their respective level, as shown in Figure16. Results showed that both specimens generally exhibit more relative displacement between level 1 and 2 than between level 2 and 3. Also, the relative displacement observed between level 1 and 2 for both specimens increased with seismic intensities. Significant difference in relative displacement values between each level and the base for both specimens is observed for seismic tests of 80% and onwards. The above result is in good agreement with the damage patterns observed in Table 3 and 4 whereby most of the damage are concentrated around level 1 and 2 for both systems.

7 ROCKING BEHAVIOUR OF DOU MEMBERS

During experiments, the front members were observed to have a larger rocking angle than the back members, particularly for the Symmetric specimen, and that the damage intensity and area distribution were greater in the Symmetric specimen than the Asymmetric case. As these two structural forms are usually designed as the corridor frame of the entire Dieh-Dou timber building, it raises the need to understand how the rocking behaviour of both structural forms causes damage on the structural elements so as to enable future conservation specialists to provide more practical evaluation method and repair advice.

By taking the mean vertical deflection measured between the two bottom Dou members, the rocking behaviour under various loadings are evaluated, as shown in Figure17. Taking the 17kN/42% loading test as an example, results shown that the front Dou members (black solid line) of the Symmetric specimen have a larger rocking angle than the back Dou members (red dotted line) (Figure 18). In the case of Asymmetric specimen, although the deflection intensity for the front and back members is not very distinct, slightly larger rocking angle is generally observed for the front members compared to the back members. This observation is in agreement with the damage pattern observed for both systems as the front Dou member of Symmetric specimen tends to be damaged much earlier than the Asymmetric one.

The above rocking behaviour might be due to the geometric of the specimens. In both specimens, the front bottom Dou has a smaller base than the back bottom Dou. Hence the greater surface contact at the back as compared to the front might give rise to higher rotational rigidity, as shown in Figure 17. Also, the geometry of the specimen with respect to the location of the gravity center of the roof load tends to make the entire structure rock forward. As a result, the stronger forward force caused more damage to the front structures. The above results also matched with the observations in Table 3 and 4.

8 CONCLUSION

Dynamic tests have been carried out to investigate the structural behaviour of the Taiwanese traditional Dieh-Dou timber frame. Two semi full-scale specimens (Symmetric and Asymmetric) were tested under different vertical loads and the following conclusion can be drawn from the experimental results:

1. Symmetric specimen tends to damage more easily and faster than the Asymmetric set and the fracture modes between the two systems are different. Although more damage regions are found in the Symmetric case, most of the recurring damage areas usually developed around the same region, subsequently spreading from one frame to another and eventually moving to the upper layers. In addition, Symmetric specimen

generally exhibits lower secondary stiffness at an earlier stage than the Asymmetric case. Hence a larger response was observed in the Symmetric case and thus more damage resulted. This study suggests that the Symmetric specimen might be more vulnerable to damage at an earlier stage than the Asymmetric case.

2. Large seismic intensity caused damages on both specimens with a dead load of 35kN, which corresponds to the span distance of 6m. Damage pattern generally begins from the bottom Dou members and subsequently spreading upwards to the upper Dou, horizontal Gong members and traverse Shu members. Friction force between the contact surfaces of the adjoining members is especially critical for the maintenance of overall structural integrity of the traditional oriental timber frame. When friction between the mortise-tenon connections could no longer withstand the large seismic force, amplified rocking and rotation intensity lead to inelastic deformation.
3. The Dou member, typically the front Dou, is usually the first one to be damaged and the fracture mode is generally caused by horizontal shear. The maintenance of an intact cruciform mortise region of the Dou is crucial towards the overall structural stability.
4. The rocking angle of front structures is observed to be greater than the back, and that the Symmetric specimen tends to have a larger rocking angle than the Asymmetric set. This could be due to the lesser surface contact at the front bottom Dou as compared to the back where the contact surface of back bottom Dou is much wider, thus giving rise to a higher rotational rigidity. Hence more structural strengthening is recommended on the bottom Dou and front section members for future repair.
5. Although increase in vertical loads will improve the overall joint stiffness, making the adjoining members less likely to rock and deform, but under high seismic loadings, the large inertia force will magnify the rocking effect and causes greater deformation to the global structure. This study suggests that the effects of varying vertical loadings should be taken into consideration during future evaluation process.
6. By applying the free vibration theory, the theoretical stiffness was obtained and mapped onto the dynamic results of both Symmetric and Asymmetric specimens. Satisfactory initial stiffness prediction results were achieved particularly for seismic tests range between 20% and 60%. Hence the application of free vibration theory and SDOF system to predict the stiffness of global structure could be considered as an alternative for future initial stiffness evaluation of the Dieh-Dou timber frame.

9 ACKNOWLEDGMENT

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10 REFERENCES

Architecture and Building Research Insitute (ABRI). 1999. *A preliminary report on the structural failures of buildings: 921 Chi-chi earthquake* [in Chinese]. Taipei: Ministry of Interior.

Chang, W-S. 2005. "On rotational performance of traditional Chuan-Dou timber joints in Taiwan". PhD thesis, Taiwan, Tainan: National Cheng Kung University.

Chang, W.S., Wakita, T., Kitamori, A., Komatsu, K., Kataoka, Y. & Hsu, M.F. 2012. Dynamic properties of a traditional complex bracket sets in an oriental temple. In *Proceedings of the 12th World Conference on Timber Engineering: Poster papers*, ed. Quenneville, P., 241-244. Auckland, New Zealand.

Chao, C-C. 2014. Emergency repair proposal for Tainan city historic building: Ma-Dou Hu-Ji Temple [in Chinese]. Tainan, Taiwan: Cultural Affairs Bureau.

Chen, C.W. Photographer. 2007. "[Timber frame structural survey of Wang family Ancestral Hall, November 29, 2007.]" Photograph. From the photographer's private collection.

Chun, Q., Yue, Z. and Pan J.W. 2011. Experimental study on seismic characteristics of typical mortise tenon joints of Chinese southern traditional timber frame buildings. *Science China: Technological Sciences*, 54(9): 2404-2411. DOI: 10.1007/s11431-011-4448-3.

Council for Cultural Affairs (CCA). 2000a. *Post-earthquake reconnaissance report for historic buildings: 921 Chi-chi earthquake and 1022 Chiayi earthquake* [in Chinese]. Taipei: CCA.

CCA. 2000b. *Post-earthquake structural evaluation report for historic buildings: 921 Chi-chi earthquake and 1022 Chiayi earthquake* (Volume 1 and 2) [in Chinese]. Taipei: CCA.

D'Ayala, D. & Tsai, P-H. 2008. Seismic vulnerability of historic Dieh-Dou timber structures in Taiwan. *Engineering structures*, 30(8): 2101-2113. DOI: 10.1016/j.engstruct.2007.11.007.

Fang, D.P., Iwasaki, S., Yu, M.H., Shen, Q.P., Miyamoto, Y. & Hikosaka, H. 2001a. Ancient Chinese timber architecture, I: experimental study. *Journal of structural engineering*, 127(11): 1348-1357. DOI: 10.1061/(ASCE)0733-445(2001)127:11 (1358).

Fang, D., Iwasaki, S., Yu, M., Shen, Q., Miyamoto, Y., and Hikosaka, H. 2001b. Ancient Chinese Timber Architecture. II: Dynamic Characteristics. *Journal of Structural Engineering*, 127(11), 1358–1364. DOI:10.1061/(ASCE)0733-445(2001) 127:11(1348).

Fujita, K., Sakamoto, I., Ohashi, Y. & Masahiko, K. 2000. Static and dynamic loading tests of bracket complexes used in traditional timber structures in Japan. In *Proceedings of the 12th World Conference on Earthquake Engineering*, Paper no. 0851. Auckland, New Zealand.

Hsu, M-F and Chang, W-S. 2011. The study of Taiwanese Traditional Dieh-Dou timber frame bracket complex structural behavior [in Chinese]. *Research report No. NSC 99-2221-E-006-156-*. Taipei, Taiwan: National Science Council.

Hsu, M-F and Chen, W-J. 2006. Full-scale Experiment Study on Traditional Chuan-Dou Timber Structures [in Chinese]. *Research report No. PG9502-0416.* Taipei, Taiwan: Architecture and Building Research Institute (ABRI).

Hsu, M-H, Chung, H-Y. & Tseng, Y-J. 2001. The evaluation of the timber global frame structural characteristics [Chapter 5; in Chinese]. In *A study on the earthquake-induced damage of historic buildings and its future maintenance: (1) Timber and Bamboo structures*. Edited by NCKURDF. Taipei, Taiwan: CCA.

NCKU Research and Development Foundation (NCKURDF). 2001. A study on the earthquake-induced damage of historic buildings and its future maintenance: (1) Timber and Bamboo structures [in Chinese]. *Research report No. CCA89-16*. Taipei, Taiwan: Executive Yuan Council for Cultural Affairs (CCA).

Shih, C-H. 2014. Seismic evaluation of Ma-Dou Hu-Ji Temple [Chapter 4; in Chinese]. In *Emergency repair proposal for Tainan city historic building: Ma-Dou Hu-Ji Temple*. Edited by Chao. Tainan, Taiwan: Cultural Affairs Bureau.

Suzuki, Y., Katagihara, K., Iwasa, Y. Takata, K., Yamamoto, M., Goto, M., Kitahara, A. 2001. Dynamic characteristics and seismic performance of traditional wooden structure by shaking table tests. In *Proceedings of U.S.-Japan Joint Workshop and Third Grantees Meeting U.S. - Japan Cooperative Research in Urban Earthquake Disaster Mitigation,* 328-337. Seattle, USA.

Suzuki, Y. and Maeno, M. 2006. Structural mechanism of traditional wooden frames by dynamic and static tests. *Structural Control and Health Monitoring*, 13(1): 508-522. DOI: 10.1002/stc.153.

Yeo, S. Y., Komatsu, K., Hsu, M-F & Chang, W-S. 2013a. A preliminary study on the structural stiffness of Taiwanese traditional Dieh-Dou Asymmetric timber frame. In *Proceedings of the 63th Annual Meeting of Japan Wood Research Society*. Iwate, Japan.

Yeo, S. Y., Hsu M. F., Komatsu, K., Chang, W. S. 2013b. Dynamic characteristics of Taiwanese traditional Dieh-Dou timber structures. Structural studies, repairs and maintenance of heritage architecture XIII, ed. Brebbia, C.A., 481-490. Southampton: WIT Press.

Yeo, S. Y., Hsu, M-F, Komatsu, K., Chung, Y-L and Chang, W-S. 2014. Damage behaviour of Taiwanese traditional Dieh-Dou timber frame. In *Proceedings of the World Conference on Timber Engineering (WCTE)*. Quebec, Canada.

Yue, Z. 2014. Traditional Chinese Wood Structure Joints with an Experiment Considering Regional Differences. *International Journal of Architectural Heritage*, 8(2): 224–246. DOI:10.1080/15583058.2012.688179.

Figure caption(s) (as a list)

Figure 1. Typical Taiwanese Han Chinese traditional timber frame: (a) Chuan-Dou frame (Architectural Institute of Taiwan, 2003); (b) Dieh-Dou frame (Chen, 2007) and; (c) The naming of structural members of Dieh-Dou timber frame

Figure 2. Damage percentage overview of the historic buildings in Taiwan after Chi-Chi earthquake (Data source originates from CCA 2000 and further analyzed by Chang 2005)

Figure 3. Typical damages observed in Dieh-Dou timber frame after the Chi-Chi earthquake: (a) Joint dislocation between the timber column–beam region (left) and timber column base–stone column (right); (b) Shear crack causing misalignment of bracket complexes. (NCKURDF 2001)

Figure 4. (a) Initial design of the prototype building: Entrance Hall of Chung Ancestral Hall; Internal main frame design of a typical Dieh-Dou Main hall of (b) Yuan-he Temple and (c) Jiang Ancestral Hall.

Figure 5. Overview of the dimensions and joint designs of Symmetric and Asymmetric specimens: (a) side view; (b) front view; (c) back view and (d) joint design of one sub-unit (Measurements in centimeters)

Figure 6. Span width between two Dieh-Dou timber frames: (a) Typical design; (b) Span design overview in Taiwan.

Figure 7. Test schedules and time history details used for test specimens.

Figure 8. Positioning of the measuring devices for both specimens (using Symmetric specimen as example)

Figure 9. Comparison of the final damage pattern between (a) the front corridor Dieh-Dou timber frame observed during Chi-Chi Earthquake (D'Ayala and Tsai 2008); (b) the Symmetric specimen when subjected to 26kN/80% intensity (0.64g) test and; (c) the Asymmetric specimen under 26kN/100% intensity (0.80g) test.

Figure 10. Failure mechanism of the Dou under the 42% and 60% intensity tests

Figure 11. Effects of vertical loads on the natural frequency (a) and structural stiffness (b) of both specimens before the main test

Figure 12. Effects of vertical loads on the natural frequency and structural stiffness of (a) Symmetric and (b) Asymmetric specimens during dynamic tests

Figure 13. Percentage change in natural frequency measured before and after each test for both systems

Figure 14.Hysteresis loops for (a) Symmetric specimen; (b) Asymmetric specimen under 35kN vertical load for 42% and 60% loading tests

Figure 15. Overview of the maximum response of both structural forms: (a) Maximum deflection and (b) Maximum shear force.

Figure 16. Comparison of maximum relative displacement between each level of Symmetric and Asymmetric specimens

Figure 17. Sample calculation for the mean vertical deflection of bottom Dou

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Table 2. Estimation of roof dead load for the three different span distances

Table 3. Damage pattern of Symmetric specimen

Table 4. Damage pattern of Asymmetric specimen

Table 5. Overview of the natural frequencies, stiffness and damping ratio of the two structural forms

(a) (b) (c)

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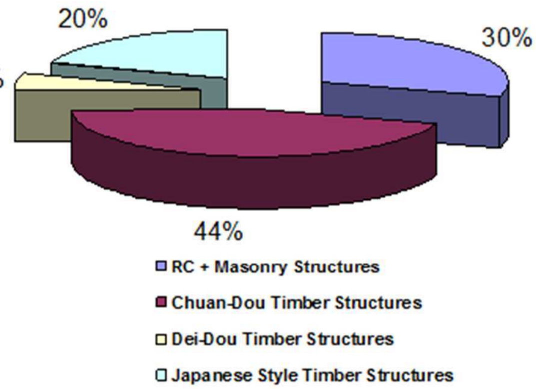

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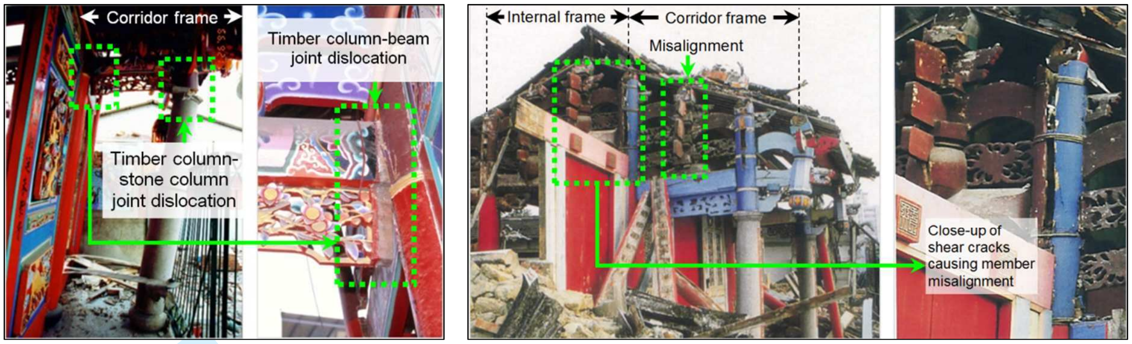

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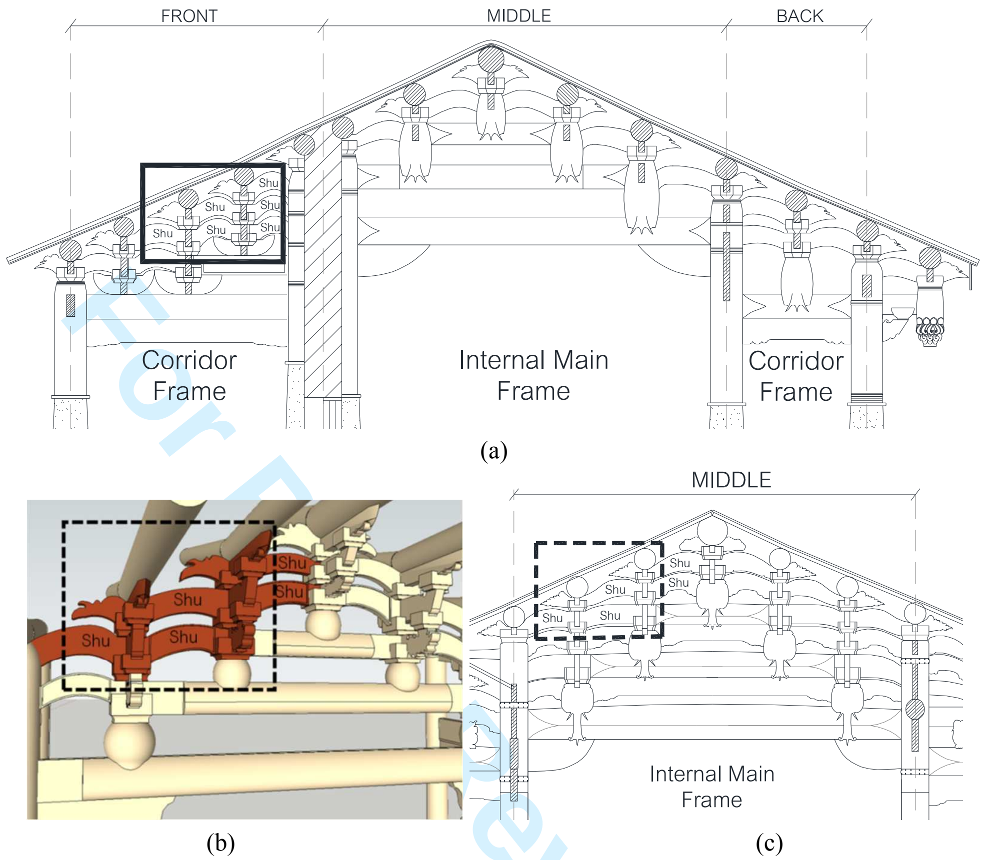

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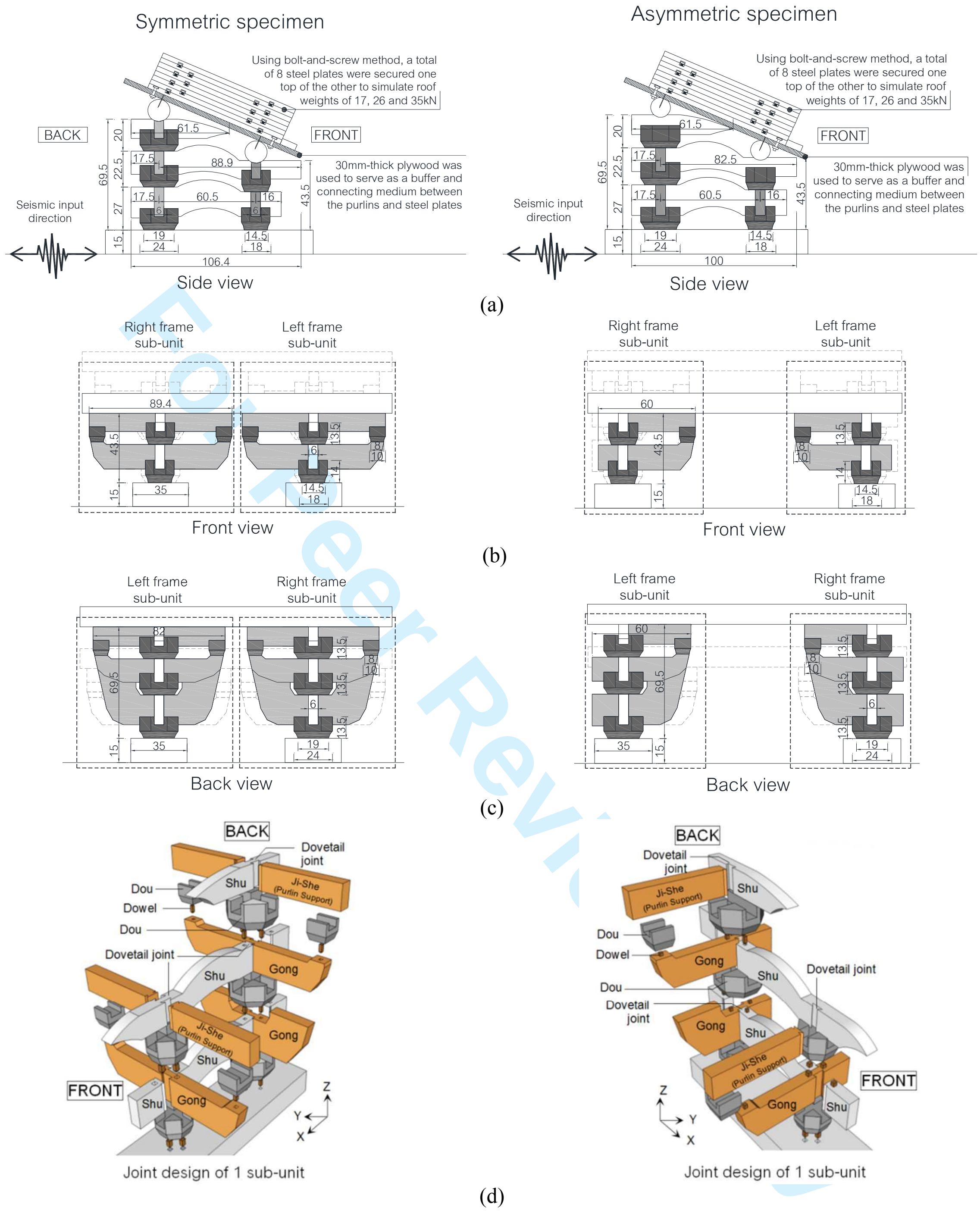

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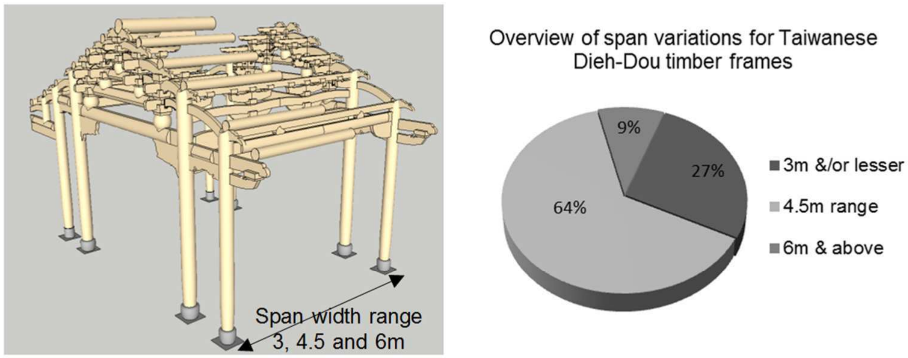
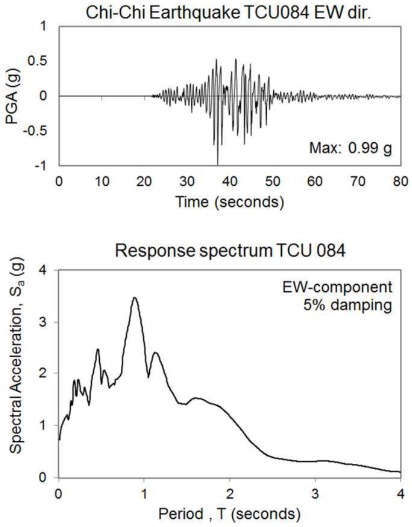


(a) (b)

Figure 6. Span width between two Dieh-Dou timber frames:
(a) Typical design; (b) Span design overview in Taiwan.

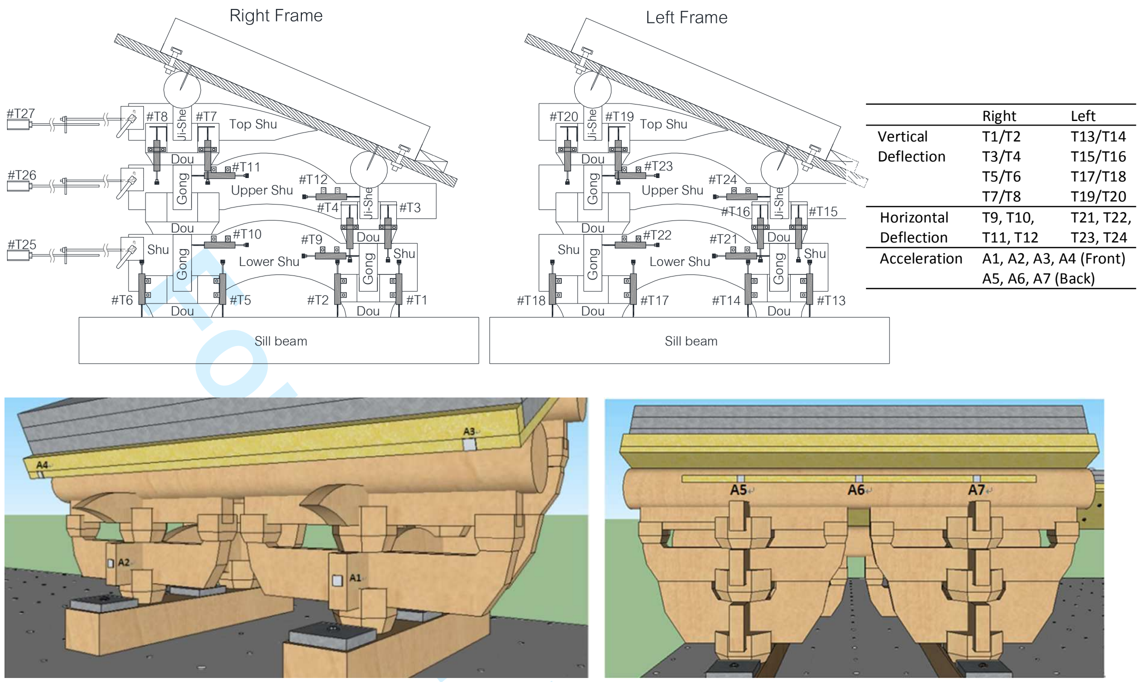


Test Number	Installation Details	Chi-Chi Time History TCU 084 EW (100% = 0.80 g)
S/A00	Self-weight	White noise 0.06 g
S/A02	17kN	(20%) 0.16 g
S/A05	26kN	
S/A08	35kN	
S/A11	17kN	(42%) 0.34 g
S/A14	26kN	
S/A17	35kN	
S/A20	17kN	(60%) 0.48 g
S/A23	26kN	
S/A26	35kN	
S/A29	26kN	(80%) 0.64 g
S/A32	26kN	(100%) 0.80 g

(a) Original Chi-Chi seismic wave from station TCU084 and its response spectrum.

(b) Test schedules for Symmetric (S) and Asymmetric (A) specimens

Figure 7. Test schedules and time history details used for test specimens



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(a) (b) (c)

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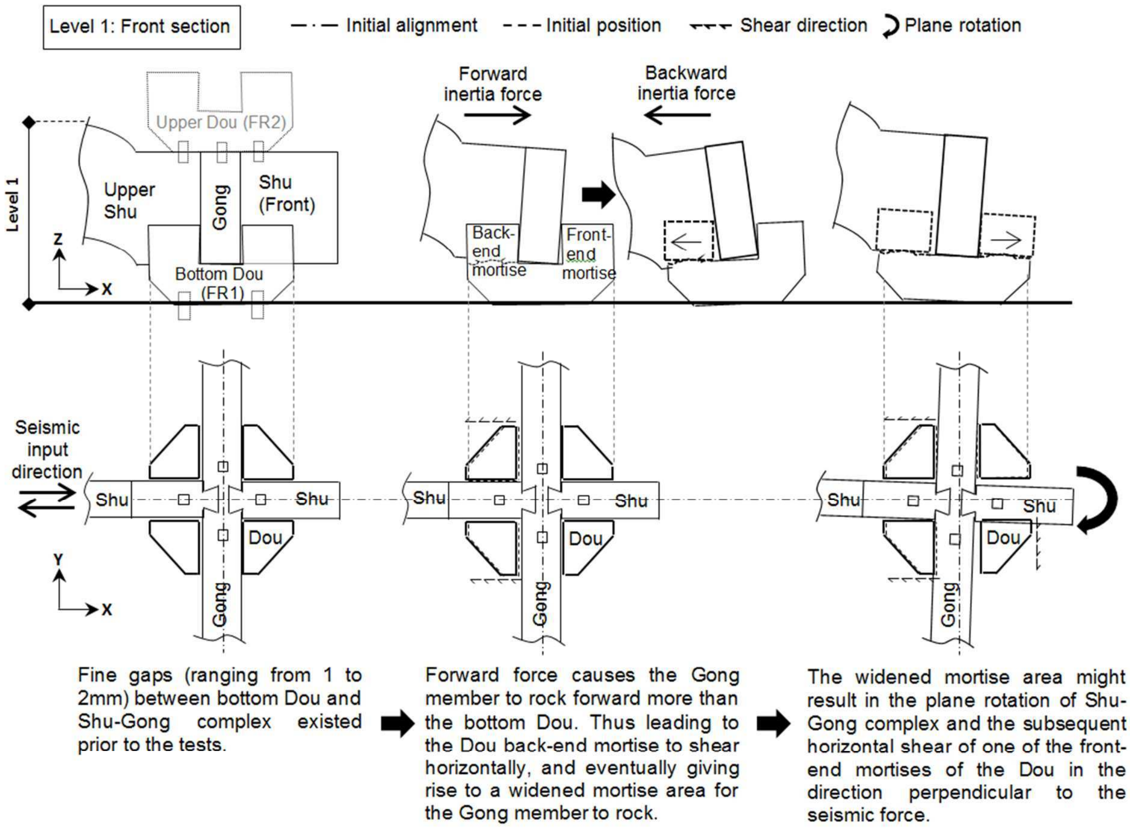


Figure 10. Failure mechanism of the Dou under the 42% and 60% intensity tests

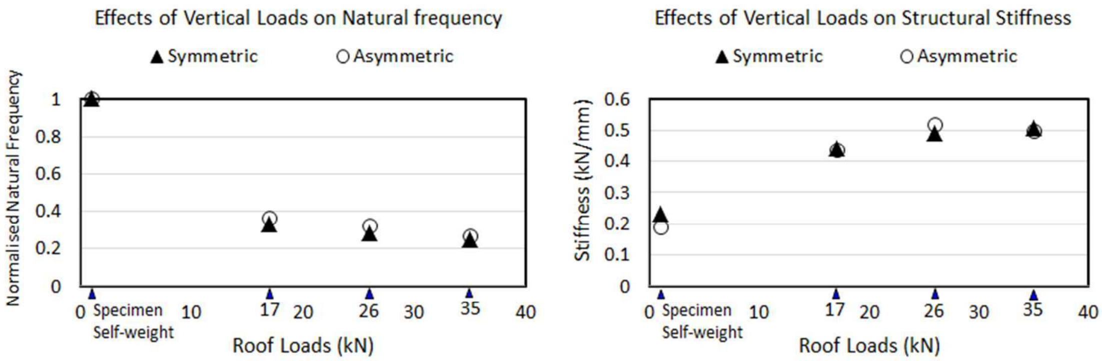


Figure 11. Effects of vertical loads on the (a) natural frequency and; (b) structural stiffness of both specimens before the main test

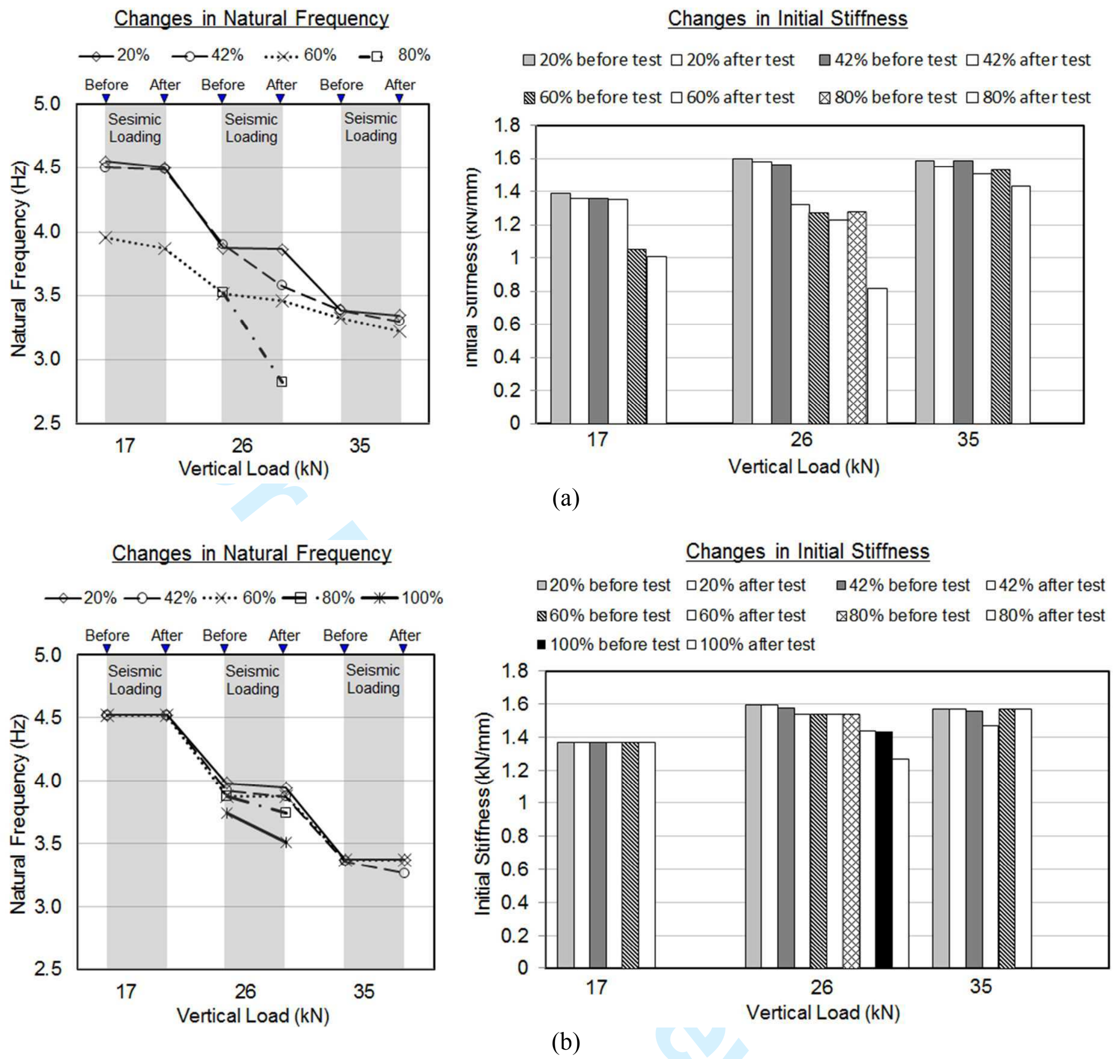


Figure 12. Effects of vertical loads on the natural frequency and structural stiffness of (a) Symmetric and (b) Asymmetric specimens during dynamic tests.

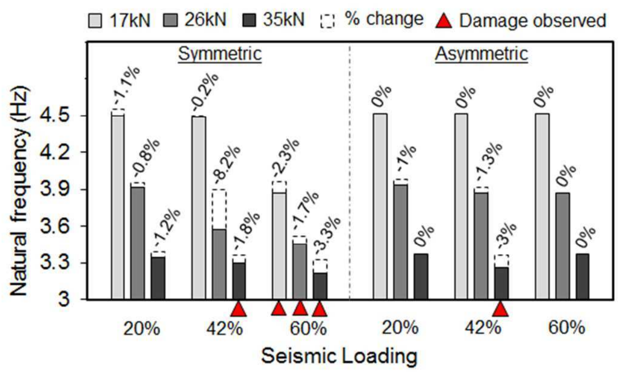
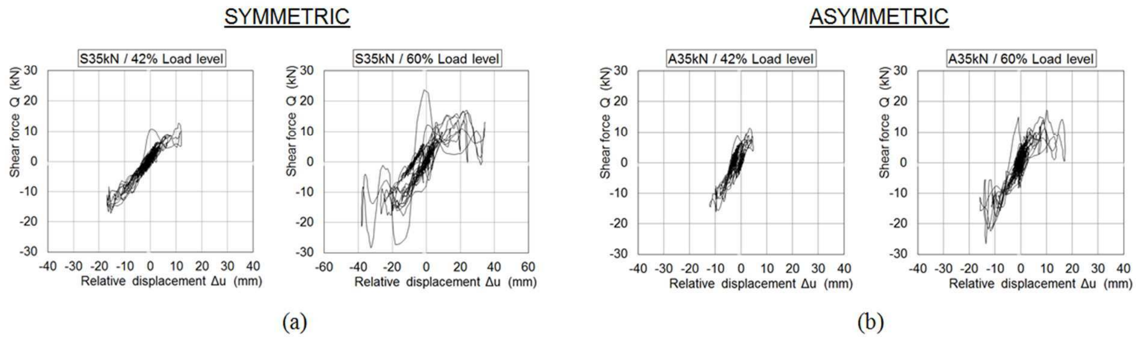
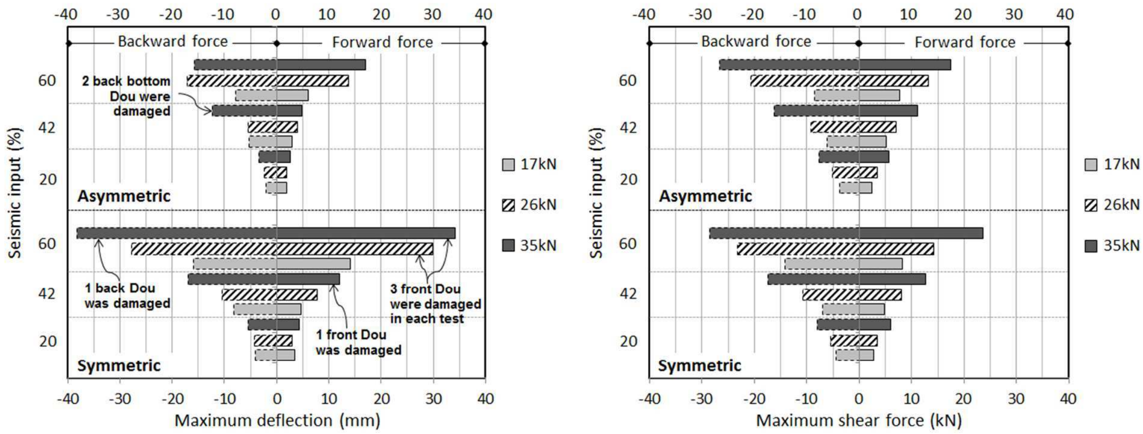


Figure 13. Percentage change in natural frequency measured before and after each test for both systems



(a) (b)

Figure 14. Hysteresis loops for (a) Symmetric and (b) Asymmetric specimen under 35kN vertical load for 42% and 60% loading tests



(a) (b)

Figure 15. Overview of the maximum response of both structural forms:
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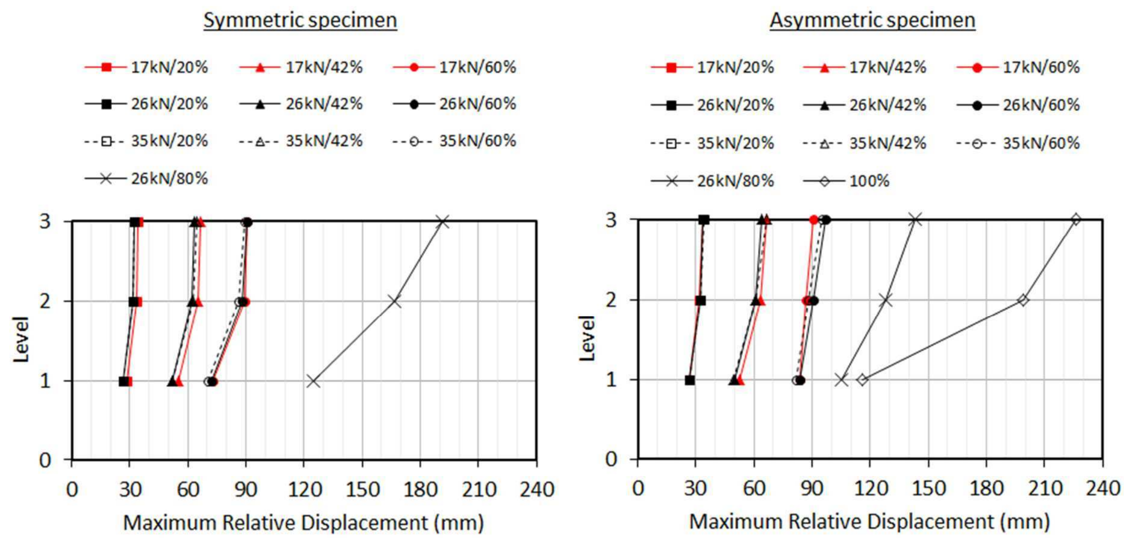

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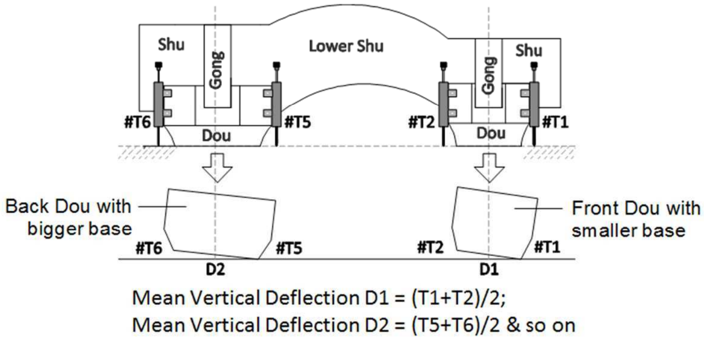


Figure 17. Sample calculation for the mean vertical deflection of bottom Dou

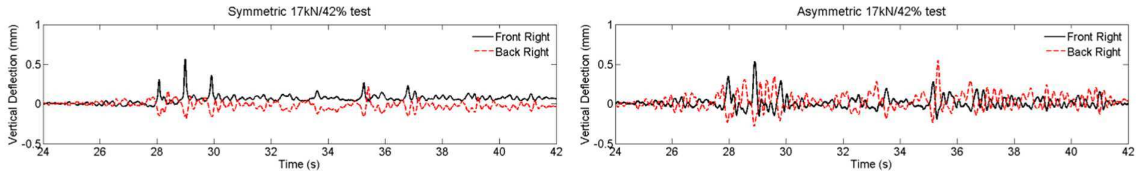


Figure 18. Rocking behaviour of the Dou members of both specimens under 17kN/42% seismic tests

Table 1. Unit dead load calculation for a Dieh-Dou timber roof of $1m^2$ area coverage
(Shih 2014; Original in Chinese and translated into English by the first author)

Items	Unit	Quantity	Unit weight (kN/m^2)	Sub-total Weight (kN/m^2)
Pan tiles (0.24 x 0.18 x 0.06m)	piece	60	0.0052	0.3
Roll tiles (0.125 x 0.21 x 0.09m)	piece	18	0.0074	0.1
Mortar layer	m^3	0.1	20	2.0
Sheathing tiles	m^3	0.015	20	0.3
Wood battens (0.60 x 0.35m)	m^3	0.021	8	0.2
Main ridge and side ridges	-	3	0.50	1.5
			Total Weight	4.4

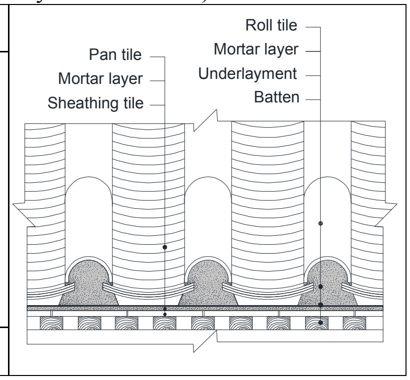


Table 2. Estimation of roof dead load for the three different span distances

Pitch angle (degree)	Unit Load (kN/m^2)	Measurement Length (m)	Measurement Span width (m)	Area (m^2)	Estimated Roof Load (kN)
30	4.4	1.32	3	3.96	17.4 → 17
		1.32	4.5	5.94	26.2 → 26
		1.32	6	7.92	34.8 → 35

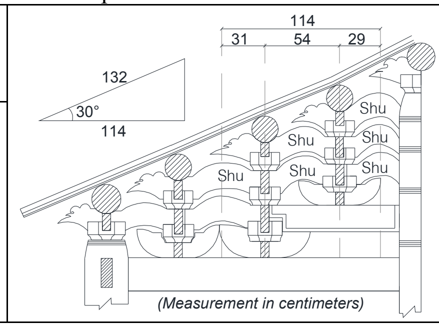
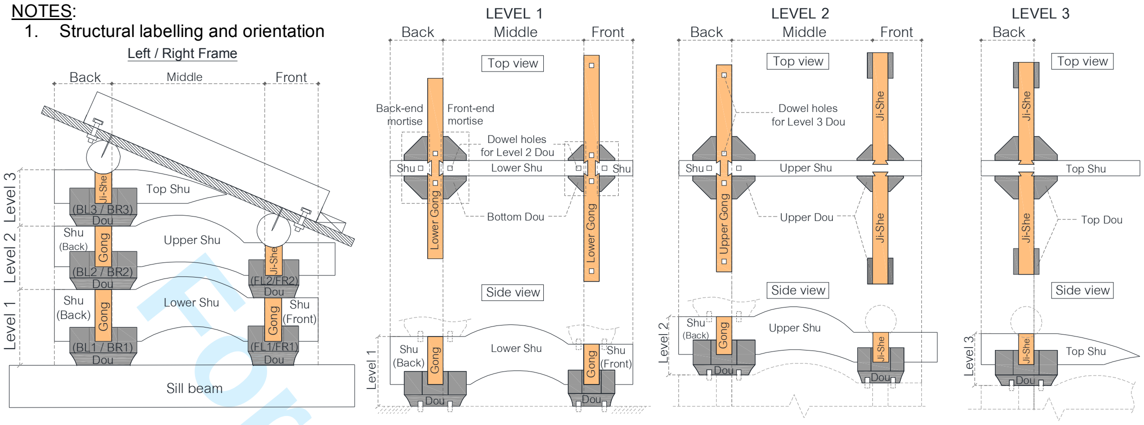


Table 3. Damage pattern of Symmetric specimen

Symmetric specimen

NOTES:

1. Structural labelling and orientation



2. Recurring damage count: 1st time damage, 2nd time damage, 3rd time damage, 4th time damage
3. Shear force direction: V = Vertical shear 45° = 45° shear H = Horizontal shear = Plane rotation

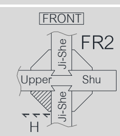
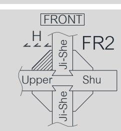
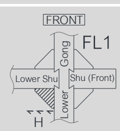
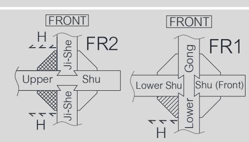
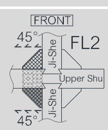
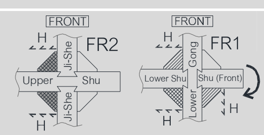
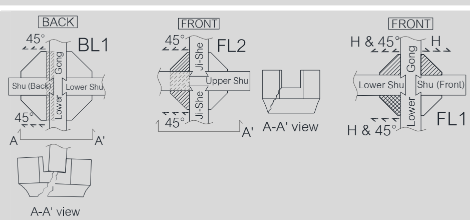
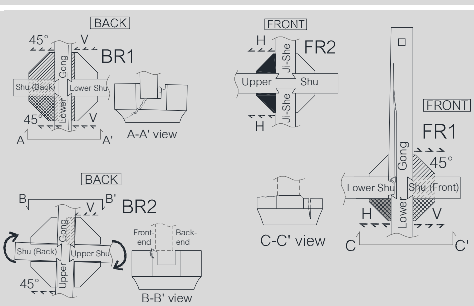
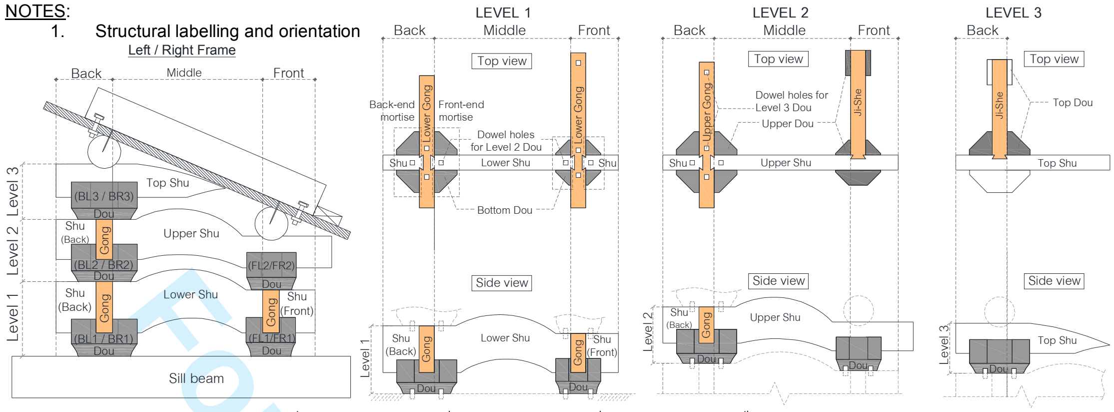
Roof Load	Seismic Input	Primary damage observed	
		Left frame	Right frame
17 kN 26 kN 35 kN	0.160g (20%)	No visible damage observed on-site	
17 kN 26 kN	0.336g (42%)	No visible damage observed on-site	
35 kN		No visible damage observed on-site	
17 kN	0.480g (60%)	No visible damage observed on-site	
26 kN			
35 kN			
26 kN	0.640g (80%)		
26 kN	0.800g (100%)	Aborted	

Table 4. Damage pattern of Asymmetric specimen

Asymmetric specimen

NOTES:

1. Structural labelling and orientation



2. Recurring damage count: 1st time damage, 2nd time damage, 3rd time damage, 4th time damage
3. Shear force direction: V = Vertical shear, 45° = 45° shear, H = Horizontal shear, = Plane rotation

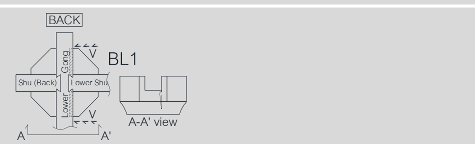
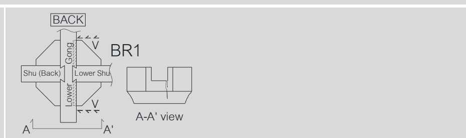
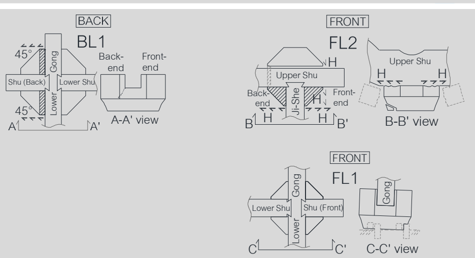
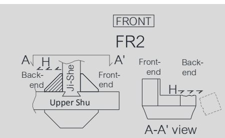
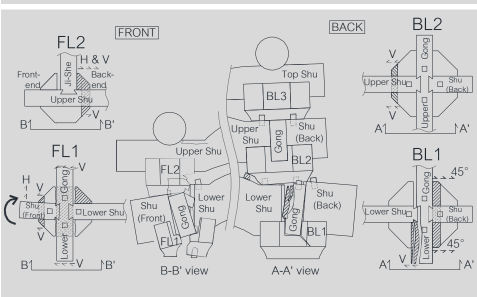
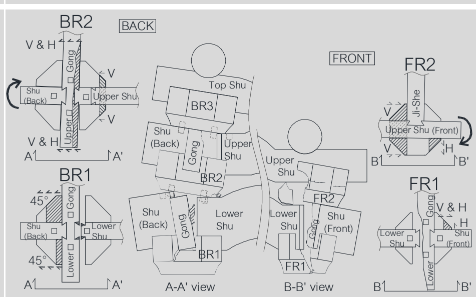
Roof Load	Seismic Input	Primary damage observed: Left frame	Primary damage observed: Right frame
17 kN 26 kN 35 kN	0.160g (20%)	No visible damage observed on-site	
17 kN 26 kN	0.336g (42%)	No visible damage observed on-site	
35 kN			
17 kN 26 kN 35 kN	0.480g (60%)	No visible damage observed on-site	
26 kN	0.640g (80%)		
26 kN	0.800g (100%)		

Table 5. Overview of the natural frequencies, stiffness and damping ratio of the two structural forms

SYMMETRIC

Dead Load [kN]	Input Level	20% f [Hz]	20% K1 [kN/mm]	20% K2 [kN/mm]	20% Damping ratio [%]	42% f [Hz]	42% K1 [kN/mm]	42% K2 [kN/mm]	42% Damping ratio [%]	60% f [Hz]	60% K1 [kN/mm]	60% K2 [kN/mm]	60% Damping ratio [%]	80% f [Hz]	80% K1 [kN/mm]	80% K2 [kN/mm]	80% Damping ratio [%]	100%
17	Before	4.55	1.39	--	2.84	4.50	1.36	--	2.83	3.96	1.05	--	2.86					Aborted
	After	4.50	--	1.36		4.49	--	1.35		3.87	--	1.00						
26	Before	3.95	1.60	--	2.84	3.90	1.56	--	2.85	3.52	1.27	--	2.94	3.53	1.28	--	13.78	
	After	3.92	--	1.58		3.58	--	1.32		3.46	--	1.23		2.82	--	0.82		
35	Before	3.39	1.59	--	2.86	3.39	1.59	--	2.88	3.33	1.53	--	3.03					
	After	3.35	--	1.55		3.30	--	1.50		3.22	--	1.43						

ASYMMETRIC

Dead Load [kN]	Input Level	20% f [Hz]	20% K1 [kN/mm]	20% K2 [kN/mm]	20% Damping ratio [%]	42% f [Hz]	42% K1 [kN/mm]	42% K2 [kN/mm]	42% Damping ratio [%]	60% f [Hz]	60% K1 [kN/mm]	60% K2 [kN/mm]	60% Damping ratio [%]	80% f [Hz]	80% K1 [kN/mm]	80% K2 [kN/mm]	80% Damping ratio [%]	100% f [Hz]	100% K1 [kN/mm]	100% K2 [kN/mm]	100% Damping ratio [%]
17	Before	4.52	1.37	--	2.84	4.52	1.37	--	2.84	4.52	1.37	--	2.85								
	After	4.52	--	1.37		4.52	--	1.37		4.52	--	1.37									
26	Before	3.94	1.59	--	2.84	3.92	1.58	--	2.86	3.87	1.54	--	2.91	3.87	1.54	--	3.08	3.74	1.44	--	4.67
	After	3.94	--	1.59		3.87	--	1.54		3.87	--	1.54		3.74	--	1.44		3.51	--	1.26	
35	Before	3.37	1.57	--	2.85	3.36	1.56	--	2.87	3.37	1.57	--	2.92								
	After	3.37	--	1.57		3.26	--	1.47		3.37	--	1.57									

Visible damage(s) was/were observed after test