STATIC LOADING TESTS OF THREE-DIMENSIONAL FRAME STRUCTURE SIMULATING A JAPANESE TRADITIONAL TIMBER HOUSE

S. Ohmura[1] , R. Hatada[2], M. Sugino[3] , Y. Hayashi[4]

[1] *Research Engineer, Building Research Institute, ohmura@kenken.go.jp*
[2] *Graduate Student, Kyoto University, rp-hatada@archi.kyoto-u.ac.jp*
[3] *Associate Professor, Kyoto University, rp-sugino@archi.kyoto-u.ac.jp*
[4] *Professor, Kyoto University, hayashi@archi.kyoto-u.ac.jp*

Abstract

In Japan, there are a lot of Japanese traditional timber houses, which form the cultural townscapes and are used for living spaces. On the other hand, the past large earthquakes had caused the severe damage of the timber houses such as collapses in recent years. In order to reduce such damages, it is important to investigate and evaluate the seismic performance of the Japanese traditional timber houses.

The Hokuriku region has traditional timber houses include the characteristic structure like Fig. 1 and 2. The structure consists of four large hanging wall planes in a square shape and out-of-plane beams which are crossed at right angles and connected each other with double cogging. However, it has not been clarified how the out-of-plane beams effect the seismic performance of the seismic direction. There is no previous research which conducts static loading tests of three-dimensional Japanese traditional timber frame structures.

From the above, the purpose of this study is to investigate how the out-of-plane beams effect the seismic performance of the planes, such as the damage mode or the load-deformation relationship. In this paper, static loading tests of the three-dimensional frame structure and the plane frame structure simulating a Japanese traditional timber house are conducted. The three-dimensional specimen and the loading setup of the test are shown in Fig. 2 and 5, respectively. The specimen is fixed at the bottom and loaded horizontally at the top during the test. The effect of the out-of-plane beams are analyzed compared with the test result of the plane structure.

As the results, the out-of-plane beams transmit horizontal force when the specimen is loaded at the top in the in-plane direction and have the effect which reduces the deformation angle of the in-plane columns. In particular, the out-of-plane beams are expected to prevent the whole house from collapsing when the structure suffers a large deformation during severe earthquakes.

Keywords: static loading test, three-dimensional timber structure, Japanese traditional timber houses

1. Introduction

In Japan, there are a lot of Japanese traditional timber houses, which form the cultural townscapes and are used for living spaces. On the other hand, the past large earthquakes had caused the severe damage of the timber houses such as collapses in recent years. In order to reduce such damages, it is important to investigate and evaluate the seismic performance of the Japanese traditional timber houses.

The Hokuriku region has traditional timber houses include the characteristic structure like Fig. 1 and 2, called "*Waku-no-uchi*" in Japanese [1]. The structure consists of four large hanging wall planes in a square shape and out-of-plane beams which are crossed at right angles and connected each other with double cogging. Mitsuji et al. (2009) [2] performed microtremor measurement of Japanese traditional houses with "*Waku-no-uchi*" and reported the vibration characteristic. However, it has not been clarified how the out-of-plane beams effect the seismic performance of the seismic direction. There is no previous research which conducts static loading tests of three-dimensional Japanese traditional timber frame structures.

From the above, the purpose of this study is to investigate how the out-of-plane beams effect the seismic performance of the planes, such as the damage mode or the load-deformation relationship. In this paper, static loading tests of the three-dimensional frame structure and the plane frame structure are conducted. The three-dimensional specimen simulates the structure called "*Waku-no-uchi*". The test methods and results are explained in the chapter 2 and 3, respectively. Then, the chapter 4 shows the conclusions of this paper.

Fig. 1 – An example of the structure called "*Waku-no-uchi*"
in a Japanese traditional timber house [1]

2. Test methods

This chapter explains the specimens, the loading setup and the measurement setup of the static loading tests. The purpose of the tests is to investigate the effect of out-of-plane beams in the three-dimensional structure by comparing the test results between the three-dimensional and plane specimens. In the tests, the specimens are subjected to a horizontal load at the top and shear deformation. The tests continue cyclic loading with gradual increasing amplitude until the amplitude reaches the limit or the specimen loses restoring force.

2.1 Specimen

The list of four specimens is shown in Table 1. Two of the specimens w3 and n3 have three-dimensional structure. The others w2.5 and n2.5 have plane structure. The first letters of the specimens (w or n) indicate information of walls (Wall or No wall). The figures of the names (3 or 2.5) indicate dimensions of the specimens (3 or 2.5). The figure of 2.5 means that the specimens w2.5 and n2.5 are plane (two-dimensional) structure with the same column-beam S joints as w3 and n3. The details are to be mentioned later.

Table 1 – List of specimens

	Three-dimensional structure	Plane structure
Wall	 w3	 w2.5
No wall	 n3	 n2.5

The drawings of the three-dimensional specimen (w3, n3) and the plane specimen (w2.5, n2.5) are shown in Fig. 2 and 3, respectively. The frame members are timber and the walls (w3, w2.5) are dry-mud panels. The section size and species of the frame members are shown in Table 2. The beam X, Y_U and Y_L are out-of-plane beams of the three-dimensional specimen. We analyze the test results focusing on the effect of the out-of-plane beams in section 3.2.

The feature of the structures are the timber members connected each other without metal fittings. Fig. 4 shows the details of the major joints of the specimens. The members have notches at the joints and are connected to the other members at the notched parts. This construction method without metal fittings is one of the characteristics of Japanese traditional timber houses. During earthquakes, the structures are expected to resist seismic force with the members embedded each other at the joints.

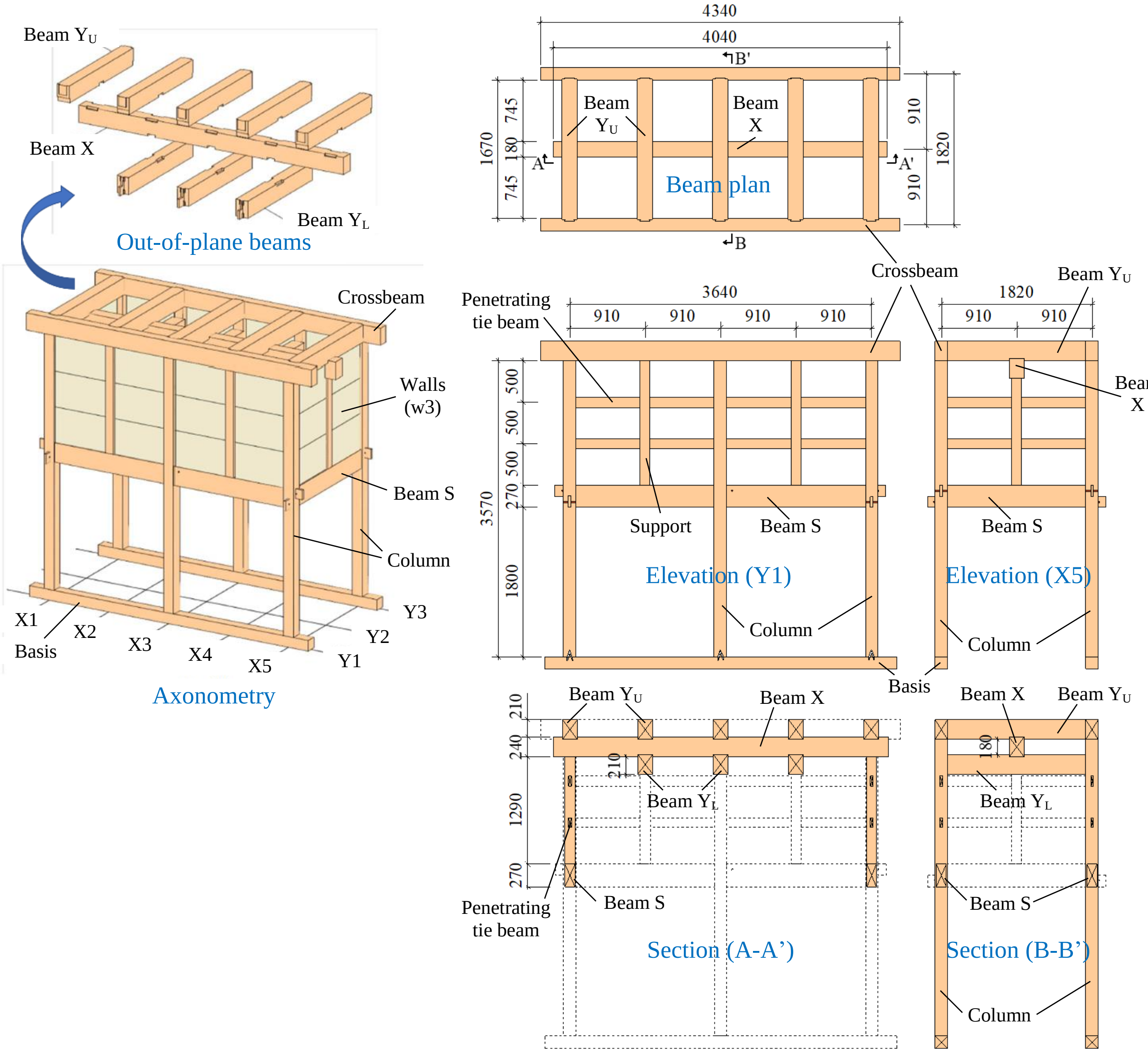


Fig. 2 – Three-dimensional specimen (w3, n3)

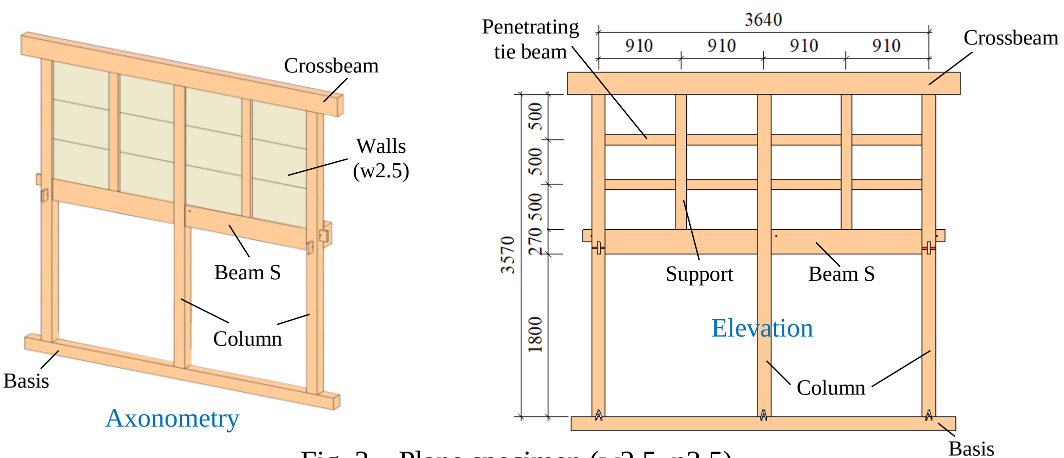
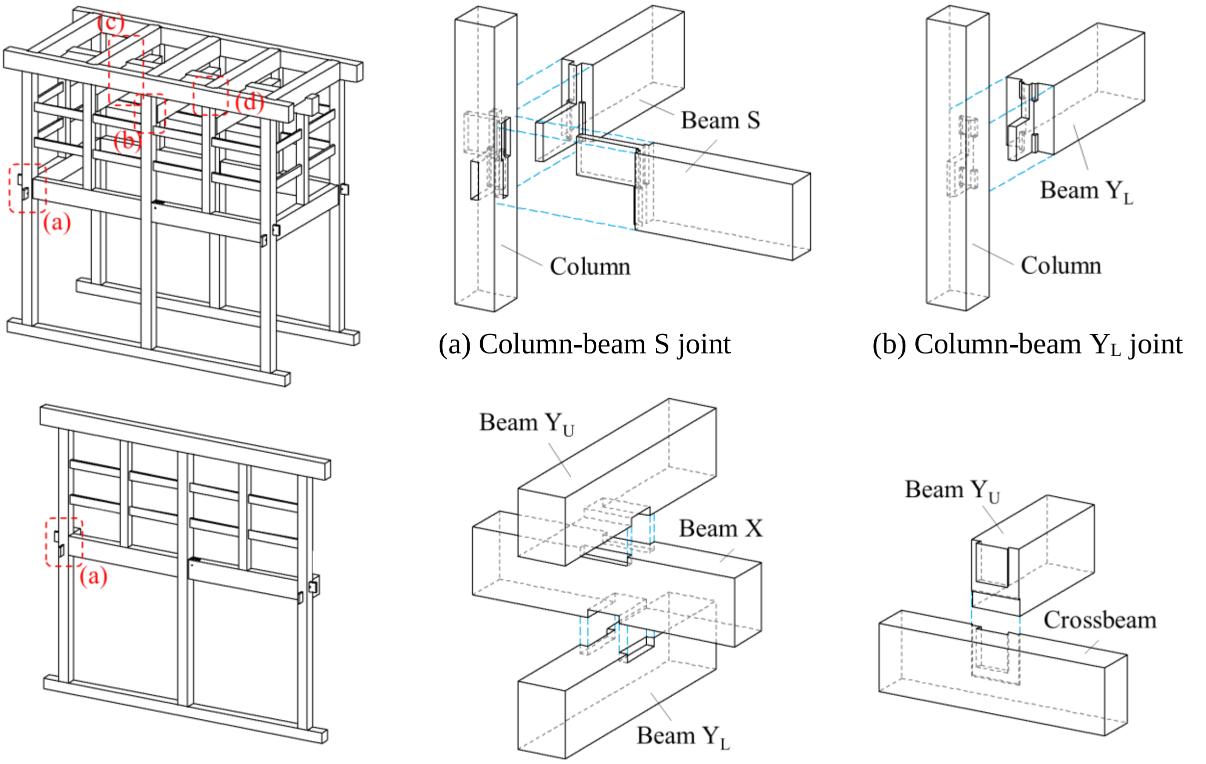


Fig. 3 – Plane specimen (w2.5, n2.5)

Table 2 – A list of the frame members

Member	Section size (mm)	Species	Specimen	
			w3, n3	w2.5, n2.5
Column	150×150	Cedar	○	○
Support	120×120	Cedar	○	○
Penetrating tie beam	120×30	Cedar	○	○
Basis	150×150	Cedar	○	○
Crossbeam	240×150	Oregon pine	○	○
Beam S	270×120	Oregon pine	○	○
Beam X	240×180	Oregon pine	○	-
Beam Y_U		Oregon pine	○	-
Beam Y_L		Oregon pine	○	-



(a) Column-beam S joint

(b) Column-beam Y_L joint

(c) Beam Y_U-beam X-beam Y_L joint

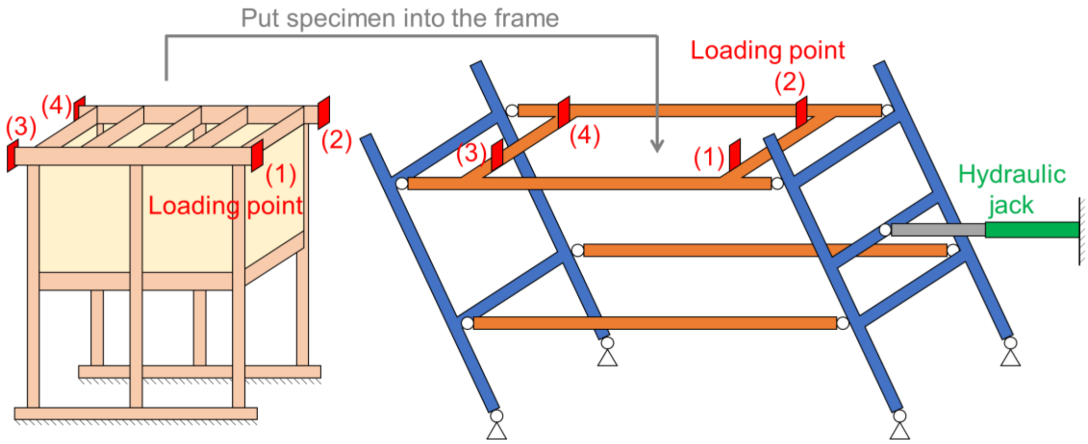
(d) Crossbeam-beam Y_U joint

Fig. 4 – Details of the main joints

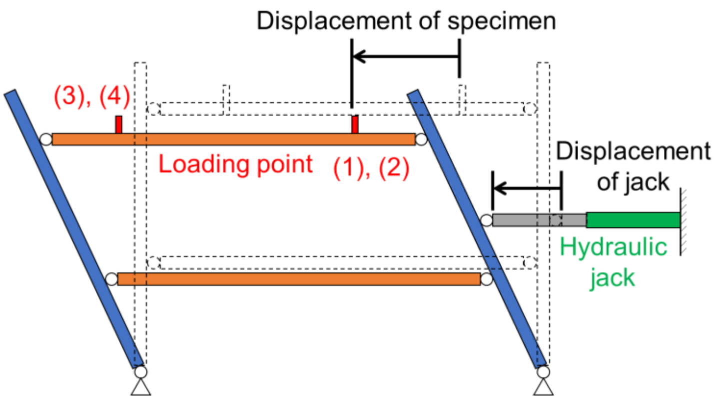
2.2 Loading and measurement setup

The loading setup of the three-dimensional specimen is shown in Fig. 5. The loading device developed in [3] is improved to apply to three-dimensional structures. The loading frame is made of steel and pin support structure. The beams of the loading device are connected to the columns with a pin. Therefore, the loading frame can cause shear deformation. During the static loading test, the hydraulic jack connected to a reaction wall controls the shear deformation of the loading frame. The specimens are putted into the loading frame and subjected to a horizontal load at the top from the loading frame.

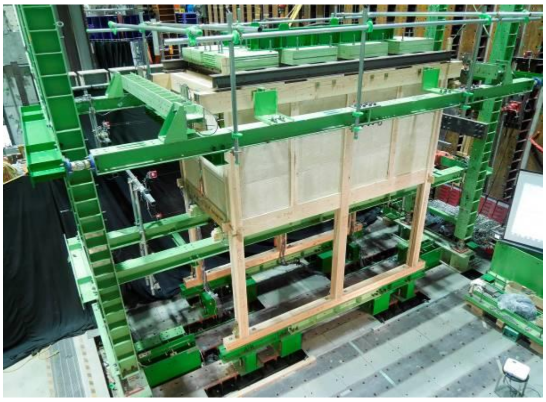
The loading mechanism is the same as [3]. In this paper, the left side is the positive direction. During loading to the positive direction, the hydraulic jack pushes the loading frame to the left side. Then, the loading frame pushes the specimen at the loading points (1) and (2) to the left side horizontally. The displacement of the specimen at the loading points (1) and (2) is the same value. Thus, the specimens are able to be subjected to shear deformation up to 1/5.6 rad. On the other hand, during the negative direction, the loading frame pushes the specimen at the loading points (3) and (4) to the right side. Note that the loading points transmit only horizontal force and does not prevent the specimen from vertical displacement.



(a) Loading device and specimen



(b) Loading mechanism (Positive direction)



(c) Actual condition

Fig. 5 – Loading setup of the three-dimensional specimen

The specimens are weighted vertical load on the top to prevent the columns pulling out as shown in Fig. 6. The vertical load W_{3D} and W_{2D} are 62.3 kN and 32.8 kN, respectively.

The shear deformation angle R and the restoring force P are defined as Eq. (1) ~ (4). The displacement of the crossbeam (d_{Y1}, d_{Y3}, d) and the load of the loading point (P_{Y1}, P_{Y3}, P) are measured with displacement sensors and load cells, respectively. The P of w3 and n3 is defined as restoring force for one plane structure to compare with w2.5 and n2.5. The test schedule is controlled by the value of the R. The loading schedule of the tests is shown in Table 3. The cyclic loading of one target angle is repeated twice. The order of the tests is as No.1 ~ 4 in the table. First, the test of n3 is performed up to 1/20 rad and stopped before the specimen is damaged. Next, the frames of n3 are reused as w3 by reforming and putting walls on n3. Then, the test of w3 is performed until the R reaches the limit 1/5.6 rad or the specimen loses the restoring force. The tests of n2.5 and w2.5 follow the same process.

[Three-dimensional specimen w3, n3]

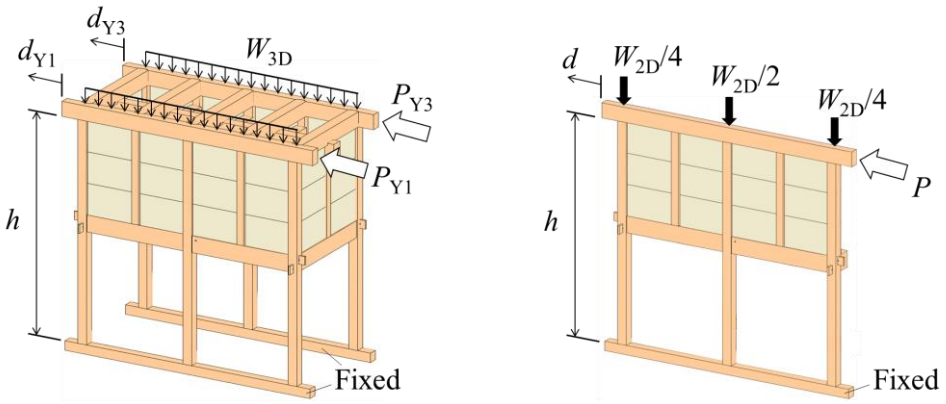
$$\text{Deformation angle: } R = \{ (d_{Y1} + d_{Y3}) / 2 \} / h = d_{Y1} / h \quad (1)$$

$$\text{Restoring force: } P = (P_{Y1} + P_{Y3}) / 2 \quad (2)$$

[Plane specimen w2.5, n2.5]

$$\text{Deformation angle: } R = d / h \quad (3)$$

$$\text{Restoring force: } P = P \quad (4)$$



(a) w3, n3 (b) w2.5, n2.5

Fig. 6 – Vertical load and measurement setup (Positive direction)

Table 3 – The loading schedule of the tests

No.	Specimen	Target angle (rad)										
		1/120	1/100	1/75	1/50	1/30	1/20	1/15	1/10	1/8	1/6	1/5.6
1	n3	○	○	○	○	○	○	-	-	-	-	-
2	w3	○	○	○	○	○	○	○	○	○	○	○
3	n2.5	○	○	○	○	○	○	-	-	-	-	-
4	w2.5	○	○	○	○	○	○	○	○	○	○	○

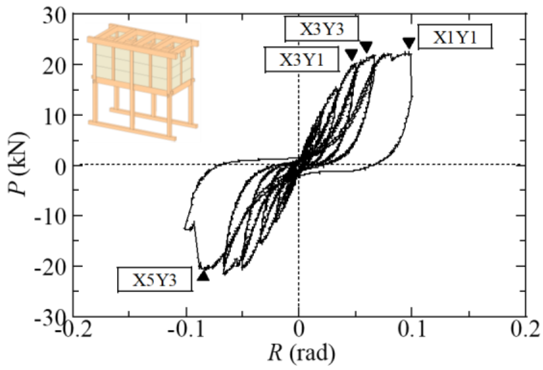
3. Test results

This chapter shows the test results and investigates the effect of the out-of-plane beams of the three-dimensional specimen. First, the load-displacement relationship and damages of each specimen are shown. Then, comparisons of the test results between the three-dimensional plane specimens are mentioned.

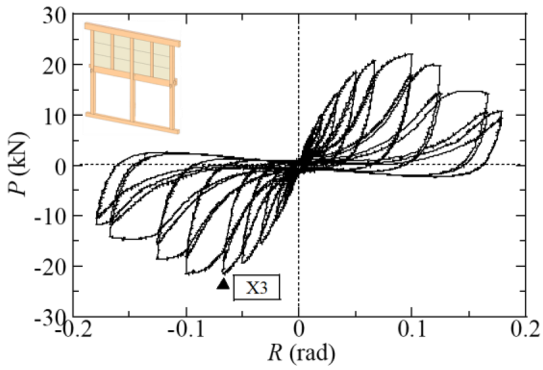
3.1 Load-displacement relationship and damages

The load-displacement relationship of each specimen is shown in Fig. 7. The *P* and *R* in the axis are defined in the section 2.2. In this section, the results of the specimens with walls (w3 and w2.5) are focused. The results of the specimens with no walls (n3 and n2.5) are used in the section 3.2.

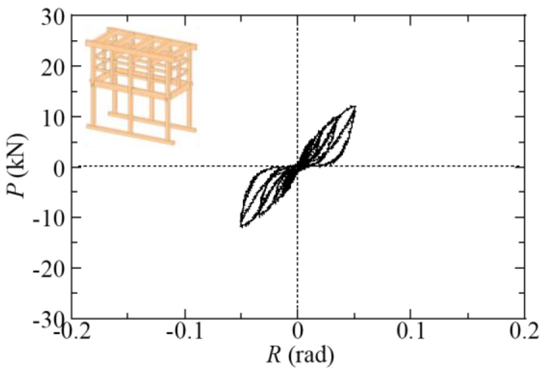
The pictures of the front side at the maximum shear deformation angle are shown in Fig. 8. The observed main damages were breakage of columns at the column-beam S joints and breakage of walls. In the test of w3, the four of six columns broke until the cycle of R=1/10 rad and the whole specimen lost the restoring force. As shown in Fig. 9, breakage of the columns occurred at the joints because of defect of section (refer to Fig. 4 (a)) and bending moment of the columns. On the other hand, in the test of w2.5, the walls had severe damages as shown in Fig. 8 (b) and the whole specimen kept the restoring force up to 1/5.6 rad.



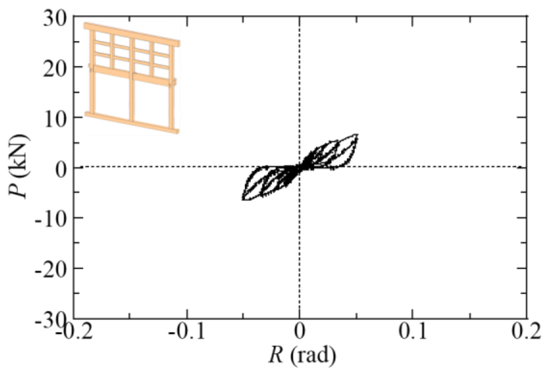
(a) w3



(b) w2.5



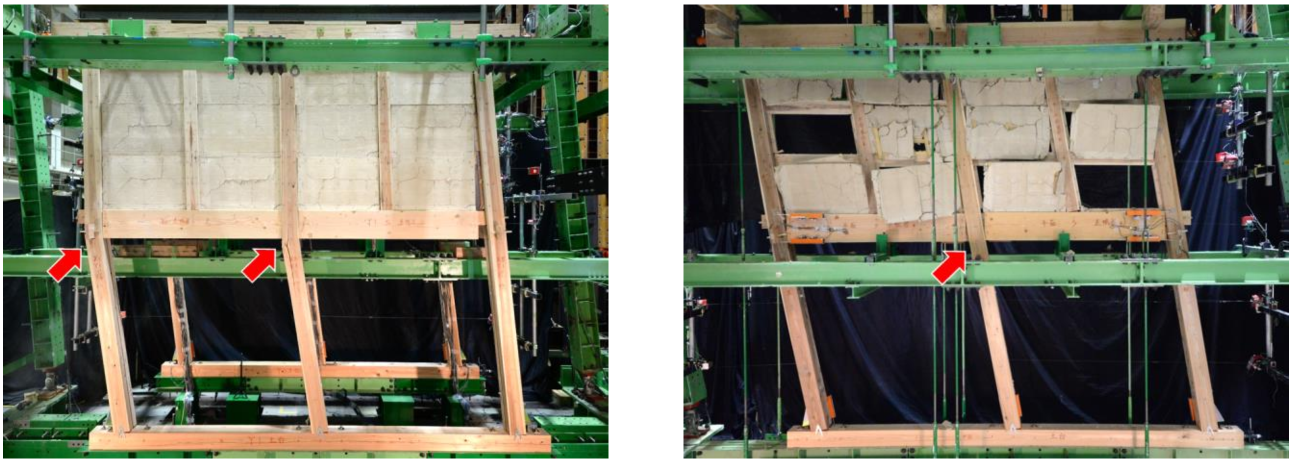
(c) n3



(d) n2.5

Fig. 7 – Load-displacement relationship

(▼: Breakage of column)



(a) w3 (R=1/10 rad) (b) w2.5 (R=1/5.6 rad)

Fig. 8 – The front side at the maximum shear deformation angle

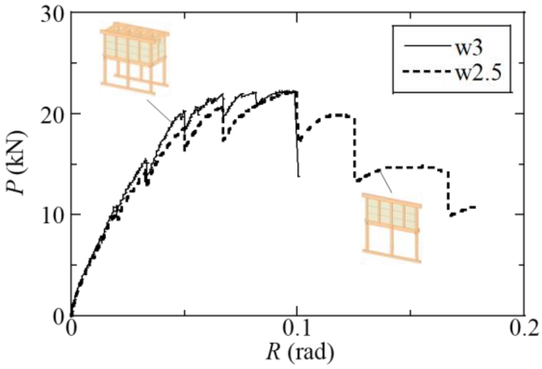
(Red arrows point to breakage of columns)

(a) Entire specimen (b) Column X1Y1 (c) Column X3Y1

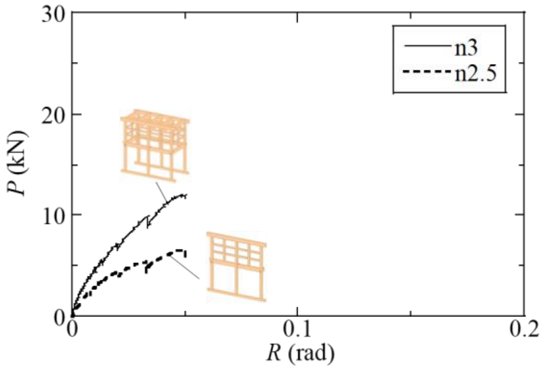
Fig. 9 – Breakage of columns (w3, R=1/10 rad)

3.2 Comparison between the specimens

First, a comparison of the load-displacement relationships between three-dimensional specimen and plane specimen is shown in Fig. 10. The specimens with walls had almost no difference. However, in the case of the specimens with no walls, the three-dimensional specimen n3 indicated the restoring force P which was about twice higher than that of the plane specimen n2.5.



(a) Wall (w3, w2.5)

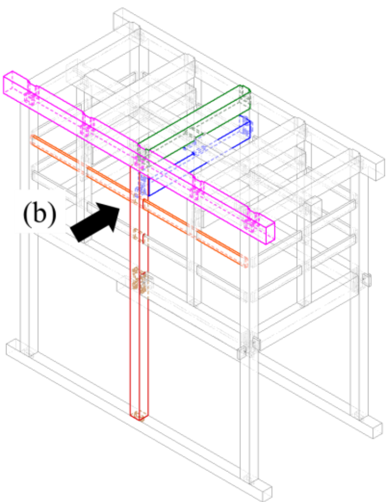


(b) No wall (n3, n2.5)

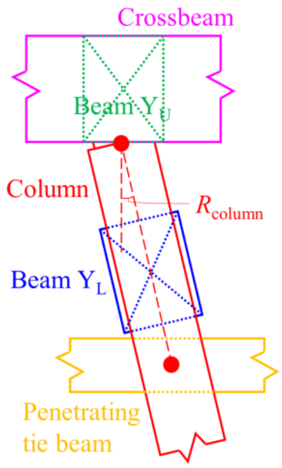
Fig. 10 – Comparison of load-displacement relationship

(Positive direction)

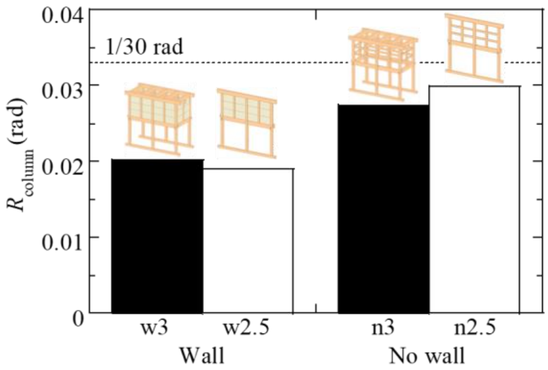
Next, the deformation angle of the in-plane columns is compared in Fig. 11. The R_{column} is defined as Fig. 11 (a) and (b) to analyze the shear deformation of the part with the out-of-plane beams. Fig. 11 (c) shows two results. One is that the R_{column} of the specimens with no walls was larger than that with walls. The other is that the R_{column} of n2.5 was larger than that of n3.



(a) Specimen



(b) Definition of R_{column}



(c) Comparison of R_{column} (R=1/30 rad)

Fig. 11 – Comparison of deformation angle of the in-plane columns

From the above, the followings are expected. The out-of-plane beams transmitted horizontal force when the specimen was loaded at the top in the in-plane direction and had the effect which reduces the deformation angle of the in-plane columns. Especially, the effect became stronger as the shear deformation of the part with the out-of-plane beams became larger. Therefore, the out-of-plane beams are expected to prevent the whole house from collapsing when the structure suffers a large deformation during severe earthquakes.

4. Conclusions

In this paper, static loading tests of the three-dimensional frame structure and the plane frame structure simulating a Japanese traditional timber house are conducted. The conclusions are as follows.

a) The static loading system for three-dimensional structures was developed. The loading frame made of steel members can deform a three-dimensional structure up to 1/5.6 rad of a shear angle by pushing the top of the structure horizontally.

b) In the test of the three-dimensional specimen with walls, the four of six columns broke until the cycle of 1/10 rad and the whole specimen lost the restoring force. On the other hand, the plane specimen with walls kept the restoring force up to 1/5.6 rad as the walls were being damaged.

c) The load-displacement relationships had almost no difference between the three-dimensional specimen and the plane specimen with walls. However, in the case of the specimens with no walls, the three-dimensional specimen indicated the restoring force which was about twice higher than that of the plane specimen.

d) The out-of-plane beams transmitted horizontal force when the specimen was loaded at the top in the in-plane direction and had the effect which reduced the deformation angle of the in-plane columns. In particular, the out-of-plane beams are expected to prevent the whole house from collapsing when the structure suffers a large deformation during severe earthquakes.

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