FULL SCALE STATIC LOADING TESTS FOR TWO STORIED PLANE FRAME OF TRADITIONAL TOWN HOUSE IN KYOTO, JAPAN

Yasuhiro Hayashi1, Noriko Takiyama2, Shinichi Hirosue3, Takuya Matsumoto4, Atsushi Nakagawa5

ABSTRACT: We have conducted static loading tests of plane frame of a two-storied traditional town house in Kyoto, Japan. In our study, we have developed a lateral loading system in order to apply large shear deformation angle of 0.2 rad. Based on our tests, the deformation performance and stress transferring mechanism of town houses are well understood. Concentration of deformation or damage in a specific story will be prevented by the existence of pillars and toriniwa portion.

KEYWORDS: Static loading tests, Traditional town house, Two-storied plane frame

1 INTRODUCTION
There are many traditional wooden town houses forming the historical townscape in Kyoto, Japan. On the other hand, there are a lot of old wooden buildings collapsed in the Hyogo-ken Nanbu, Kobe earthquake in 1995. Therefore, it is important to carry out seismic retrofit of town houses in Kyoto but their seismic performance (horizontal loading capacity and deformation capacity) are not clarified enough. Supposing a two-storied town house in Kyoto, in this research, we have conducted horizontal static loading tests of a plane frame which passes in the ridge direction. Then, the response behaviour of town houses during strong ground motions is discussed based on our test results.

2 OUTLINE OF EXPERIMENTS
2.1 SPECIMENS
In order to understand the structural properties of a two-storied town house, five specimens are used for the static loading tests as shown in Fig.1. A plane frame, which passes the central pillar, daikoku-bashira, in the ridge direction, is called as Specimen-D. The height and width of Specimen-D are about 5.2m and 5.8m, respectively. It is one of the evident features of town houses in Kyoto that there are many through columns (pillar). A mud wall is placed in the first floor of rooms. The type of joints, the dimensions and material of members are determined based on the specification used in actual traditional town houses, in Kyoto. Dimensions and material of principal members are listed in Table 1. The Specimen-D can be divided into the room (Specimen-DR) and a narrow street with open ceiling space called toriniwa (Specimen-DT). Furthermore, Specimen-DR is also divided into the first floor (Specimen-DR1) and second floor (Specimen-DR2). Pillars are placed on the natural stones and are not fixed at all. Therefore, the sliding or uplift of pillars is free.

2.2 LOADING SYSTEM
Cyclic loading tests with gradually increasing displacement amplitude are conducted. The height of specimen is 5.255m. Therefore, the maximum half amplitude of displacement at the roof level is about 1.0m.
in order to make the maximum shear deformation angle up to 0.2 rad. To apply such a large deformation, the following loading system has been developed.

The loading frame consists of two plane frames. Each frame consists of two steel pillars and two horizontal steel beams and is connected each other so that their movement should be same. Pillars are supported by pin joints at the bottom, and horizontal beams are also connected to pillars by pin joints. Therefore, loading frame is unstable in the in-plane direction. In order to apply the horizontal displacement to a specimen, specimen is connected to loading frame through load cells at roof level or second floor level. In-plane horizontal displacement of a specimen is controlled by a hydraulic jack, whose stroke is 1m, connected to pillars. We perform the loading by amplifying displacement using the principle of the lever as shown in Fig. 2. The loading process is shown in Fig. 3. The deformation angle $R$ is the horizontal displacement of the top of the specimen divided by the height 5.255 m. The positive and minus deformation angles are loading in the right and left directions, respectively.

Weights corresponding to the fixed load and movable load of a town house are set on the top and second floor.
level of specimens. The fixed load (weight) and movable load (the weight of specimen) is listed in Table 2. The axial force for each column is calculated and listed in Table 2. Total weight of Specimen-D is about 50kN. And the axial force for the **daikoku-bashira** of Specimen-D, column ‘c’ in Table 2 is about 23 kN. Therefore, half of the total weight is applied to **daikoku-bashira**.

### 3 TEST RESULTS AND DISCUSSIONS

#### 3.1 DAMAGE PROGRESS

First, damage progress of a mud wall and frames as deformation increase is investigated. The progress of typical damage to the Specimen-D is shown in Fig. 4 and typical damage condition of beam-column joints and uplift status of column base are shown in Photo 2. A mud wall starts cracking around horizontal members inside the mud wall at 1/20 rad. and the center of mud wall cracks in a vertical direction at 1/15 rad. End failure at the tenon of beams starts to occur at the rotational angle of 1/30 rad. as shown in Photo 2(c).

Splitting failure occurs in the fiber direction near the cotter slot of a beam-column joint at 1/15 rad. as shown in Photo 2(e). Although capital tenon and tenons at beam-column joints fractured, but no pillar does not break at all until it reaches 1/8 rad. of deformation angle. Figure 5 shows the relationship between the 1st story deformation angle and 2nd story deformation angle. The 2nd story deformation angle is 2.5 times as large as 1st story deformation angle at 1/75 rad. But the deformations of the first and second stories tend to be nearly equal as deformation angle increases. This tendency is due to the deformation equalization effects of pillars such as **daikoku-bashira** and **toriniwa**, and failure in the mud wall and beam-column joints. Namely, the **toriniwa** and pillars play a role to prevent damage concentration to the first or second story.

Next, the relationship between horizontal load applied to the top of Specimen-D and deformation angle is shown in Fig. 6. Resisting force of Specimen-D disappear around the deformation angle of 1/8 rad. due to the PΔ effects.

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**Photo 2: Typical damage of specimen-D**

- Uplift at column base
- Uplift at column base
- Failure at tenon end
- Bending of cotter
- Splitting failure at beam-column joint

**Figure 4: Schematic damage process of specimen-D**
3.2 RESTORING FORCE CHARACTERISTICS
Figure 7 shows the skeleton curves in the right and left directions. Restoring force in the left direction is 1.5 times as large as that in the right direction. The asymmetry of skeleton curve is mainly due to the asymmetrical location of mud wall, namely asymmetrical column base uplift and mud wall failure as shown in Fig. 4.

Figure 8 shows the comparison between Specimens-D, Specimen-DT and Specimen-DR. There is almost no difference in skeleton curves of Specimen-D and DR, and the maximum strength of Specimen-DT is very small. Namely, the restoring force of toriniwa is very small. However, as described before, the toriniwa and pillars play a role to prevent damage concentration to the first or second story.

3.3 BEHAVIOURS OF COLUMN BASE
Uplift and sliding behaviour of columns for Specimen-D are shown in Figs. 4 and 9. The uplift of column base occurred around a mud wall due to the tensile force induce by the rocking of the mud wall. Therefore, the uplift of side pillar, ‘a’ in Fig. 9(a), occurred under positive (rightward) loading, but the uplift of stand column, ‘b’ in Fig. 9(a), occurred under negative (leftward) loading. Column base uplift increases as shown in Fig. 9(a), as the deformation angle increases up to 1/20 rad. or 1/15 rad. After that, the uplift decreases after the mud wall is heavily damaged. The maximum uplift of side pillar is about 21mm and is much larger than that of stand column which is restricted to move upward by a beam.

On the other hand, frame does not slide as one-body system as shown in Fig. 9(b). This is because the ratio of the horizontal loading capacity to the total weight is about 0.09 and is less than friction coefficient of about 0.4 between wood and stone. However, some columns with small axial force slide independently. Especially, the sliding of side pillar is predominant after the mud wall is heavily damaged. The axial force of side pillar is not so large and the pillar moves so that the width of mud wall should spread.

3.4 STRESS TRANSMITTING MECHANISM
The shear force of columns is calculated from the bending moment identified using strain gauges stuck on columns as shown in Fig. 10(a). The 1st story shear force is equal to the 2nd story shear force, because horizontal load is applied to the top of frame. Therefore, the shear force of the mud wall is calculated from those of columns as shown in Fig. 10(b). Shear force distributions and bending moment diagram for representative deformation angles are shown in Figs. 10(c) and 11, respectively. The maximum shear forces of mud wall in the right and left loading directions are about 7kN and 9kN, respectively, as shown in Fig. 10(b). Therefore, the maximum shear force of mud wall is larger than the maximum restoring force because there is an oppositely-directed shear force to the loading direction in the daikoku-bashira pillar as shown in Figs.
10(a), 10(c), and 11(a). In addition, the oppositely-directed shear force decreases as the damage of mud wall become severer as shown in Figs. 10(a) and 11(b). Therefore, it is considered that the oppositely-directed shear force is due to the existence of the mud wall.

### 3.5 COMPARISON WITH CURRENT DESIGN METHOD

Finally, the 1st story shear forces obtained from our experimental test results and estimation by the current design method are compared in Fig. 12. The experimental result is calculated from the load-deformation relationship by excluding the $P\Delta$ effects. Estimation by the current design method is based on the summation of skeleton curves for unit structural elements. Therefore, it is pointed out that the asymmetrical restoring force characteristics with respect to the loading directions are not considered in the current design. Furthermore, the loading capacity estimated from the current design method drastically decreases due to the failure in the mud wall. However, according to the experimental results, the plane frame holds the restoring force of 5kN or more even at the deformation angle of 1/10 rad.
4 CONCLUSIONS

We have conducted static loading tests of plane frame of a two-storied traditional town house in Kyoto, Japan. In our study, we have developed a lateral loading system in order to apply large shear deformation angle of 0.2 rad. Based on our tests, the deformation performance and stress transferring mechanism of town houses are well understood as follows.

(a) No pillar breaks until the horizontal restoring force is lost around the deformation angle of 1/8 rad. due to the $P \Delta$ effect.

(b) Concentration of deformation or damage in a specific story will be prevented by the existence of pillars and toriniwa portion.

(c) Since the ratio of the horizontal loading capacity to the total weight is less than 0.2, specimen frame does not slide as one-body system. However, some columns with small axial force move independently.

(d) The following phenomena, which are neglected in the current seismic design method for the traditional wooden buildings in Japan, have been observed.
   1) Uplift of columns near a mud wall
   2) Asymmetric restoring characteristics
   3) Oppositely-directed shear force to the loading direction

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