ABSTRACT: Based on the shaking table experiments conducted on two different structural forms (Symmetric and Asymmetric form), the damage pattern of the traditional Dieh-Dou timber structure was studied. Using the 1999 Chi-Chi earthquake time history (TCU 084), roof loads of 17, 26 and 35kN were applied to the specimens under uni-directional excitation mode. Results shown that structural damage for both structural forms generally occur from 336 gal onwards. When friction between the mortise-tenon connections could no longer withstand the large seismic force, amplified rocking and torsion intensity lead to inelastic deformation. Damage pattern all begins from the bottom Dou members, spreading from the front and subsequently moving upwards to the upper Dou, horizontal Gong and traverse Shu members. More structural strengthening is recommended on the bottom Dou and front section members for future post-seismic repair.

KEYWORDS: Traditional Dieh-Dou timber frame, bracket system, shaking table experiment, rocking, rotation

1 INTRODUCTION

Bracket system and heavy roof are unique characteristics of traditional oriental timber frame. Of which, ‘Chuan-Dou’ and ‘Dieh-Dou’ frames are the two main types commonly found in Taiwan (Figure 1). Chuan-Dou frame is commonly 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 in Taiwan. In this study, focus will be placed primarily on the Dieh-Dou frame. Dieh-Dou timber 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: Two main types of Taiwanese traditional timber frame: (a) Chuan-Dou type © NCKURDF; (b) Dieh-Dou type © C-W Chen

During the 1999 Chi-Chi earthquake had destroyed or severely damaged many valuable traditional timber-frame historic timber buildings in Taiwan, to-date, not much research was done on the structural performance of the Dieh-Dou timber frame [1-7]. Thus, the Taiwanese...
engineers are still debating over the optimal evaluation method for the Dieh-Dou frame. However, before a proper structural evaluation can be established, a detail understanding of the damage pattern should be made. Hence in this paper, the damage trend of the Dieh-Dou timber frame when subjected to seismic force will be discussed.

2 EXPERIMENT

2.1 PREPARATION FOR THE SEMI FULL-SCALE SHAKING TABLE TEST

In this shaking table experiment, the geometric dimensions of individual members of the test specimens originated from the initial design of the Entrance Hall (Figure 3a). However, as the original design was slightly different from the conventional Dieh-Dou timber frame, hence slight revision was made to the design so that the results obtained from the revised test specimens could apply to other parts of the Dieh-Dou timber frames (Figure 3b). Two different structural forms (symmetric and asymmetric specimens, Figure 4), made of China Fir (*Cunninghamia lanceolata* Hook. var. *lanceolata*), were fabricated based on the above-mentioned revised design. 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. As for the jointing design, only dove-tail mortise/tenon joint and dowel connection were used on the specimens (Figure 4).

Figure 3: Areas where the revised specimen design could be applied to: (a) Corridor frame of the Entrance hall; (b) Internal main frame of a typical Dieh-Dou Main hall ©SY Yeo

Figure 4: Overview of symmetric and asymmetric design, connected mainly by dove-tail joints and wooden dowels ©SY Yeo

2.2 EXPERIMENT PROCEDURE

To understand the dynamic behaviour of traditional Dieh-Dou timber structure under different combination of structural forms and roof loads, two semi full-scale China Fir specimens of different structural forms (symmetric and asymmetric specimens, Figure 5) were tested on the shaking table of National Centre for Research on Earthquake Engineering (NCREE) in Taipei.

Both specimens were subjected to three different levels of roof weights – 17, 26 and 35kN – each representing the span interval between two parallel frames of 3, 4.5 and 6 meters respectively (Figure 7a). The 1999 Chi-Chi earthquake time history (TCU 084, Figure 6) was applied.
to the specimens and tested uni-directionally. Although the seismic record used has a Peak Ground Acceleration (PGA) of 989 gal, but in this experiment, the amplitude was downscale to 160, 336, 480, 640 and 800 gal, to represent the test levels of 20, 42, 60, 80 and 100% respectively. A point to note is on the choice of 42% (336 gal) instead of 40% test level. This is mainly because after the Chi-Chi earthquake, it was found that majority of Taiwan fell within Zone 1, which corresponds to PGA index of 0.33g (330 gal). Hence in this experiment, 42% (336 gal) was used instead so as to apply to the current Taiwan building regulations.

Figure 6: The original Chi-Chi earthquake seismic wave of TCU 084 EW Direction.

3 RESULTS AND DISCUSSION

3.1 DAMAGE PATTERN FOR BOTH SYSTEMS

Results shown that structure damage for both structural forms generally occur from 336 gal (42%) onwards [6]. Due to the difference in joint connection design, the force distribution affects overall damage patterns for both systems. The symmetric specimen tends to damage more easily and at an earlier stage than the asymmetric specimen. The damage pattern generally 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), as shown in Figure 8.

Being the critical linker between each level, the Dou member is commonly 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, and coupled with uneven rocking between the Dou and the Gong member, the overall magnified force will cause the Dou member to be fractured more easily during the course (Figure 9).

Figure 7: Span distance between two Dieh-Dou timber frames (a) Typical design; (b) Span design overview in Taiwan ©SY Yeo

System identifications were carried out between every test to monitor the integrity of the entire structures. When visible fractures were observed after a test, active reinforcement was carried out to reinstate as much of its structural stiffness as possible for the next test. Basically both specimens were designed to undergo the same test schedules whereby only the 26kN case was tested up to 100% and the remaining two cases (17kN and 35 kN) were only tested up to 60% seismic inputs. However when the symmetric specimen underwent the 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 reason for selecting the 26kN case to run the full test is because nearly two-thirds of the Dieh-Dou timber frames in Taiwan fell within the span distance of 4.5m, as shown in Figure 7b. The statistics figures were derived mainly from the first author’s personal research whereby the span distance of 110 Taiwanese national monuments with Dieh-Dou timber frame were recorded and compiled under the three main categories of 3m, 4.5m and 6m. In this study, the parameters used are mainly roof load, acceleration and rotation.

Figure 8: Final damage patterns of 26kN test for (a) Symmetric and (b) Asymmetric specimen under 80% (640gal) and 100% (800gal) respectively ©SY Yeo
Also, the maintenance of an intact cruciform mortise region of the Dou is crucial towards the overall structural stability, particularly during high seismic testing. As illustrated in Figure 9, when the two back-end mortises of the Dou were fractured severely, the widen mortise region resulted in 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. Hence, as long as the general cruciform mortise area of the Dou is relatively intact, the Dou member will be able to hold the Shu-Gong complex together to a certain extent.

3.2 EFFECTS OF ROTATION ON THE GLOBAL STRUCTURE MOVEMENT

Before the 480gal-testing, the dowels of the bottom Dou members were pulled out slightly from the sill mainly due to the rocking caused by high frequency shaking. But the behaviour was relatively within elastic range, hence no visible crack was observed when the Dou members return in-place. From on-site observation and video records, initial fracture first began from 336 gal onwards.

Forward thrust caused by the adjoining horizontal Gong members against the mortise region of the Dou led to horizontal shearing. Also, uneven distribution of inertia force and rocking (caused by uneven movement of the top and bottom parallel structures about the X-Y plane) became too great for the bottom Dou dowels to resist and consequently, the entire Dou was pulled out from the sill beam (Figure 10).

As seen in Figure 10, significant rotational difference is observed in the symmetric case as the PGA measured at both left and right bottom sections are different. This suggested a X-Y plane rocking effect whereby some of the Dou members on the right are already damaged during the first round of the seismic input. Under such circumstances, inelastic deformation occurred as the returning force was unable to let the already damaged Dou return to its original position; the Dou was subsequently sheared vertically by its own dowels and horizontally by the Gong member. In such case, the stiffness of the symmetric specimen was reduced from 1.27kN/mm to 1.23kN/mm and thus more deflection and damage resulted during the 2nd impact force. In the case of the asymmetric set, although similar rotation angle was observed in the first round of impact force, but the responded acceleration measured from the both left and right sections were similar, hence no visible damage was seen as not much X-Y plane rocking took place.

Under 640gal (80%) and 800gal (100%) testing, intense rocking and rotation also caused the rest of the members above bottom Dou to be lifted up together and when it returned back, the high impact downwards force not only caused more vertical shearing on the bottom Dou, but also on the Gong members and adjoining traverse Shu members. Similar damage trend were repeated all the way to the middle tier members.

![Figure 9: General damage patterns of Dou for 42% and 60% Symmetric specimen testing](https://example.com/figure9.png)
3.3 EFFECTS OF OPPOSING ROCKING BEHAVIOUR OF THE FRONT AND BACK BOTTOM DOU ON THE GLOBAL STRUCTURE

Next, a comparison of the front and back bottom Dou rocking behaviour was conducted by simply taking the mean vertical deflection measured between the two bottom Dou members, as shown in Figure 11. Results shown that the rotational behaviour of the front and back bottom Dou is seen to be in the opposing direction throughout all the tests, in other words, both the front and back bottom Dou do not rock in synchrony (Figure 12).

Such opposing rotational behaviour could be due to the existing fine gaps (1-3mm) present between the Dou and Shu-Gong complex during installation. Hence when the specimen was subjected to shaking, the front and back structures might rock at slightly different pace due to the inherent gaps. Such unsynchronized movement indirectly restrained the front structure from rotating too much to the front, and thus helps to maintain the stability of the global structure during low seismic tests (20% to 42%), as seen from the relatively well-defined hysteresis loops of both systems under low seismic input (Figure 13).

Figure 10: Example showing uneven rotation and movement observed between the left and right front bottom sections of both specimens under 26kN/60% test.

Figure 11: Sample calculation for mean vertical deflection of bottom Dou ©SY Yeo

Figure 12: Typical example showing uneven rotation between the left and right bottom Dou during 20% test.

Figure 13: Typical examples of hysteresis loops observed in both structural forms under 20% test.
Unsynchronized front and back Dou rocking behaviour continued all the way to high seismic testing, as shown in Figure 14. Despite of a larger vertical deflection value due to higher seismic inputs, the damage observed in such cases were localised within the Dou members and majority of the fractures were caused by horizontal shear.

Although the damage gave rise to a widen mortise region, the cruciform mortise shapes of these damaged Dou were not totally destroyed. This damage enhanced the unsynchronized rocking behaviour between the front and back structures and thus slowed down the entire structure rocking as the stiffness was significantly reduced. Under these circumstances, the Shu-Gong complex is still intact with no visible damage.

From on-site observation and video records, it appeared that as long as the dove-tailed connections of the Shu-Gong complex is not damaged, unsynchronized rocking of bottom Dou members coupled with tight dove-tail connection will help to hold the global structure intact for both systems.

3.4 DESIGN OF STRUCTURE WITH RELATION TO OVERALL STABILITY

Increasing roof loads amplify the seismic force with increasing seismic input [1, 5, 6] were observed in both structural forms. From on-site observation and measured rotation, the “forward” force is found to be much stronger than the “backward” force from 480 gal/60% test onwards. Thus this might account for the front complex members being pulled out at first instance and more damage occurrences at the front than at the back for both structural forms. Also, from the results obtained from the above bottom Dou rocking comparison method (Figure 11), it is found that majority of the front Dou members rock more than the back Dou, and that most of the Dou members tend to rock towards the forward direction than backward direction, particularly during high seismic tests (Figure 14).

Another possible reason could be due to the lesser surface contact at the front as compared to the back where the contact surface of bottom back Dou is wider thus giving rise to higher rotational rigidity (Figure 15). Also, the geometry of the specimen with respect to the location of the gravity centre 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.

**Figure 14:** Unsynchronized rocking behaviour and their respective hysteresis loops of both specimens during high seismic tests.

**Figure 15:** Example showing rotation difference between the front and back bottom Dou of both specimens under 60% (480 gal) test.
Table 1: Comparison on the rotation between the front and back members of the two structural forms.

<table>
<thead>
<tr>
<th>Dead Load (kN)</th>
<th>20% test</th>
<th>42% test</th>
<th>60% test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Back</td>
<td>Front</td>
<td>Back</td>
</tr>
<tr>
<td>Symm. Asym.</td>
<td>0.003</td>
<td>0.003</td>
<td>0.006</td>
</tr>
<tr>
<td>Symm. Asym.</td>
<td>0.002</td>
<td>0.001</td>
<td>0.008</td>
</tr>
<tr>
<td>Symm. Asym.</td>
<td>0.003</td>
<td>0.002</td>
<td>0.013</td>
</tr>
</tbody>
</table>

Also illustrated in Figure 15, it is noted that both the front and back bottom Dou members of the symmetric specimen generally tend to rotate at least 1.5 to 2 times more than the asymmetric specimen during high seismic test of 60%. Having cross-referenced with the lower seismic test results of 20% and 42% (Table 1), there is generally not much rotational difference between the front and back bottom Dou members of both structural forms. Hence it is likely that under low seismic shaking, the difference in structural forms has very little effect on the rocking intensity, but rather, the effect of opposing rocking behaviour between the front and back bottom Dou members might play a more dominant role in structural stability. Structural form difference might only exert its influence, in terms of rocking intensities and amplification, during high seismic shaking of 60% and above.

3.5 EFFECTS OF STRUCTURE FORMS ON THE DEFLECTION INTENSITY

With reference to the Figure 4, the distinct difference between the asymmetric and symmetric specimen is mainly on the number of structural members contributing between two frames. Hence, symmetric specimen can be considered to be having roughly twice as many structural members than the asymmetric set. It was commonly believed that the symmetric design is better in terms of energy absorption and dissipation, and thus more structurally sound than the asymmetric one. Thus to find out if different structural forms have any effect on the deflection intensity, a chart comparison between both structural forms, with respect to their maximum deflection and shear force measured from the hysteresis loops, was made (Figure 16).

From Figure 16, three critical observations could be made. Firstly, the symmetric specimen generally tends to deflect around 2 times more than the asymmetric set. Secondly, the maximum deflection of each vertical load will generally increase exponentially with increasing seismic intensities. Even though 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. Thirdly, the intensity of maximum shear force measured from both systems is relatively similar for low seismic test range. Although 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.

Table 2: Overview of the natural frequencies, stiffness and damping ratio of the two structural forms.
From the data obtained from white noise tests conducted before and after each seismic loading test, the natural frequencies (f) and stiffness values (K) were derived and tabulated in Table 2. The damping ratios were obtained by using the half-power bandwidth method. Generally, the f and K values measured before test were much higher than those measured after test. But the difference margin was only more prominent in the heavier roof loads and larger seismic tests of 42% onwards.

A closer look on specific cases with similar initial stiffness value (measured before test; hereinafter K1) and damping ratios, a weaker secondary stiffness (measured after test; K2) was generally observed in these cases. Specimen with a weaker K2 and a lower damping ratio tends to exhibit larger response during dynamic test, and consequently more deformation was resulted. The above scenario was first observed in the symmetric specimen as lower K2 values began at an earlier stage of 60% loading test. Thus the symmetric specimen might encounter a larger response and more damage than the asymmetric set.

4 CONCLUSIONS

In this paper, the damage pattern of traditional Dieh-Dou timber structure under different combination of structural forms and roof loads was studied. The following conclusions can be made:

1. When friction between the mortise-tenon connections could no longer withstand the large seismic force, amplified rocking and rotation intensity lead to inelastic deformation.

2. Damage pattern generally begins from the bottom Dou members and subsequently spreading upwards to the upper Dou, horizontal Gong members and traverse Shu members. Front section is more prone to damage than back section due to lesser surface contact. Hence more structural strengthening is recommended on the bottom Dou and front section members for future repair.

3. Unsynchronized rocking of bottom front and back bottom Dou members is commonly observed throughout the tests. Such opposing interaction of the front and back structures, coupled with dove-tail connection, help to restore the global structure stability to a certain extent.

4. Symmetric specimen generally exhibits lower secondary stiffness and damping ratios 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.

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