On-Site Lateral Loading Test of a Traditional Timber House in Japan

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Abstract

This paper presents the results of a static lateral loading test performed on a traditional timber farmhouse in Japan. The aim of this research is to clarify the horizontal load carrying capacity and the failure mode of this type of house by full-scale experiment. The house is situated in Yamaguchi prefecture, which is in the southwestern part of Japan, and was built in the late 18th century. The experiment was performed by placing static loading equipment within the house, and placing two reaction supporting systems outside the house. A lateral cyclic loading test was carried out and the maximum lateral load and the failure mode were determined. Static analysis using a theoretical mud wall model was also performed. The results of this analysis are discussed in comparison with those of the experiment.

Keywords: timber joint; mud wall; failure mode; static loading test.

Introduction

Structures in Japan are forced to face severe natural hazards such as earthquakes and typhoons during their lifetime. In order to ensure their structural safety, it is essential to determine their horizontal load carrying capacity. Traditional farmhouses in Japan are usually made of a post and beam structure with mud walls and thatched roofs. As the weather is hot and humid in the summer months, large openings are accommodated in the walls for ventilation. It is important to evaluate the horizontal load carrying capacity because these buildings are still in use, and also because the number of traditional timber houses designated as cultural properties are increasing.

The necessity of evaluating the structural performance of these traditional structures has been realized due to the devastating damage by the 1995 Hyogoken-Nanbu Earthquake. Experimental as well as analytical researches have been performed, most of which are subjected to lateral load resisting elements, such as mud walls and timber joints [1]. On-site loading tests on existing timber farmhouses have been conducted by Sugiyama et.al [2], Kawai and Sakamoto [3], Fukumoto [4] and Miyazawa [5]. All of which were static lateral loading tests of farmhouses with similar plan, loaded in the direction perpendicular to the ridge. This is mainly due to site restrictions as described later. In this research lateral loading test was performed on an existing typical farmhouse in the direction parallel to the ridge, in order to clarify the horizontal load carrying capacity

Subject

The subject of the experiment is a farmhouse owned by the Harada family, referred to as the Harada House hereafter. It is situated in Yamaguchi Prefecture, which is located in the southwestern part of Japan, and was built in the late 18th century. From historical records of the vicinity, the Harada house could have experienced three large earthquakes, in 1793, 1987 and 1991, none of which caused serious damage in the surrounding district. Additionally there is no record of structural damage to the Harada House from past earthquakes.

The exterior, plan, and sections of the Harada House are shown in Figures 1, 2, 3 and 4 respectively. The entrance, barn and kitchen, which are all *doma* (mud floor rooms), are located on the east side of the building. Four living rooms and bedrooms with *tatami* mat flooring are located on the west side. This planning is a typical example of a 17th to 19th century farmhouse. The house is 11.0 m by 15.6 m in plan and approximately 7.7 m from the floor to the apex of the roof. The building is a post and beam structure with solid mud walls and mud walls with openings (hanging walls). The horizontal load

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Fig.1. South side of Harada House

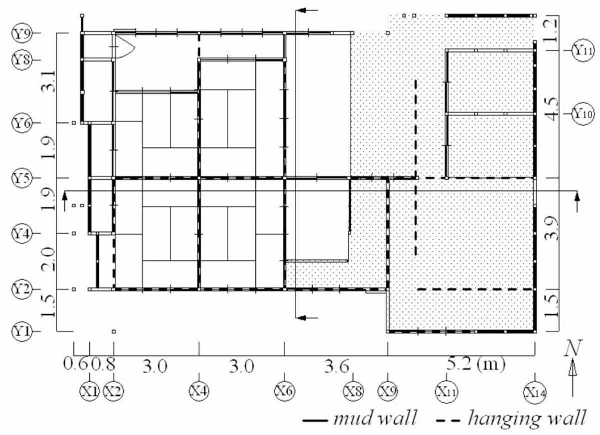


Fig.2. Plan

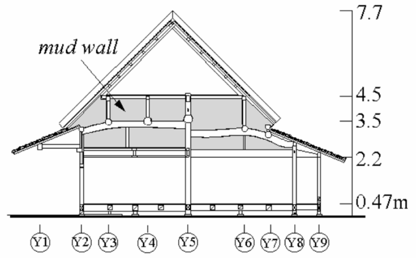


Fig.3. N-S section

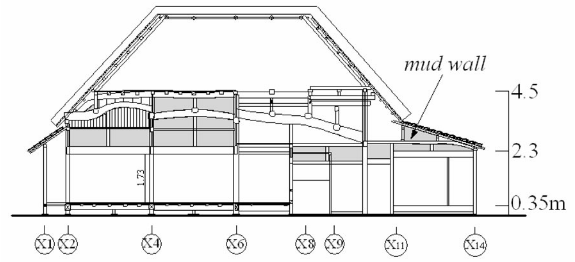


Fig.4. E-W section

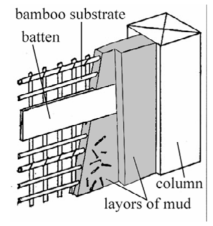


Fig.5. Detail of mud wall

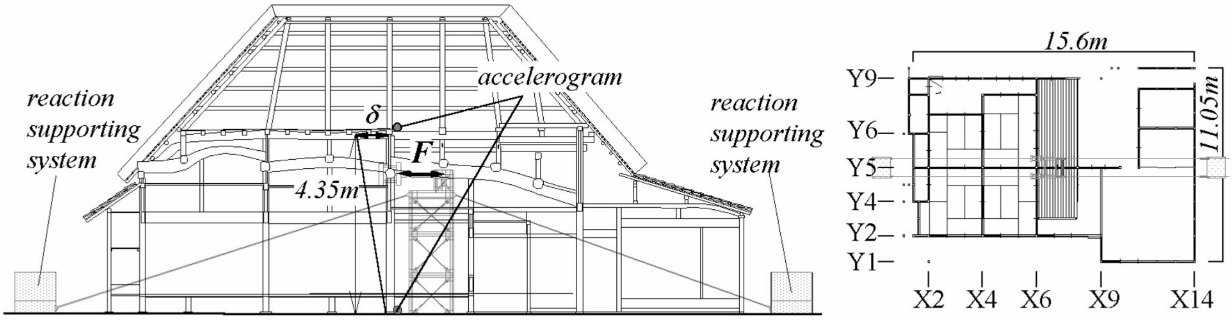


Fig.6. Loading Apparatus

resisting elements are the mud walls and hanging walls, which are made from a bamboo substrate encased in dried mud as shown in Fig 5.The dead load of the subject was evaluated by measuring the specific gravity of all the elements and materials in the building. Most of the columns and structural beams in the building consist of Japanese red pine, the walls are made of mud and bamboo and the roof was firstly thatched with miscanthus then covered with zinc plates. Clay tile roofing was partially used on the terrace roof. The total weight was 490 kN.

Methods

Four test methods were used in this study; microtremor measurement, forced vibration testing, static lateral loading testing and material testing of the beams. The microtremor measurement and forced vibration test were carried out to clarify the fundamental vibration characteristics of the structure. Microtremor measurements were additionally performed between the static lateral loading tests to determine the damage, or the effect of the static test on the vibration characteristics of the structure.

The static lateral loading test was performed using a horizontal loading apparatus constructed inside the structure and by placing two reaction supporting systems outside the house, as shown in Fig. 6. The displacement of the columns was measured using 51 displacement transducers, and the load by a load cell placed between the beam and the hydraulic jack. The main horizontal displacement was measured at 4.35 m from the ground.

The static lateral loading test followed the procedure set-out in Table 1. During the first phase, static cyclic loading was performed in the N-S direction and then in the E-W direction to a maximum story drift of 1/120 rad. to define the structural performance in the elastic range. The cyclic loading test was then carried out in the W direction until the story drift reached 1/15 rad.

and failure of the main column was observed. This determined the maximum horizontal load carrying capacity and the procedure of failure.

The static lateral loading test was mainly focused on loading in the E-W direction for the following reasons: (1) the horizontal load resisting elements are fewer in the E-W direction, (2) from the planning of the house it was assumed that it would be more difficult to set reinforcement devices in the N and S elevations. (3) The few preceding studies in this field were all performed in the N-S direction, which is parallel to the ridge. This is mainly due to site restrictions, as farmhouses are usually planned to have the ridge running in the East West direction and have gardens in the north and south side of the house, where the loading apparatus can be installed. The experiments were carried out in August 2000.

Table 1 Experimental Procedure

Name	Test (in chronological order)
V1	Microtremor measurement & forced vibration test
NS1	Static cyclic loading test N-S direction. Max drift 1/240 rad.
V2	Microtremor measurement & forced vibration test
NS2	Static cyclic loading test in N-S direction. Max drift 1/120 rad.
V3	Microtremor measurement & forced vibration test
EW1	Static cyclic loading test in E-W direction. Maximum drift 1/240 rad.
V4	Microtremor measurement & forced vibration test in E-W direction
EW2	Static cyclic loading test in E-W direction. Maximum drift 1/120 rad.
V5	Microtremor measurement & forced vibration test in E-W direction
W1	Static cyclic loading test in W direction. Maximum drift 1/15 rad.
V6	Microtremor measurement & forced vibration test

Vibration Characteristics

The fundamental vibration characteristics of the building were determined from the microtremor measurements and forced vibration testing results. The microtremor measurements were also recorded after each static lateral loading test, to determine damage or stiffness degradation and the influence of the static test on the vibration characteristics of the building. The natural frequency and damping factor of the building are shown in Fig. 7 and Fig. 8. The accelerograms were set in the points shown in Fig. 6.

The results of the microtremor measurements show that in the initial state (V1) the natural frequency (first mode) of the specimen was 3.19 Hz in the N-S direction, and 3.03Hz in the E-W direction. The natural frequency is higher in the N-S direction as there are more mud walls and hanging walls in the N-S direction compared with the E-W direction.

After the initial state the natural frequency declines due to stiffness degradation influenced by the damage from the preliminary static lateral loading test. A forced vibration test was performed and the free vibration characteristics were determined. The damping factor was determined from the logarithmic decrease in the free vibration wave profile. In the initial state the damping factor was 7.81% in the N-S, and 9.12% in the E-W direction respectively.

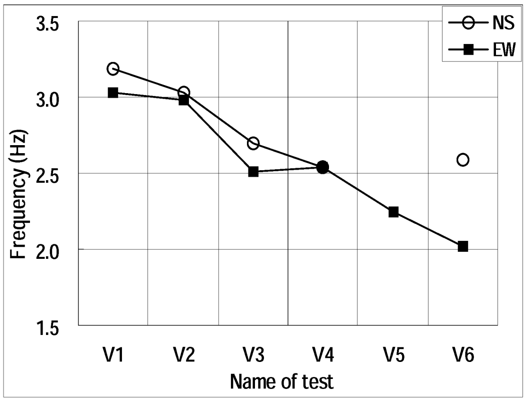


Fig.7. Natural Frequency from Micro Tremor Measurement

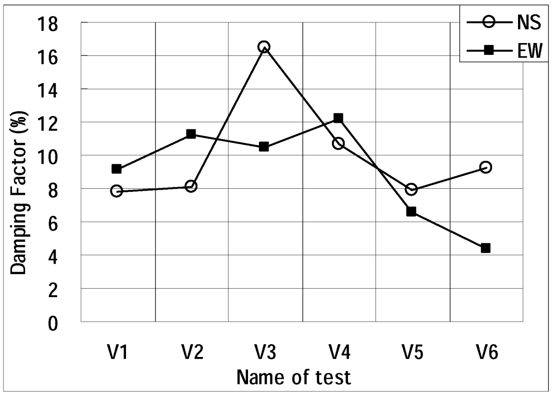


Fig.8. Damping Factor from Forced Vibration Test

Load Displacement Relationship

The load displacement relationships of the building in the N-S direction (NS1 and NS2) and E-W direction (EW1 and EW2) are shown in Fig. 9 and Fig. 10 respectively. The horizontal displacement was measured at the X6Y5 column (Fig. 2) at a height of 4.35 m. The secant modulus of elasticity at story drift angle 1/120 rad. (horizontal displacement 36 mm) in the N-S and E-W direction was 1.1 kN/mm and 0.88 kN/mm respectively. The hysteresis characteristics are similar in both directions displaying a slightly pinched spindle shaped curve. No significant damage was observed from the cyclic loading test after the maximum cycle of 1/120 rad in the N-S direction. After the cyclic loading of 1/120 rad. in the E-W direction, minor cracks at the

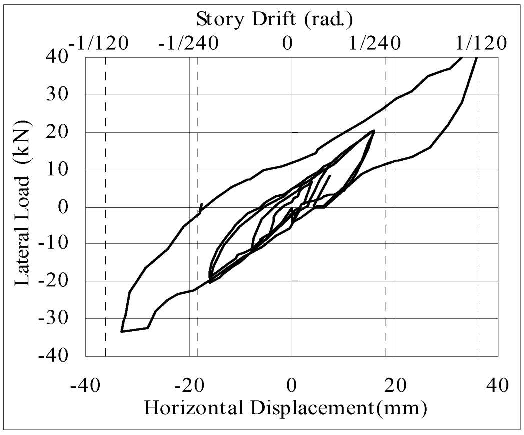


Fig.9. Load displacement Relationship NS1 and NS2

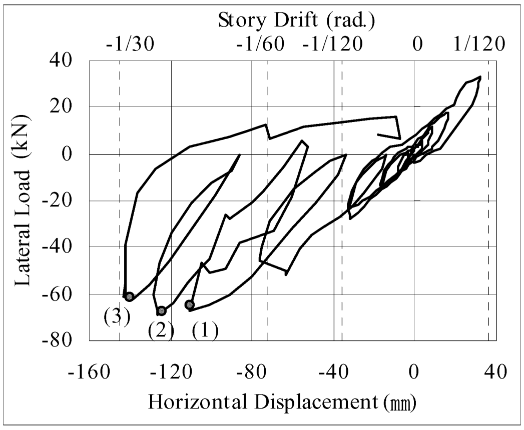


Fig.11. Load displacement relationship EW1, EW2 and W1

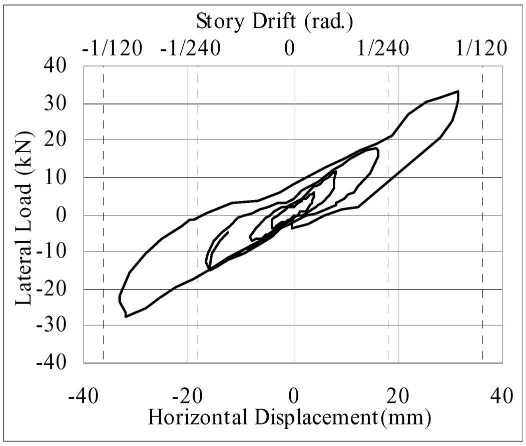


Fig.10. Load displacement relationship EW1 and EW2

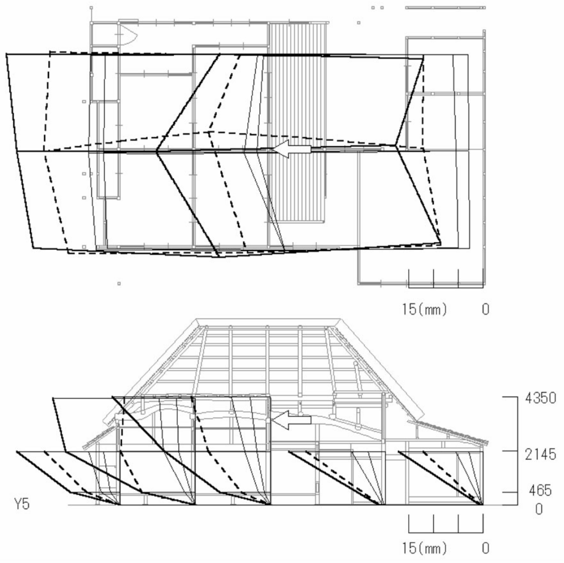


Fig.12. Horizontal displacement characteristics

corners of hanging walls were observed.

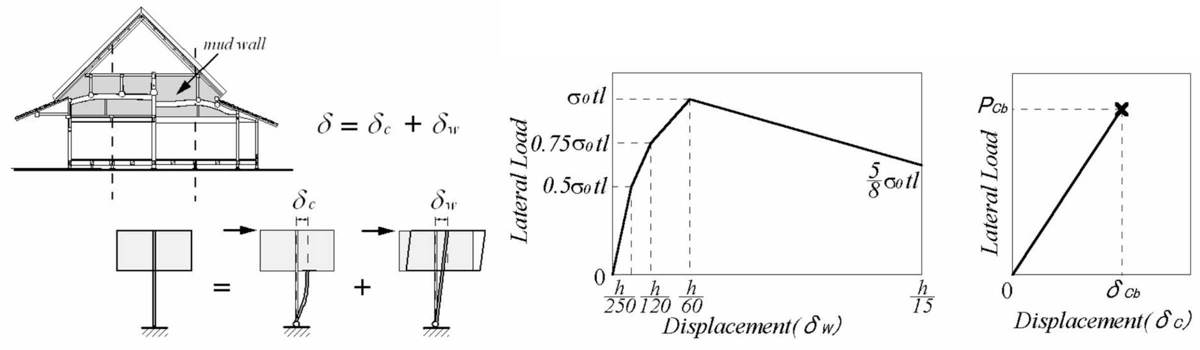
Fig. 11 shows the load displacement relationship in the large deflection range (EW1, EW2 and W1). The stiffness degradation can be observed after story drift angle 1/60 rad. (horizontal displacement 72.5 mm). The maximum load was 68.8 kN at 1/31.6 rad. (126.5 mm). The base shear coefficient determined from the maximum load and the weight of the structure□(490kN) was calculated as 0.14. The failure mode was as follows (numbers correspond to those shown in Fig. 11). (1) bending failure of the center column (Y5X6) at the joint with the floor, (2) shear failure of the center column (Y5X6) at the hanging wall, (3) the beam in the X9 section fell from the column because of failure of the beam column joint (Y8X9) and the load decreased rapidly.

Fig. 12 shows the deflection characteristics of the plan and the section. The deflection in the plan shows the horizontal displacement of each column at the top of the opening (2145 mm) level. The figure demonstrates that the loading point (indicated as an arrow) displays the largest deflection and the horizontal diaphragm is not very rigid. Fig. 12 also shows the deflection of each column in the Y5 column line. The bending deflection of the column can be observed at the top of the opening.

Static Analysis

The static lateral load carrying elements of the Harada house are the mud walls and hanging walls. Analytical models of these elements were constructed using (1) a shearing model to portray the mud wall and (2) a multi-linear model to represent the load displacement relationship of the mud wall as illustrated in Fig. 13 by Uchida et.al. [7]. The horizontal displacement of the hanging wall was calculated from the sum of the bending displacement of the column (δ_C) and the shearing displacement of the mud (δ_W) as shown in Fig. 13 by Maekawa, Kawai et.al [8].

The shear strength of the mud wall (σ_0) has been determined from preliminary studies by Fujita, Sakamoto



t: thickness, l: length, h: height of the wall, P_{Cb}: bending strength σ_0: shear strength of mud wall

Fig.13. Structural mechanism of hanging wall

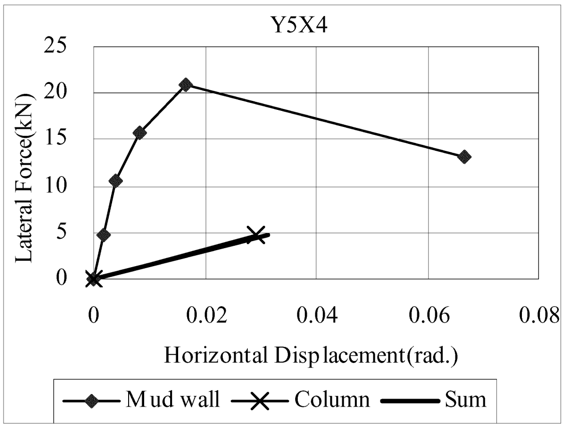


Fig.14. Load Displacement of Y5X4

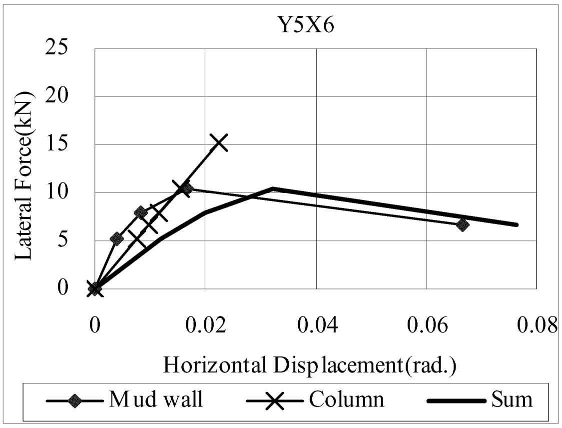


Fig.15. Load displacement of Y5X6

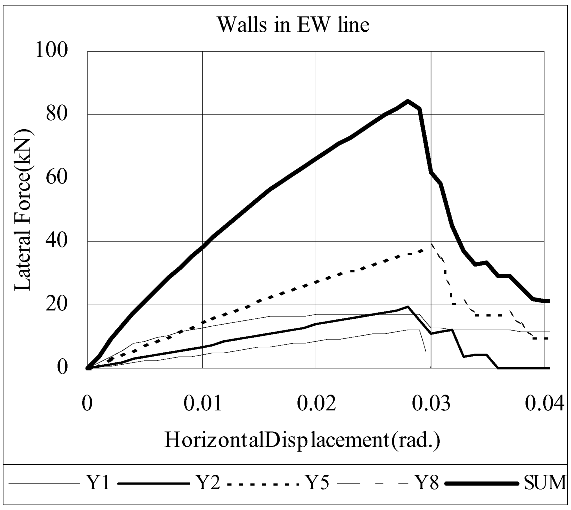


Fig.16. Load displacement relation the elements

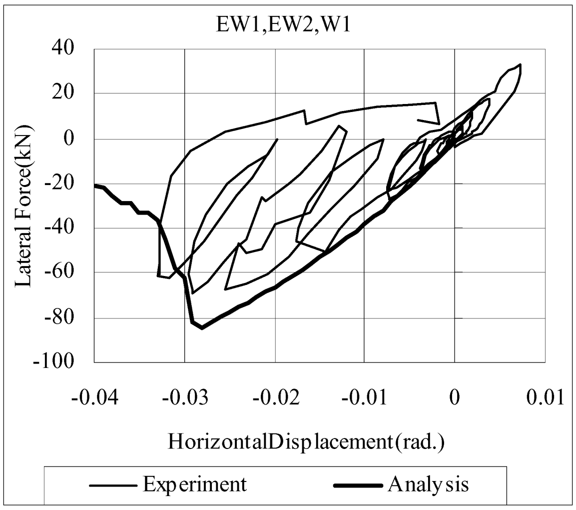


Fig.17. Results of experiment and analysis

et.al. [9] as 0.10 MPa. The Young's modulus of the column (Japanese red pine) was determined from material testing to be E = 9000 MPa. The bending strength of the column was also determined from material testing to be 40 MPa; taking into consideration the unevenness of the material, especially at the joint, the value was decreased by 0.8 and P_{Cb} = 32 Mpa was used as the bending strength of the column. Figures 14 and 15 show two examples of the load displacement relationship of the hanging wall element.

When the bending strength of the column is less than the shear strength of the mud wall, as in Y5X4, bending fracture of the column occurs at 1/25 rad. and the strength of the element decreases rapidly. When the bending strength of the column is greater than the shear strength of the mud wall, the strength decrease occurs gradually and shows a ductile behavior.

The mud wall and hanging wall models were applied to the structure, and static push over analysis was performed. The height of the rigid floor was presupposed to be 4.35 m, and torsional displacement was ignored. Fig. 16 shows the calculated load displacement relationship of all the walls and hanging walls in the E-W direction.

At approximately 1/30 rad. bending failure of the columns can be observed. The thick red line shows the sum of all the planes on the basis of the rigid floor assumption. Fig. 17 shows the results of the experiment and the push over analysis. The thick line is the total sum of all the walls. The analytical stiffness is fairly close to that of the experiment until approximately 1/60 rad. when stiffness degradation occurs as observed from the experimental results. The maximum horizontal load was determined to be 84.3 kN at 1/36 rad. from the static analysis, whereas the experimental results determined the load to be 68.8 kN at 1/31.6 rad. The results show that the analytical maximum load is 23% higher than the experimental result. The experimental results showed that failure was as a result of the bending failure of the Y5X6 column at 1/27 rad. with a decrease in the horizontal load observed. The analytical results showed that the first column to fail was the Y2X9 column at 1/36 rad. The other columns started to show bending failure at approximately 1/30 rad. with a rapid decrease in the load observed.

The difference between the experimental results and the analytical results can be attributed to the fact that (1) although the results of the material test and the sectional deficiency of the column at the joint have been taken into account in the analysis, material deterioration at the column and the *sashigamoi* (horizontal member) joint has not been taken into consideration. (2) The horizontal loading was applied around the Y5X6 column, which may have caused stress concentration in this area. (3) The analytical results are based on the rigid plane assumption, but in reality the horizontal diaphragm structure of the roof and ceiling must be taken into account.

The experimental results show that the bending failure of the column occurs at the joint at an earlier stage but that the load degradation is slower.

Conclusion

Static lateral loading testing on an actual farming house was performed. The maximum load was 68.8 kN at 1/31.6 rad. The maximum base shear coefficient was Co = 0.14. The observed failure mode was bending failure of the column at the joint of the horizontal members. The horizontal load resisting elements of the structure are the mud wall and hanging wall.

Analytical models of the mud wall and hanging wall were applied to the structure, together with the values determined from material testing. The results of the static push over analysis showed fairly good agreement with those of the experiment until approximately 1/60 rad. However when the horizontal displacement exceeded 1/60 rad. stiffness degradation was observed from experimental results, whereas the static analysis showed that the stiffness increased until 1/30 rad. Bending failure occurred in the columns and the load decreased rapidly. The difference between the experimental results and those of the analysis is thought to be attributable to material deterioration at the column and the *sashigamoi* (horizontal member) joint, stress concentration caused by the loading equipment and the soft horizontal diaphragm structure of the roof and ceiling. The experimental result showed that bending failure of the column occurs at an earlier stage but that the load degradation is slower than the analytical results.

The results showed that the horizontal load displacement characteristics of a traditional timber house can be simulated fairly well by adapting a mud wall and hanging wall model, until approximately 1/60 rad. However in the larger deflection range, deterioration of the timber, especially at the joint and the stiffness of the horizontal diaphragm needs to be taken into consideration in order to evaluate the horizontal load carrying capacity of traditional timber structures.

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