WCTE 2016
World Conference on Timber Engineering
August 22-25, 2016 | Vienna, Austria

EXPERIMENTAL STUDY ON DYNAMIC BEHAVIOR OF WOODEN HORIZONTAL HYBRID STRUCTURE

Yoshihiro Yamazaki[1], Hiroyasu Sakata[2], Shoko Hiyama[3], Sayoko Sawada[4] and Di Wu[5]

ABSTRACT: In Japan, construction of wood structures for public buildings is encouraged for environmental reason. Low-rise large wood buildings sometimes involve RC cores to enhance the seismic performance and the fire resistance. In this paper, the seismic resistant performance of horizontal hybrid structure is demonstrated through shaking table test of scaled specimens. At first, one third scaled specimens of shear walls and floor diaphragms were tested. Then, shaking table tests of three-story and three-span specimens was conducted. Three types of specimens with different arrangement of shear walls and different stiffness of floor diaphragm were tested. The performance was discussed by referring to maximum displacement, shear force distribution and vibration modes. In all specimens, 50 to 70% of seismic force acting on wood part was transmitted to core through floor diaphragms, which led to good seismic performance.

KEYWORDS: Hybrid structure, Seismic performance, Large wood building, Vibration mode, Shaking table test

1 INTRODUCTION [123]

In Japan, wooden buildings have been built mainly as small detached houses so far. However, construction of wood structures for public buildings is also encouraged for environmental reason. Low-rise large wood buildings sometimes involve RC cores to enhance the seismic performance and the fire resistance as shown in Figure 1. Most of seismic force acting on wood part are expected to be transmitted to RC core through floor diaphragms. Therefore wood part just has to withstand vertical loads and the reduced lateral loads, which realizes wide and open space with less shear walls in wood part. However, there are some problems in structural analysis since wood structure and RC structure have large difference in stiffness, weight and other vibration properties. For example, while floor diaphragms are generally assumed to be infinitely rigid, floor diaphragm of wood structure is not enough stiff to satisfy the assumption. Moreover, floor diaphragm has to have strength enough to transmit seismic force action on wood parts to core parts through the diaphragms.

A prototype of such wooden horizontal hybrid structure was presented by Architectural Institute of Japan in 2012 [1]. Through the seismic design procedure of the prototype, it was revealed that the evaluation of seismic force distribution was quite difficult. Therefore the authors proposed evaluation method of seismic force distribution of horizontal hybrid structure using continuous model [2]. In this paper, the seismic performance of horizontal hybrid structure is demonstrated through shaking table test of scaled specimens.

In chapter 2, elemental tests of scaled specimens is introduced. One third scaled shear wall and floor diaphragm are tested. In chapter 3, experimental plan of shaking table tests on horizontal hybrid structure is introduced. Three types of specimens with different arrangement of shear walls and different stiffness of floor diaphragm are tested. Although RC cores are represented by steel jigs in this experiment, shear force between wood part and core part are able to be measured by load cell. In chapter 4, experimental results of shaking table test is presented. The performance is discussed by referring to maximum displacement, shear force distribution and vibration modes.

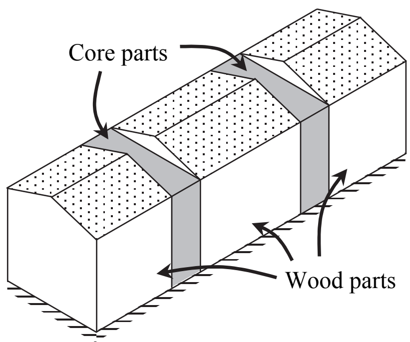


Figure 1: *An example building of wooden horizontal structure*

[1] Yoshihiro Yamazaki, Tokyo Institute of Technology, yamazaki.y.ai@m.titech.ac.jp
[2] Hiroyasu Sakata, Tokyo Institute of Technology, sakata.h.aa@m.titech.ac.jp
[3] Shoko Hiyama, Tokyo Institute of Technology, hiyama.s.aa@m.titech.ac.jp
[4] Sayoko Sawada, Tokyo Institute of Technology, sawada.s.ae@m.titech.ac.jp
[5] Di Wu, Tokyo Institute of Technology, wu.d.ab@m.titech.ac.jp

2 ELEMENTAL TESTS OF SCALED SPECIMENS

2.1 SPECIMENS AND TEST METHOD

Architectural Institute of Japan(AIJ) provided a prototype of hybrid structures of wood and RC as shown in Figure 1. It intends three-story school building having RC core parts. Wood parts consist of glued-laminated timber's framing and plywood sheathing walls and floor diaphragms. The timber beams and the core parts are connected by conventional bolts connections. We set a specimen modelled by this building.

Specimens of shear walls and floor diaphragms were tested, which were one third scaled. The elevation and the detail of the connections are shown in Figure 2. Bolts and metal parts are hidden in wooden members because of fire resistance. Parameters for shear wall specimens are the number of stories and walls. The one for floor diaphragm specimens is nail pitch. 33, 50 and 100mm of pitches were tested. Although three-story three-span structure is considered in shaking table test stated later, two-story frame and two-span floor diaphragm subjected to point load at the top are tested here. They are equivalent in terms of base shear force and corresponding overturning moment.

2.2 TEST RESULTS

Shear force-deformation angle relation of typical specimens are shown in Figure 3. The hysteresis loops are similar to the one of real scale specimens. Any failures did not occur up to 1/50rad. Finally, tensile failure of bolt connections was observed in the case of specimens with small nail pitch. The scaled specimens were likely to behave as expected.

3 EXPERIMENTAL PLAN OF SHAKING TABLE TESTS ON HORIZONTAL HYBRID STRUCTURE

3.1 SPECIMENS

According to our previous research, natural periods of wood parts and core parts are quite different, and the seismic behavior of two parts can be evaluated separately [2]. Therefore only the wood part was represented by one third specimen and core part was represented by steel jig as shown in Figure 4. One side of the wood part is connected to core part. Wood part consists of glued laminated timber frame. Core part is designed so that it has much larger stiffness and natural frequency compared to the ones of wood part. Three types of specimens with different arrangement of shear walls and different stiffness of floor diaphragm were tested as shown in Figure 5.

Elevations of specimen is shown in Figure 6. Transverse frame is provided with plywood sheathing walls whose thickness is 9mm. The nail's diameter is 2.1mm and length is 32mm, which is fastened at 100mm intervals. Longitudinal direction is moment resisting frame with semi-rigid column and beam connections. Horizontal diaphragm is plywood sheathing floor whose thickness is 12mm. The same nails as the one of shear walls are used.

Details of the connections are the same as the ones of elemental test specimens (Figure 2).

Total weight of specimens were 23.7 to 25.2 kN including additional weights of 7.3kN on 2nd and 3rd floor and 4.6kN on roof which were concrete blocks. The blocks represented equally distributed live loads and were fixed on floor plywood so that they did not prevent rotation of each plywood.

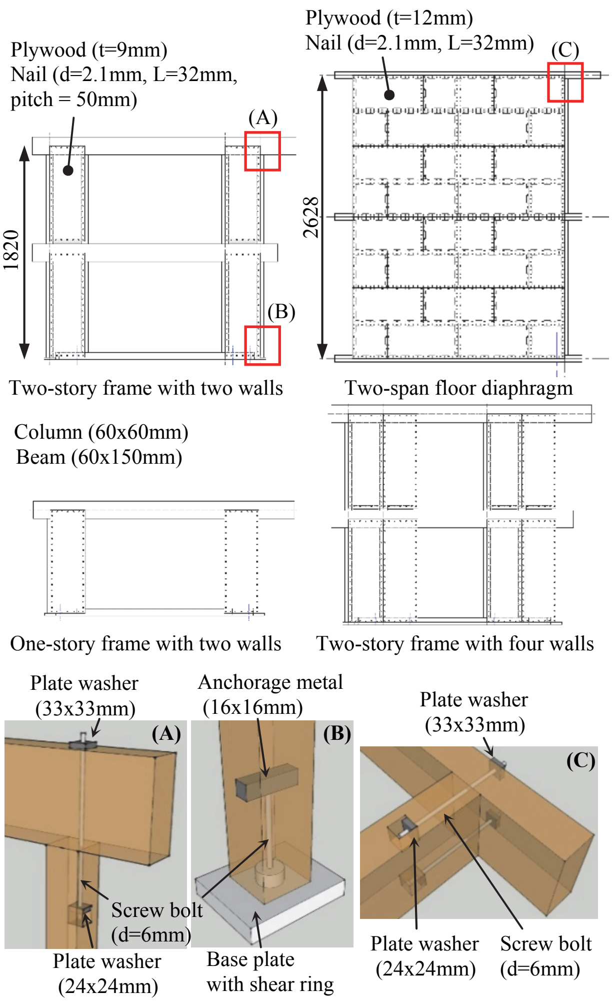


Figure 2: *Specimen of wall/floor diaphragm test*

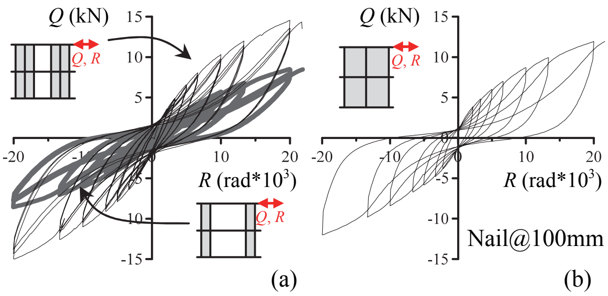


Figure 3: *Shear force-deformation angle relation of shear wall(a) and floor diaphragm(b)*

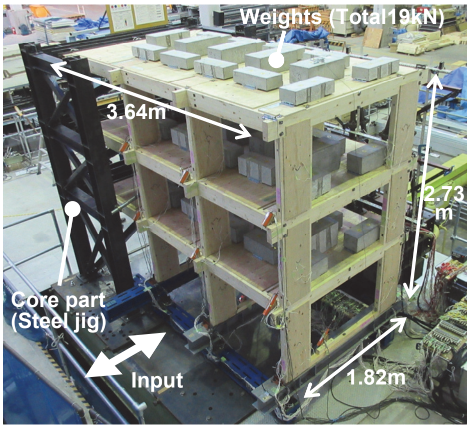


Figure 4: *Setup of shaking table test (Specimen No.1)*

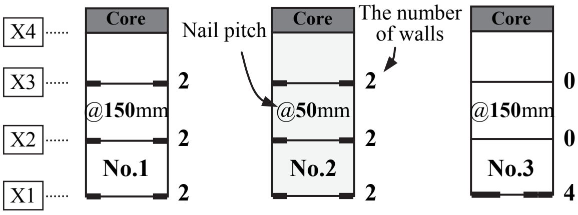
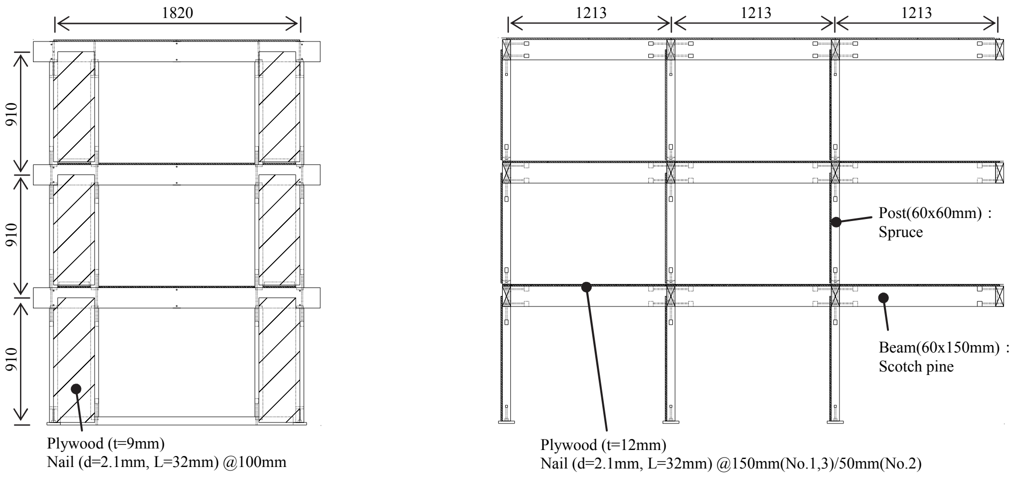


Figure 5: *List of specimens*

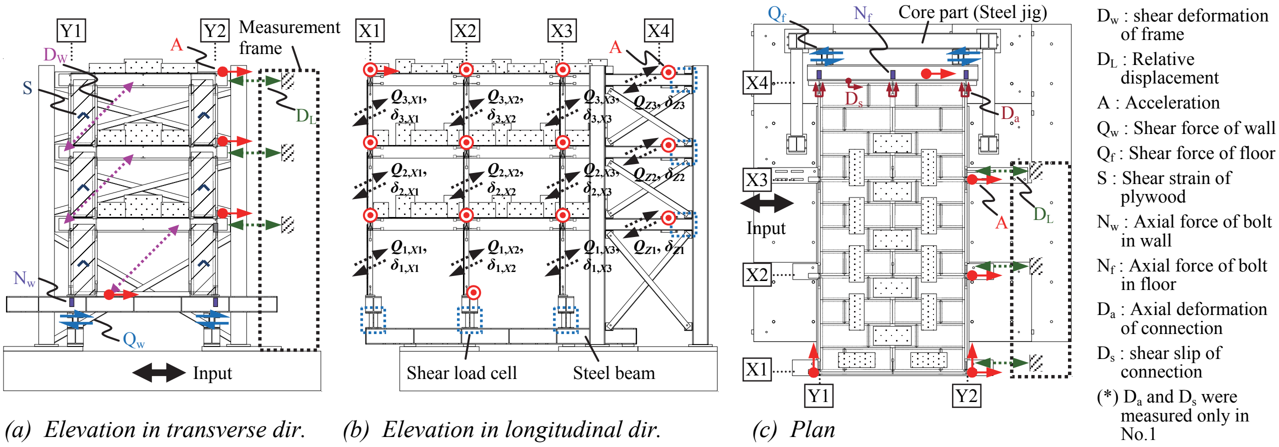
3.2 MEASUREMENT

Measurement instruments and their arrangement is shown in Figure 7. Shear deformation of each frame was measured by wire-type displacement transducer connected in 45degree direction (D_w). Relative displacement of specimen was also measured by laser-type displacement transducer (D_L) as backup. Shear force of shear walls in 1st story and floors at X4 frame were measured by shear load cell (Q_w and Q_f). Shear strain on plywood at the center of shear wall was measured by strain gauges (S), which were used for estimation of shear force of shear walls in upper stories. Shear force and shear deformation of each shear wall are defined as $Q_{i,Xj}$, $\delta_{i,Xj}$ with respect to each location. i is floor number and j is frame number, respectively. Similarly, shear force and shear deformation of each floor diaphragm are defined as Q_{Zi}, δ_{Zi} as shown in Figure 7(b).



(a) Transverse direction (No.1 and No.2) *(b) Longitudinal direction*

Figure 6: *Elevation of specimens*



(a) Elevation in transverse dir. *(b) Elevation in longitudinal dir.* *(c) Plan*

Figure 7: *Measurement and definition of shear force and deformation*

3.3 INPUT MOTION

Uni-axial input motion was applied to the specimen. Artificial earthquakes having response spectrum as shown in Figure 8 were used. Since the specimen was one third scaled, $1/\sqrt{3}$ times time scale was considered. The intensity of input motions are characterized by the peak ground acceleration (PGA). PGA = 0.1g, 0.2g, 0.4g, 0.6g and 0.8g were applied. White noise motions having 0.05g PGA were also applied in order to obtain basic vibration characteristics.

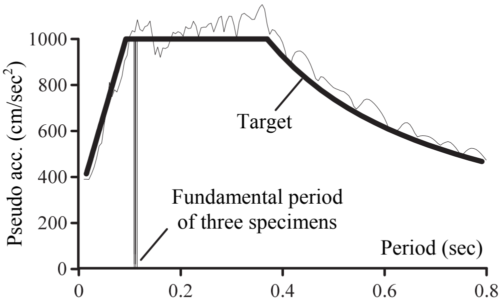


Figure 8: *Response spectrum of artificial earthquake (PGA = 0.4g)*

3.4 ADEQUACY OF MEASUREMENT OF SHEAR FORCE

Figure 9(a) shows comparison of total extercal force measured by acceleration meter F_{tot} and by load cell Q_{tot}. F_{tot} is calculated as summation of acceleration at each node multiplied by the corresponding mass. Q_{tot} is $\Sigma Q_{1,Xj}$ + ΣQ_{Zi} which are directly measured by shear load cell. They show close agreement each other.

Figure 9(b) shows relation between summation of shear strains of plywood in 1st story $\Sigma\gamma_{1,Xj}$ and shear force of the frames measured by load cell $\Sigma Q_{1,Xj}$. Strong lineality between them is observed, and the slope of the graph means calibration factor to convert shear strain to shear force of the frame. The measurement system is likely to work well.

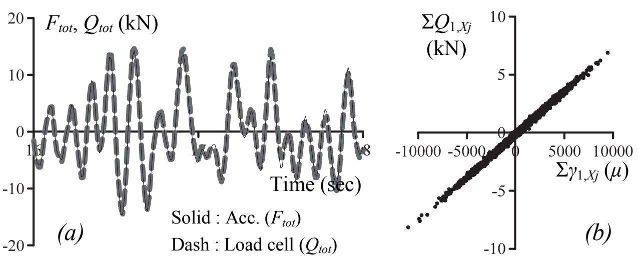


Figure 9: *Adequacy of measurement of shear force (ex: No.2, 0.4g) (a) Comparison of total external force measured by acceleration meter F_{tot} and by load cell Q_{tot} (b) Relation between summation of shear strain of plywood in 1st story and shear force of the frame measured by load cell*

4 EXPERIMENTAL RESULTS OF SHAKING TABLE TESTS ON HORIZONTAL HYBRID STRUCTURE

4.1 MAXIMUM DISPLACEMENT AND MAXIMUM INTER-STORY DRIFT ANGLE

The maximum displacement of wood part during each input motion is shown in Figure 10. The shape of the maximum displacement seems to be dominated by the 1st mode which is a quarter of sine wave [2]. When PGAs of inputs were less than 0.6g, the maximum displacement of three specimens were close. Specimen No.2 showed a good performance during the test procedure with a slow and steady increment of node displacement. Unlike specimen No.2, both specimen No.1 and No.3 had a major increment in displacement when the input rise from 0.6g to 0.8g.

Table 1 shows the maximum inter-story drift angles during each test procedure. The maximum drifts mainly occurred at X1 of 1st floor for specimen No.1 and No.2. In specimen No.3, however, the maximum drift angles were mainly largest in X2 frame, and the maximum drift angle of 2nd floor increased rapidly when the PGA varied from 0.6g to 0.8g, which was also caused by the lack of shear walls between the middle studs as expected.

Table 1: *Maximum inter-story drift angle*

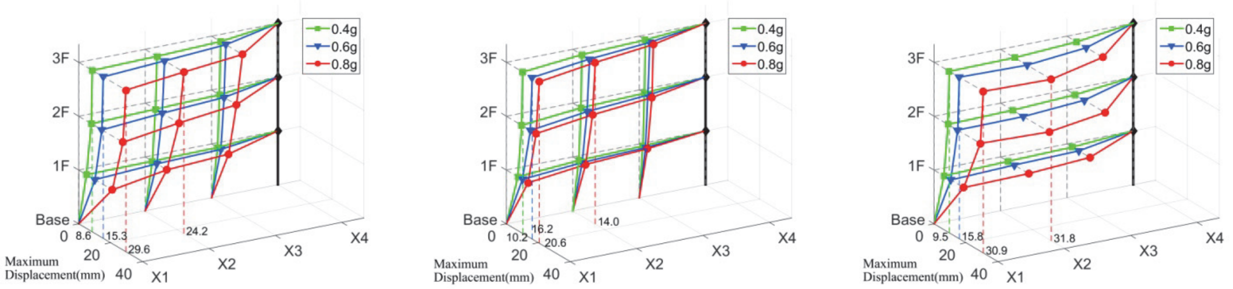
PGA	0.2g			0.4g		
Model	No.1	No.2	No.3	No.1	No.2	No.3
3F	1/1563 X1	1/1515 X1	1/1136 X2	1/862 X2	1/847 X2	1/588 X2
2F	1/416 X1	1/384 X1	1/581 X1	1/250 X1	1/192 X1	1/277 X2
1F	1/312 X2	1/333 X1	1/416 X2	1/185 X1	1/125 X1	1/142 X1
PGA	0.6g			0.8g		
Model	No.1	No.2	No.3	No.1	No.2	No.3
3F	1/500 X1	1/515 X2	1/333 X2	1/208 X3	1/312 X2	1/192 X2
2F	1/142 X1	1/156 X1	1/128 X2	1/94 X1	1/113 X1	1/61 X2
1F	1/87 X1	1/89 X1	1/86 X1	1/41 X1	1/65 X1	1/50 X1

Note. The X* means the position where the maximum drift occurs

4.2 SHEAR FORCE-DEFORMATION RELATION OF SHEAR WALL AND FLOOR DIAPHRAGM

Figure 11 shows shear force-deformation relation of shear walls in 1st story and floor diaphragm at X4 frame. Deformation in farther shear wall from core and in upper floor diaphragm was large. In the case of PGA0.4g motion, all elements showed almost linear behavior. No.2 has larger floor stiffness owing to the small pitch of nails.

In the case of PGA0.8g motion, some of elements show stiffness degradation and slip hysteresis loop. No.3 shows largest stiffness degradation because of the less number of shear walls and the lack of shear walls in inter frame. Acturally, minor pullout of nails in shear walls and floor diaphragms were observed, and some of bolts got loose after PGA0.8g motion.



(a) *Specimen No.1* (b) *Specimen No.2* (c) *Specimen No.3*

Figure 10: *Distribution of maximum displacement*

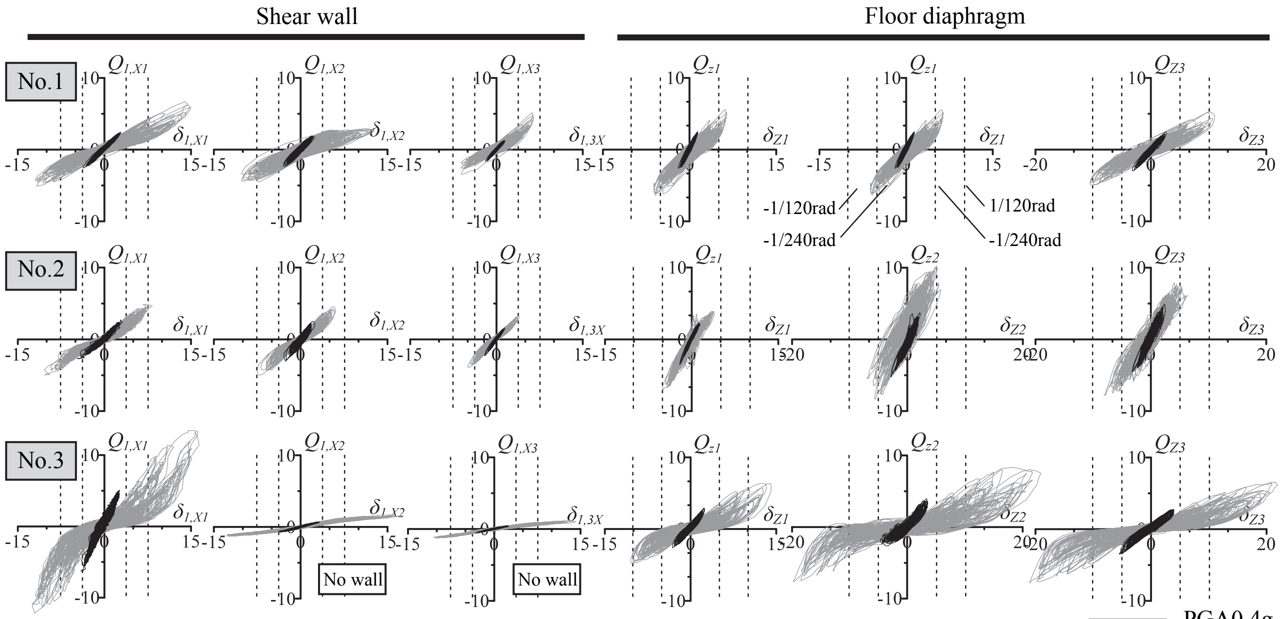


Figure 11: *Shear force-deformation relation of shear wall and floor diaphragm (Unit: kN and mm)*

After the test procedure, some damages were observed in shear walls and floor diaphragms such as minor pullout of nail and uplift of plywood as shown in Figure 12.

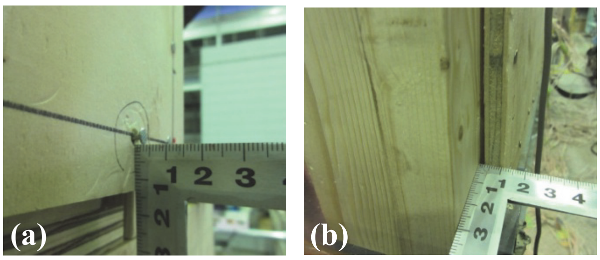
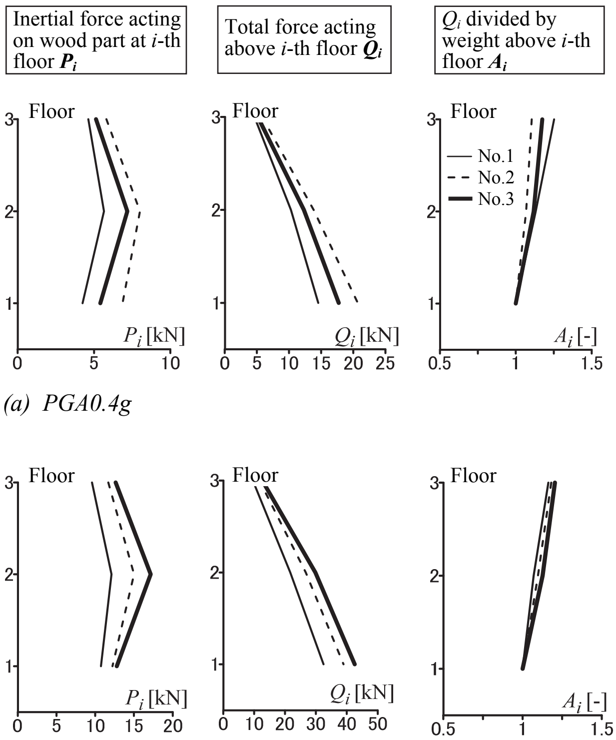


Figure 12: *Damage after test procedure (a) minor pullout of nail (b) uplift of plywood in wall*

4.3 DISTRIBUTION OF INERTIAL FORCE

Figure 13 shows distribution of inertial force acting on wood part at *i*-th floor P_i, total force acting above *i*-th floor Q_i and Q_i divided by weight above *i*-th floor A_i, respectively. A_i is generally called shear coefficient distribution, and it is normalized by A_1 (i.e. $A_1 = 1$).

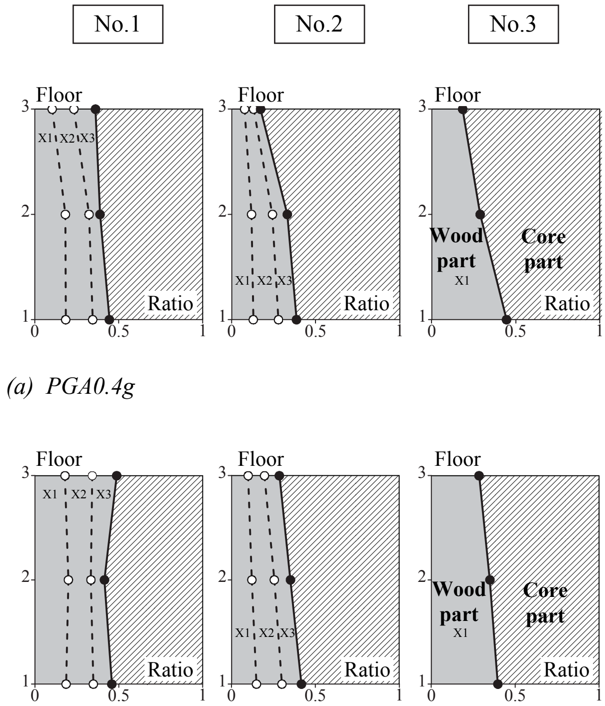
A_i at the top floor was not so high compared to normal multi-story buildings. The maximum values was 1.25 in No.1 subjected to PGA0.4G. Base shear coefficients of each specimen subjected to PGA0.4g which were calculated as Q_1 divided by total weight were 0.65, 0.92, 0.75, respectively. According to the response spectrum (Figure 8), it is likely to reach 1.0 if the structure is linear SDOF system having 5% damping. Although specimens showed linear behavior as stated before, their base shear coefficients were not so high as expected from the response spectrum. Note that most of seismic force acting on wood part are transmitted to core part as stated later. Therefore shear walls in wood part just have to share more reduced seismic force.



(a) PGA0.4g

(b) PGA0.8g

Figure 13: *Distribution of external and internal force along the height*



(a) PGA0.4g

(b) PGA0.8g

Figure 14: *Ratio of seismic force shared by wood part and core part*

4.4 RATIO OF SEISMIC FORCE SHARED BY WOOD PART AND CORE PART

Figure 13 shows ratio of seismic force shared by wood part and core part. Seismic force shared by wood part of i-th story means the one resisted by shear walls in i-th story. The rest is seismic force shared by core part, which is transmitted to core through floor diaphragms above i-th floor. The ratio is calculated using maximum values of each element's response.

The averaged ratio of core part along the height is about 50% to 70%. Therefore the original intention of horizontal hybrid structure are clearly realized. Ratios of core part of specimen No.2 are a little larger than the ones of specimen No.1 as expected, which is owing to high stiffness of floor diaphragm.

Ratios of wood part in upper floor were increased as the input motion became large. This is caused by stiffness degradation of floor diaphragm in 3rd floor.

4.5 NATURAL FREQUENCY AND DAMPING RATIO

Figure 15 shows the variation of natural frequency and damping ratio of 1st mode of the three specimens during the experiment. They are identified by analysis in white noise motion before earthquake inputs and after each test procedure. The frequency of three specimens all demonstrate a decrease during the test series with increasing PGAs, which indicates the damage accumulation and stiffness degeneration of the structures. The frequency of specimen No.3 drops more rapidly than specimen No.1 and 2 after input with PGA of 0.2g, which shows specimen No.3 is more vulnerable to strong ground motions. The natural frequency of specimen No.2 is a little higher than specimen No.1 due to its stiff floor diaphragm, and for the same reason, the specimen No.2 remained its dynamic properties well during the test procedures.

Damping ratio in initial state of all specimens were about 7%. They were increased with increasing PGAs, which is the same tendency as the one of natural frequency.

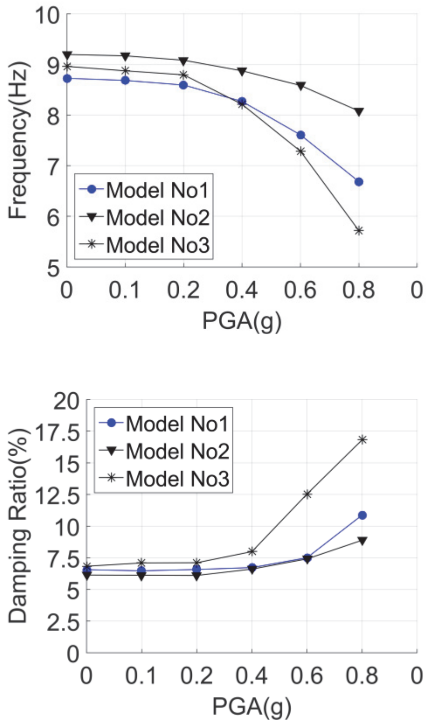


Figure 15: *Natural frequency and damping ratio of 1st mode of each specimen before earthquake inputs and after each test procedure*

4.6 VIBRATION MODE

Figure 16 demonstrates the vibration mode of specimen No.1 and 3 before the test procedure. The vibration modes of specimen No.2 are mainly the same as specimen No.1 although they are not shown on the picture.

It can be seen that the 1st mode of specimen No.1 and 3 is basically the same. The maximum displacement occurs at X1 of 3rd floor. The displacement decreases almost linearly from 3rd floor to 1st floor and from X1 to X4.

The vibration shape of the 2nd and 3rd mode shows several difference between the two specimens. The displacement of specimen No.3 is larger than specimen No.1 in the middle of 1st floor. It is apparent that the lack of shear walls between middle studs make it easier for the middle parts of the structure to participate into the vibration.

In normal conditions, the frequencies are discrete and independent for the different parts of hybrid structure, which make it possible to analyze the different part separately [2]. However, it should be pointed out that because of its unequal distribution of mass and stiffness, the horizontal hybrid structure may have many degrees of freedom even with a few stories and small scale, which makes the natural frequency hard to identify as well as the vibration modes. Modal analysis are recommended to be conducted in multiple methods. Both transfer function and stochastic subspace identification method are used in this paper.

In all the three specimens, the initial 1st and 3rd mode is mainly dominated by the wood structure while the 2nd mode is dominated by both the wood structure and the steel frame as shown in Figure 16. However, the stiffness degeneration rates of each part are usually different. If the frequencies of the two parts are close enough, "frequency crossing" may happen when hybrid structure is subjected to strong ground motions. This issue will be discussed in the further study in more detail.

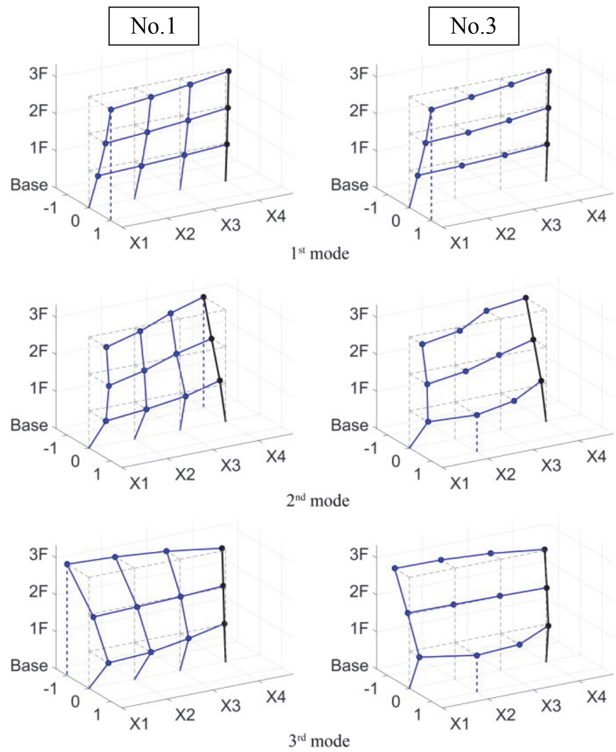


Figure 16: *Vibration mode of the first three modes in specimen No.1 and No.3 before earthquake inputs*

5 CONCLUSIONS

In this paper, seismic performance of horizontal hybrid structure was discussed. The followings are findings of this research.

1) If shear walls are located only in opposite side of core(like specimen No.3) instead of equal distribution with small intervals(like specimen No.1), it leads to the small number of shear walls to satisfy same maximum deformation in moderate earthquake. However, such specimen was more damaged in large earthquake.
2) Response base shear coefficient was not as high as expected from the response spectrum because of the low modal mass ratio, which had been predicted in our previous research [2].
3) 50 to 70% of seismic force acting on wood part was transmitted to core through floor diaphragms. Therefore not only performance of shear walls but the one of floor diaphragms clearly contribute to seismic force resistance capacity.

ACKNOWLEDGEMENT

This work was supported by JSPS KAKENHI Grant Number JP26709039(Grant-in-Aid for Young Scientists

(A)) and THE KAJIMA FOUNDATION. The shaking table test was conducted in Technology Development Division, Fujita corporation. We would like to express our gratitude to them.

REFERENCES

[1] Architectural Institute of Japan: Daikibomokuzoukenchikuno gijutsutekikadaito kaiketsuhoho(in Japanese), *Material of AIJ annual meeting*, 2012

[2] Y. Yamazaki, and H. Sakata: Simplified Modeling Method and Seismic Force Evaluation of Building Structures Involving Stiff Cores: Study on dynamic behavior of wooden horizontal hybrid structure Part1(in Japanese), *Journal of structural and construction engineering*, Architectural Institute of Japan, 720:291-301, 2016.