EXPRIMENTAL AND ANALYTICAL STUDY ON SEISMIC BEHAVIOR OF TRADITIONAL WOODEN FRAMES CONSIDERING HORIZONTAL DIAPHRAGM DEFORMATION AND COLUMN SLIPPAGE

K. Mukaibo [1], T. Kawakami [2] and Y. Suzuki [3]

[1] *Researcher, Kyoto University, Kyoto, Japan*

[2] *Staff, TAKENAKA Corporation, Osaka, Japan*

[3] *Professor, Ritsumeikan University, Shiga, Japan*

E-mail: *mukaibou@zeisei.dpri.kyoto-u.ac.jp, kawakami.takuma@takenaka.co.jp, suzuki-y@fc.ritsumei.ac.jp*

ABSTRACT:

In this paper, seismic behaviors of Japanese traditional wooden buildings are investigated by full-scale vibration tests and numerical analysis. Full-scale vibration tests of wooden frames were conducted with a huge shaking table, E-defense, in NIED. The tests focused on the deformation of horizontal diaphragms such as floor or roof frame, and the slipping behavior of columns which are directly placed on flat stone foundations. The influences of above behaviors on the seismic performance of a whole building were examined by changing the arrangement of bearing walls. From the experimental results, it is found that, in the case of the rigid diaphragm, the torsional motion is significant in the asymmetric wall-arrangement, and, in the case of the flexible diaphragm, the seismic response is more complicated depending on the wall-arrangement. It is also found that column slippage can reduce the deformation response and damage of the whole building. A seismic response analysis of the wooden frames was conducted by considering the effects of flexible horizontal diaphragm, and the numerical results agree satisfactorily with the experimental results. Further examinations are required to simulate the column slippage.

KEYWORDS: Traditional wooden building, Horizontal diaphragm, Sliding, Vibration test, Response analysis

1. INTRODUCTION

There exist many wooden houses built by a traditional post and beam construction method in Japan. Since modern metal connectors and high-stiffness bearing walls are rarely installed in these traditional wooden buildings, their frameworks are often soft and flexible. It means that the rigid slab assumption is not always satisfied. Their columns are often placed on the stone foundation without using a ground sill. Since the bottom of column is not fixed to the ground, the building can move or slide during severe earthquake motions.
In the seismic performance evaluation of traditional wooden houses, many researchers have dedicated their efforts to the structural characteristics and the seismic resisting capacity of the bearing walls and the connection joints. Sato et al. (2006) and Nakaji et al. (2007) have conducted static lateral loading tests of traditional wooden houses to clarify the lateral load capacity and the failure mode. Suda et al. (2006) has conducted a full-scale shaking table test of a traditional wooden house to evaluate the seismic performance. However, the influences of the horizontal diaphragm deformation and the column slippage on the seismic performance of a whole building have not been clarified yet.

In this paper, to make clear these problems, vibration tests of wooden frames are conducted with a huge shaking table, E-defense, in the National Research Institute for Earth Science and Disaster Prevention. The tests are performed by focusing on the deformation of horizontal diaphragm and the slipping behavior of columns which are placed free on flat stone foundations. Based on the testing results, the seismic behaviors of the wooden building including the horizontal diaphragm deformation and column slippage are presented. A numerical analysis of a testing specimen is also conducted, and the numerical results are compared with the experiment.

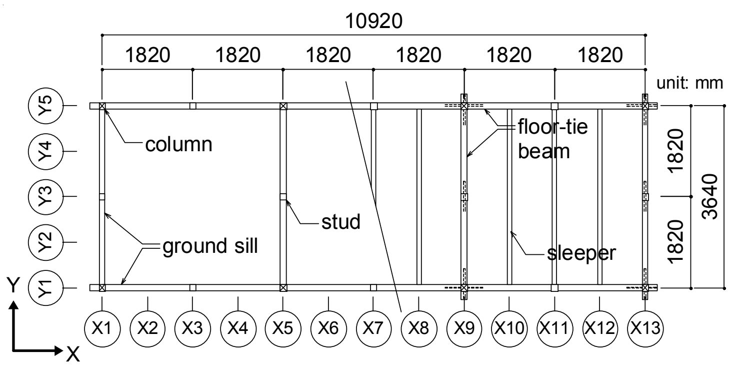
2. FULL-SCALE VIBRATION TEST

2.1 Outline

Testing specimens are one-storied wooden frameworks, and their dimensions are 10.92m×3.64m in plan. In designing specimens, the specifications of the horizontal diaphragm that is the roof of one-storied framework are three types: rigid, semi-rigid and flexible, and the specifications of the column-base connection are two types: one specimen is built with columns fixed to ground sills and the other is built with columns placed free on flat stone foundations. In the case of the specimen placed on the flat stone foundation, the bottoms of column are connected each other with floor-tie beams. Two specimens are set up on the shaking table as shown in Figure 1. The number of specimens made in this test is six. Figure 2 shows the plan views of two testing specimens. The cross sectional size of a column, a stud, a ground sill, and a floor-tie beam is 120mm×120mm, and that of beam is 270mm×120mm. These structural members are made of Japanese cedar.

As the dead load, square steel plates are mounted on the top of columns, and narrow steel plates are on the beams. Total weight of the specimen is about 108kN. Careful attention is paid to the configuration of these steel plates so as not to restrain the horizontal diaphragm deformation.

Figure 1 Two testing specimens on shaking table, the left one is fixed to ground sill, and the right one is placed on flat stone foundation



(a) with ground sill (b) with floor-tie beam
Figure 2 Plan views of two testing specimens

The specifications of horizontal diaphragm are three types: rigid, semi-rigid, and flexible model. In the rigid model, the structural plywood whose thickness is 24mm is fastened on the floor joists by nail whose length is 75mm (N75, in the Japanese Industrial Standard). In the semi-rigid model, the Japanese cedar board whose thickness is 30mm is fastened on the floor joists by nail whose length is 90mm (N90). The floor board has tongue and grooved joints. In the flexible model, the Japanese cedar board whose thickness is 15mm is fastened on the floor joists by nail whose length is 75mm (N75). The floor board has no tongue and grooved joint.

The specifications of column-base connection are two types. Figures 3 and 4 show the elevation views of two specimens and the detail drawings of column-base connections. One is a specimen whose column is connected to ground sill with tenon-mortise joint as shown in Figure 3. The ground sill is fixed to the shaking table by anchor bolts. Another is a specimen whose column placed free on the flat stone foundation as shown in Figure 4. The dimension of the base stone is 700mm×700mm in plan and 60mm in thickness. The bottoms of column are connected each other with the floor-tie beams. A spline tenon made of oak is used at the connection joint between the column and the floor-tie beam. This spline tenon-mortise joint is also used at the connection between the column and the beam.

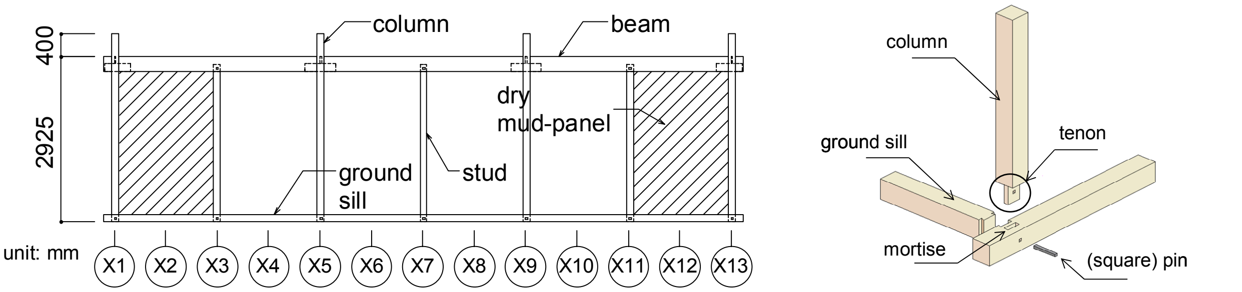


Figure 3 Elevation view of testing specimen with ground sill, and detail drawing of connection joint between column and ground sill

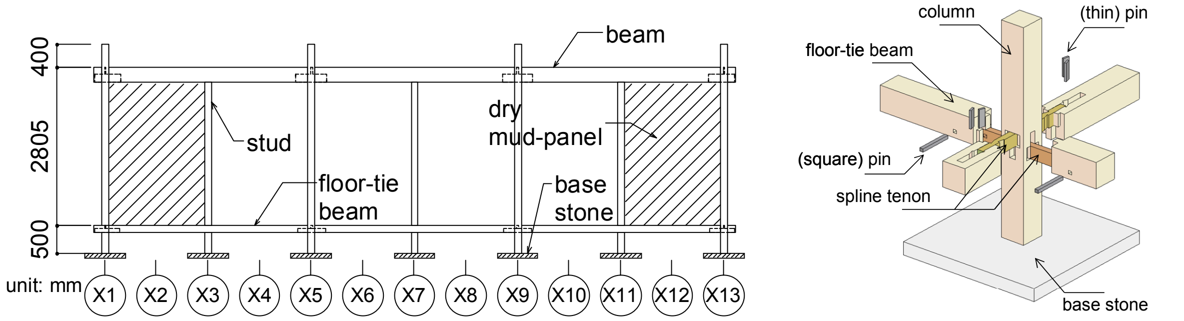


Figure 4 Elevation view of testing specimen with floor-tie beam and base stone, and detail drawing of connection joint between column and floor-tie beam

As a seismic bearing wall, a dry mud-panel (Sugiyama et al. 2006) is adopted. The bearing walls in X-direction are installed between the X1 and X3 and between the X11 and X13, in the Y1 and Y5 lines. The bearing walls in Y-direction are changed during the tests in order to investigate the effect of eccentricity. Three cases of the wall-arrangement are included as shown in Figure 5. The tests are conducted in this order.

Four types of measuring instrument are installed: accelerometers, strain gages, laser displacement sensors, and wire potentiometers. In this paper, the responses of the main structural wall lines calculated from the obtained data are considered. The main structural wall lines are the X1, X5, X9, and X13 in Y-direction and the Y1 and Y5 in X-direction. The considered responses are story drift angles, response accelerations, story shear forces, horizontal diaphragm deformation angles, and column slipping displacements.

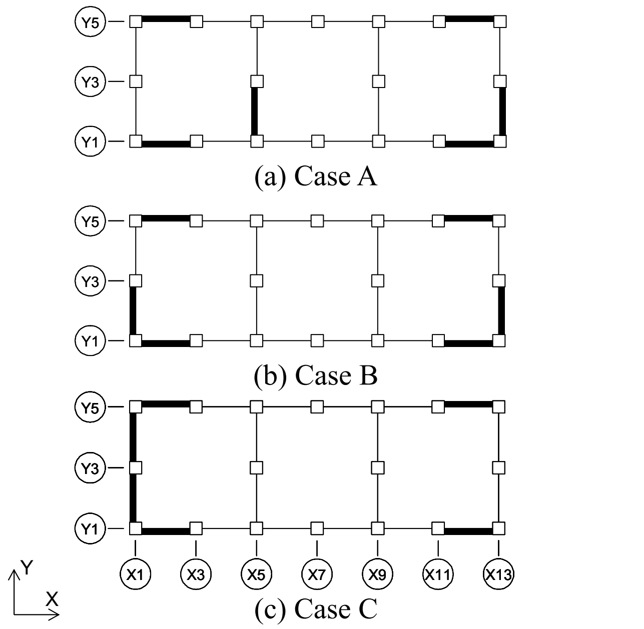
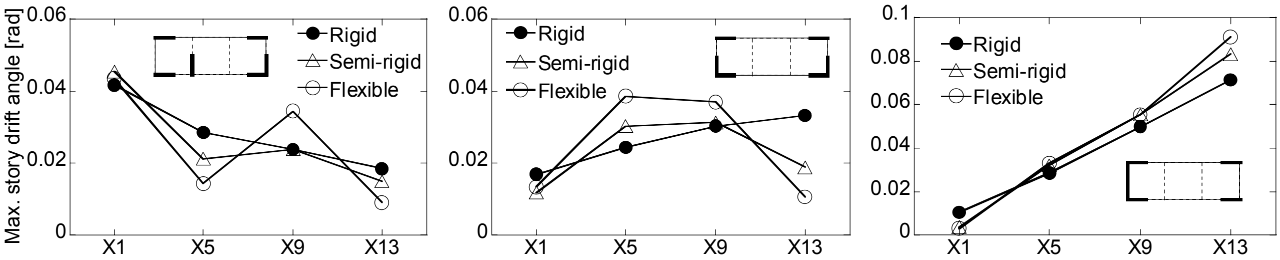


Figure 5 Plan views of arrangements of bearing walls in each specimen

As an input ground motion in shaking table tests, the artificial earthquake wave simulated by Building Center of Japan (BCJ-L2) is used. The acceleration amplitudes are adjusted to 1.0, 2.0, and 3.0m/s^2, and the specimens are excited repeatedly. After BCJ-L2 excitation, the strong earthquake motion recorded during the 1995 Hyogo-ken Nanbu earthquake (JMA-Kobe) is input in the Case C wall-arrangement. The maximum input accelerations are 6.2m/s^2 (EW comp.) in X-direction, 8.2m/s^2 (NS comp.) in Y-direction, and 3.3m/s^2 in the vertical direction.

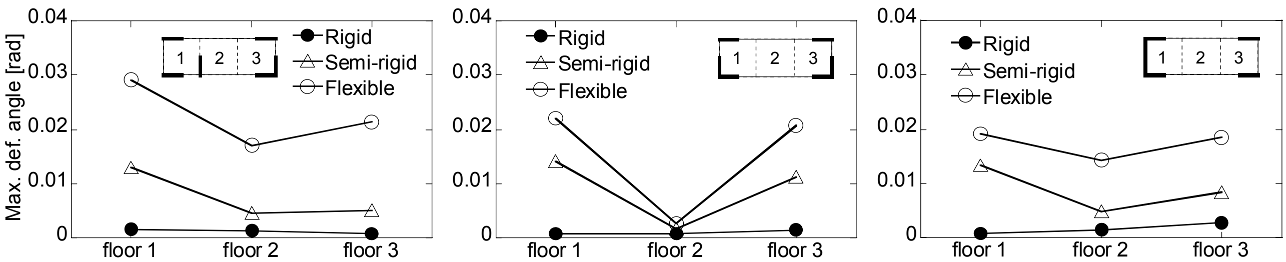
2.2 Results

Figure 6 shows the maximum story drift angles of the main structural wall lines under BCJ-L2 wave 3.0m/s^2 in Y-direction, in the cases of the specimens with the ground sill. In the Case A, the response distribution of the rigid model is almost linear. On the other hand, in the semi-rigid and flexible model, the responses of the X9 line, where dry mud-panel is not installed, are larger than those of the X5 line. Also in the Case B, the results are similar to the Case A. In the semi-rigid and flexible model, the responses of the X5 and X9 lines, where dry mud-panels are not installed, are larger than those of X1 and X13 lines. In the rigid and semi-rigid model, contrary to the guess based on the symmetric wall-arrangement, the response of the X13 line is larger than that of the X1 line. This is because the dry mud-panel installed in the X13 line was reused in changing the arrangement from the Case A to B. In the Case C, the response distribution is almost linear regardless of the specification of the horizontal diaphragm. Figure 7 shows the maximum deformation angle of the horizontal diaphragms under the same excitation as Figure 6. In the rigid model, the horizontal diaphragm deformation is relatively small, and the torsional motion is dominant. In the semi-rigid and flexible model, the horizontal diaphragm deformations are significant rather than the torsion.



(a) Case A (b) Case B (c) Case C

Figure 6 Comparisons of maximum story drift angle in each bearing wall arrangement under BCJ-L2 wave 3.0m/s^2 in Y-direction



(a) Case A (b) Case B (c) Case C

Figure 7 Comparisons of maximum deformation angle of horizontal diaphragm in each bearing wall arrangement under BCJ-L2 wave 3.0m/s^2 in Y-direction

In the case of the specimen whose column placed free on the flat stone foundation, the slipping displacement of the column bottom to the base stone was observed under JMA-Kobe wave. Figure 8 shows the slipping trace of the column bottom located at the intersection of the X1 and Y1 line. The maximum displacement of the column slippage is about 200mm in X-direction and ±100mm in Y-direction.

Figure 9 shows the comparison of the maximum story drift angle by the specification of the column-base connection under JMA-Kobe wave. The response of the specimen placed on the base stone is considerably small in contrast with the result of the specimen with the ground sill, especially in X-direction.

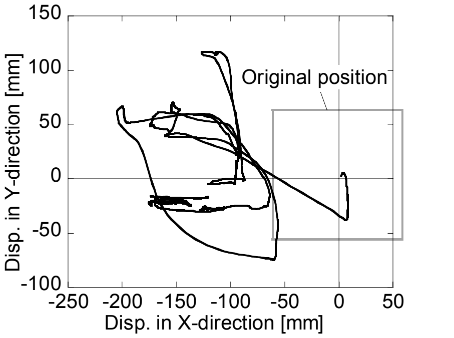


Figure 8 Slipping trace of X1Y1 column bottom under JMA-Kobe wave

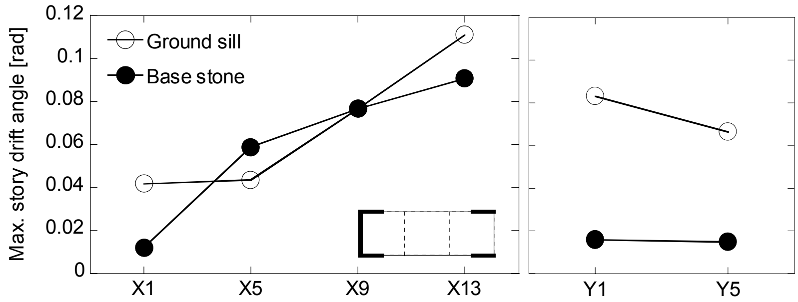
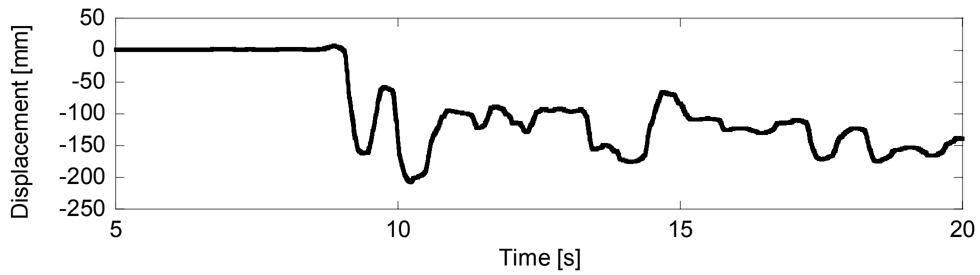
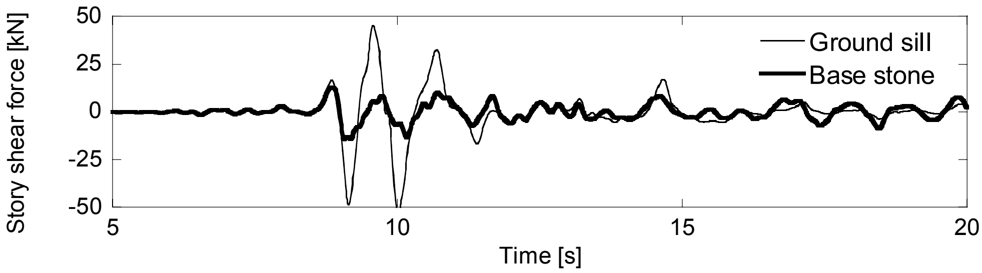


Figure 9 Comparison of maximum story drift angle by specification of column base under JMA-Kobe wave, with rigid horizontal diaphragm

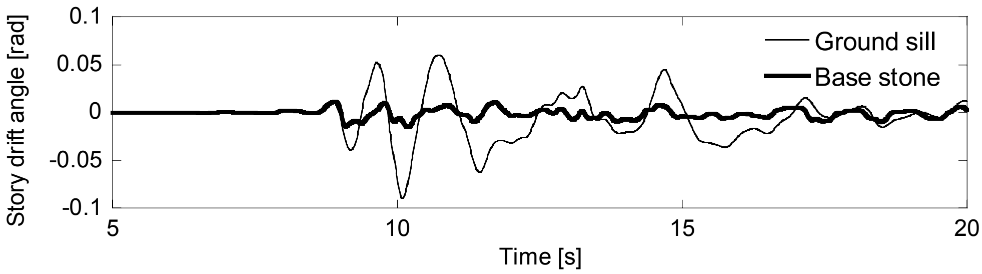
Figure 10 shows the time history of the column slipping displacement and the comparisons of the story shear force and story drift angle by the specification of the column-base connection. It is found that when the column slippage occurred, the story shear force of the specimen placed on the base stone was limited smaller in contrast with that of the specimen with the ground sill, and it resulted in the smaller response story drift. This result indicates that the column slippage may reduce the deformation response of buildings, and its mechanism is similar to a base-isolation structure. However, some of the columns were broken or cracked during the slipping behavior. In order to take advantage of its response reduction effect, it is necessary to control the column slippage and assure its safety.



(a) Time history of slipping displacement of X1Y1 column in X-direction



(b) Story shear forces in Y1 line



(c) Story drift angles in Y1 line

Figure 10 Time history of column slipping displacement (a), and comparisons of story shear force (b) and story drift angle (c) by specification of column base under JMA-Kobe wave

3. NUMERICAL ANALYSIS

3.1 Analysis Model with Flexible Horizontal Diaphragm

The specimen with flexible horizontal diaphragm is considered. The specimen tested by a shaking table is idealized as shown in Figure 11. Analysis model consists of lumped masses, horizontal diaphragms, beams, and seismic walls. Horizontal diaphragms are idealized as shear panels, and seismic walls are as shear springs. Beams may deform only in the axial direction.

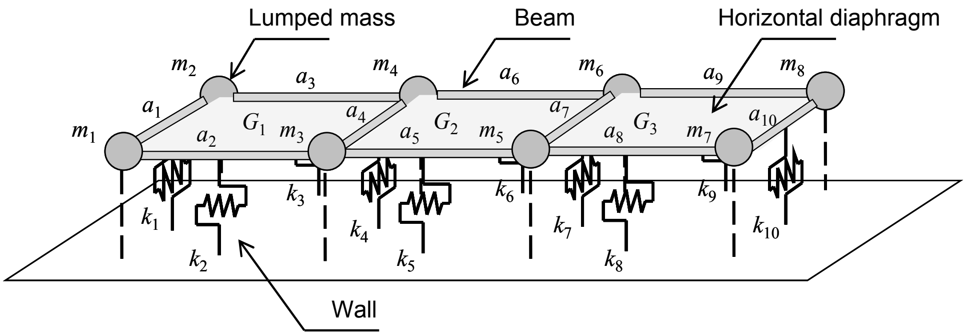


Figure 11 Analysis model for specimen with flexible horizontal diaphragm

Hysteretic restoring force characteristics of seismic walls are the summation of tri-linear and slip shape as shown in Figure 12. Table 3.1 shows model parameters of a seismic wall. These parameters are determined based on the static loading tests by Sugiyama et al. (2006). Horizontal diaphragms have restoring force characteristics of the summation of bi-linear and slip shape. Table 3.2 shows model parameters of horizontal diaphragm models. These parameters are determined based on the static loading tests conducted in advance of the shaking table tests.

In shaking table tests, since the specimen was excited repeatedly, the restoring force and stiffness gradually degraded. To reflect this degradation on the analysis, the information about the experienced maximum story drift angle in the experiment was taken into account.

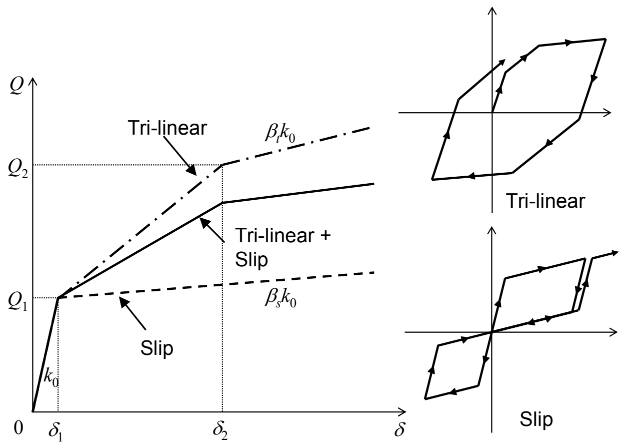


Figure 12 Restoring force characteristics of seismic wall

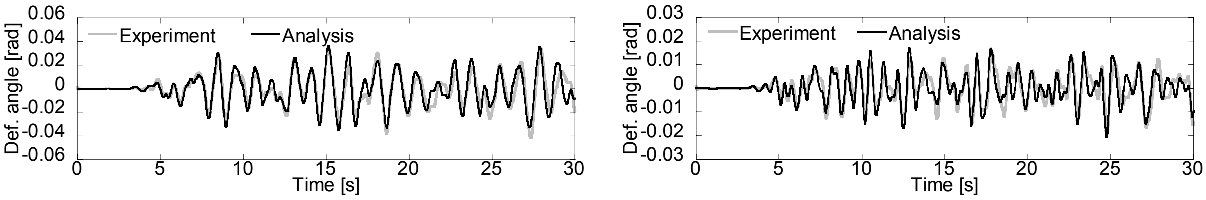
Table 3.1 Model parameters of seismic wall

1st yielding deformation of tri-linear: δ_1 [rad]	0.005
2nd yielding deformation of tri-linear: δ_2 [rad]	0.033
1st yielding force of tri-linear: Q_1 [kN]	7.0
2nd yielding force of tri-linear: Q_2 [kN]	17.5
Initial stiffness: k_0 [kN/rad]	1400
3rd stiffness of tri-linear / initial stiffness: β_t	0.056
post yielding stiffness of slip / initial stiffness: β_s	0.100
Ratio between tri-linear and slip	3:7

Table 3.2 Model parameters of horizontal diaphragm

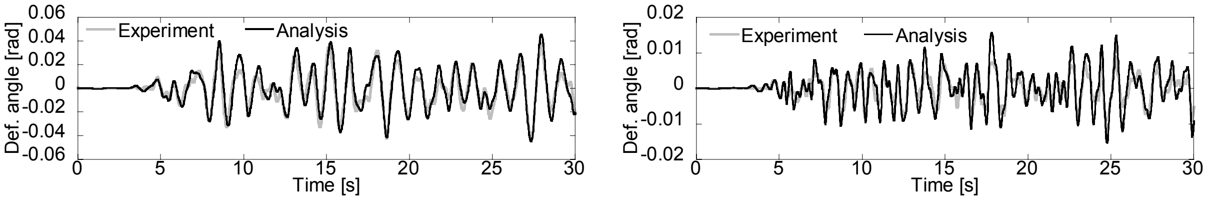
	Rigid	Semi-rigid	Flexible
Yielding deformation: δ [rad]	0.015	0.010	0.015
Initial stiffness: k_0 [kN/rad/m]	733	300	160
Post yielding stiffness / initial stiffness: β	0.078	0.183	0.286
Ratio between bi-linear and slip	3:7	4:6	4:6

Figure 13 and 14 compare time histories of response story drift angle between the analysis and experiment. For both specimens with rigid type diaphragm and with flexible type diaphragm, the numerical results show good agreements with the experimental results. Figure 15 shows the comparison of the maximum story drift angle. It is found that the presented model is capable of simulating the seismic behavior of wooden frames with flexible horizontal diaphragms.



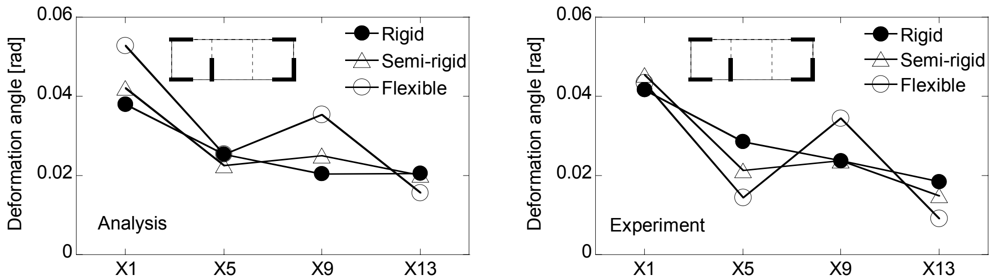
(a) X1 line (b) X13 line

Figure 13 Comparison of response story drift angle of specimen with rigid type horizontal diaphragm and Case A wall-arrangement, under BCJ-L2 wave 3.0m/s^2 in Y-direction

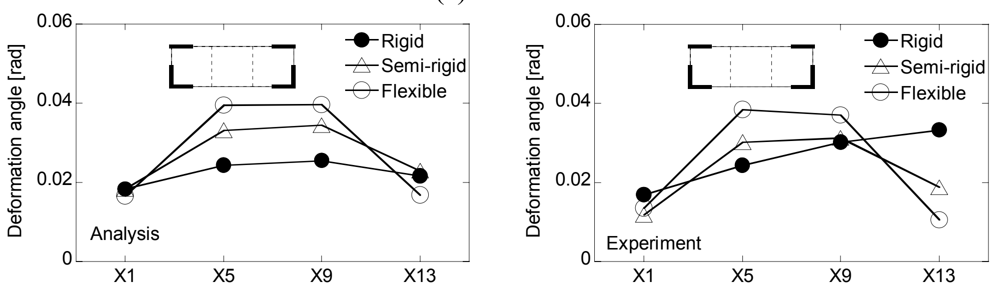


(a) X1 line (b) X13 line

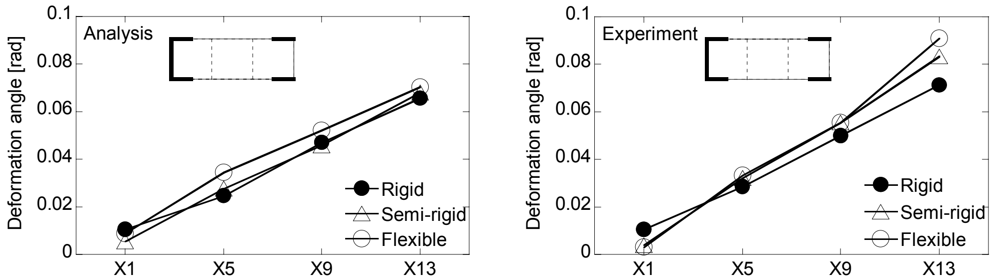
Figure 14 Comparison of response story drift angle of specimen with flexible type horizontal diaphragm and Case A wall-arrangement, under BCJ-L2 wave 3.0m/s^2 in Y-direction



(a) Case A



(b) Case B



(c) Case C

Figure 15 Comparison of the maximum response story drift angle under BCJ-L2 wave 3.0m/s^2 in Y-direction

3.2 Analysis Model Placed Free on Foundation

To simulate the behavior of the specimen placed free on stone foundations, an additional model shown in Figure 16 to the model described in the previous section is considered. However, the numerical results by using this model did not coincide with the experimental results in this study. In our another numerical analysis (Kawakami et al., 2008), satisfactory results were obtained for a similar purpose by considering vibration in the vertical direction, though a target wooden frame was more simple. So, vibration in the vertical direction will be concerned in our future research.

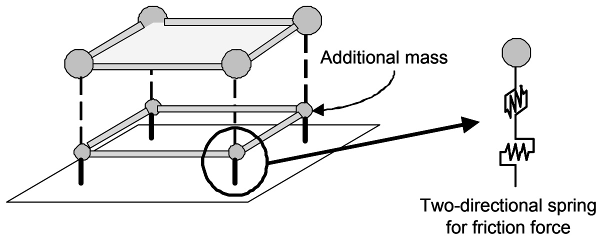


Figure 16 Analysis model for friction force

4. CONCLUSION

Based on the full-scale shaking table tests of Japanese traditional wooden frames, the influences of the horizontal diaphragm deformation and the column slippage on the seismic response of the whole building were investigated. In the case of the rigid horizontal diaphragm, the torsional motion was dominant in the asymmetric wall-arrangement. In the case of the flexible horizontal diaphragm, the deformation of the horizontal diaphragm was significant rather than the torsion. The results of the numerical analysis showed a good agreement with the experimental results, and the seismic behavior of traditional wooden frames with flexible horizontal diaphragms may be simulated by the presented model. In the cases of columns free on the foundations, the column slippage may reduce the story deformation of the building. However, the analytical clarification of the behaviors of wooden buildings with free columns was difficult in this study. Further examinations are then required in order to take advantage of its response reduction effect in seismic design.

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