SEISMIC SAFETY OF NON-STRUCTURAL COMPONENTS IN FULL-SCALE 10-STORY RC BUILDING SHAKING TABLE TEST

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Abstract

Insufficient data have been accumulated on the behavior of non-structural components in medium rise reinforced concrete residential buildings during an earthquake. Therefore, the seismic safety of non-structural components, including the interior and exterior materials, water supply vertical pipes, and furniture was verified by three-dimensional shaking table tests on a ten-story reinforced concrete building conducted at E-Defense in 2018 and 2019. This paper reports the test results of the in-plane deformation angle of the entrance steel door and the autoclaved lightweight concrete (ALC) panels as exterior materials as well as the strain measurement of the water supply vertical pipes. The results show that the maximum in-plane deformation angle of the entrance steel door was larger than the maximum story drift angle; however, the damage was slight and did not prevent opening and closing of the door after the tests. Additionally, the maximum in-plane deformation angle of the ALC panels and the maximum story drift angle were comparable, and the behavior of the ALC panels followed that of the building with the rocking behavior of the ALC panels, and there was no significant damage. Furthermore, the strain measurement of the water supply vertical pipes was less than the allowable value for an earthquake, and they showed no damage. These verification results can be used as basic data for improving the seismic safety of reinforced concrete residential buildings.

Keywords: E-defense; Full-scale shaking table test; RC building; Non-structural component; Seismic safety

1. Introduction

Measures to prevent damage to non-structural components are required to reduce human and economic damage caused by great earthquakes. Therefore, it is necessary to understand the behavior of non-structural components during an earthquake. In a previous study, the seismic performance of the exterior cladding in a full-scale four-story steel structure building was investigated by shaking table test [1]. There has not been sufficient accumulated data on the behavior of non-structural components in medium rise reinforced concrete (RC) residential buildings during an earthquake. Therefore, the seismic safety of non-structural components, including the interior and exterior materials, water supply vertical pipes, and furniture was verified by three-dimensional shaking table test on a full-scale ten-story RC building that was conducted at E-Defense in 2018 and 2019. This paper reports on the test outline and results of the in-plane deformation angle of the entrance steel doors (SDs) and the autoclaved lightweight concrete (ALC) panels as exterior materials as well as the strain measurement of the water supply vertical pipes.

2. Shaking Table Test Outline

2.1 Outline of Specimen Building

The specifications of the ten-story RC building shown in Fig.1 are shown in Table 1 [2]. The test building consisted of a rigid-frame structure with the multi-story shear wall installed in the 1st to 7th floors in the short-side direction (wall direction) and a rigid-frame structure composed of columns and beams in the long-side direction (frame direction). The shaking table test was conducted on the structure using a free-standing base sliding system developed at the National Research Institute for Earth Science and Disaster Resilience and seismic resistance system on which a basis was fixed. This paper reports on the results of the test with the seismic resistance system.

Fig. 1 – Full-scale ten-story RC building

Table 1 – Specifications of specimen building [2]

Number of stories	10
Dimension	Wall dir.: 9.4 m Frame dir.: 13.4 m
Span	Wall dir.: 3 spans at 3.1 m, 1.8 m, and 3.1 m Frame dir.: 3 spans at 4 m each
Floor height	1st floor: 2.8 m, 2nd to 4th floors: 2.6 m, 5th to 7th floors: 2.55 m, 8th to 10th floors: 2.5 m
Height	27.45 m
Weight	923 t
Structure	Wall dir.: rigid-frame structure with the multi-story shear wall installed in 1st to 7th floors Frame dir.: rigid-frame structure composed of columns and beams

2.2 Test Case

In this test, the earthquake wave recorded at the Kobe Marine Meteorological Observatory (JMA-Kobe) during the Hyogo-ken Nanbu earthquake (M7.3) used for input wave. The maximum acceleration of JMA-Kobe is 818 cm/s/s in the NS component, 617 cm/s/s in the EW component, and 332 cm/s/s in the UD component. The test case is summarized in Table 2. The test cases of No.1-4 are free-standing base sliding system and those of No.5-10 are seismic resistance system.

Table 2 – Test case

No	Input Wave	Level (%)	Input Component		
			Wall dir.	Frame dir.	Vertical dir.
1	JMA-Kobe	10	EW com.	NS com.	UD com.
2	JMA-Kobe	25	EW com.	NS com.	UD com.
3	JMA-Kobe	50	EW com.	NS com.	UD com.
4	JMA-Kobe	100	EW com.	NS com.	UD com.
5	JMA-Kobe	10	EW com.	NS com.	UD com.
6	JMA-Kobe	25	EW com.	NS com.	UD com.
7	JMA-Kobe	50	EW com.	NS com.	UD com.
8	JMA-Kobe	100	EW com.	NS com.	UD com.
9	JMA-Kobe	100	EW com.	NS com.	UD com.
10	JMA-Kobe	100	NS com.	EW com.	UD com.

3. Experimental Setup of Verification of Non-Structural Components

The floor plan of the 2nd story is shown in Fig.2 and the rough plan of the verification rooms is shown in Fig.3, whereas the setup of the verification rooms is shown in Fig.4. The verification room with interior finish on the ALC panels and seismic resistance SDs (verification room A) and the verification room without interior finish on the ALC panels and non-seismic resistance SDs (verification room B) were located as shown in Fig.2. Furniture was also installed in verification room A. The cross sections of the SDs are shown in Fig.5, whereas the elevation view of the ALC panels are shown in Fig.6. The seismic resistance SD has a lager clearance between the door and the frame than the non-seismic resistance SD. In verification room A, the in-plane deformation angle of the seismic resistance SDs installed in the wall direction and the frame direction (as shown in Fig.3) were measured. In verification room B, the in-plane deformation angle of the non-seismic resistance SDs installed in the wall direction and the frame direction (as shown in Fig.3), and of the ALC panel installed continuously as the normal wall members (ALC (N)) and the ALC panel installed on the side of the non-seismic resistance SD (ALC (S)) in the frame direction (as shown in Fig.3 and Fig.6), were measured. Displacement meters were installed as shown in Fig.7 [3], and the in-plane deformation angle of the SDs, γ_{SD}, was calculated from the displacement data using Eq. (1). The installation of the displacement meters on the SD is shown in Fig.8.

$$\gamma_{SD} = \frac{\Delta_{SD1} - \Delta_{SD2}}{2} \frac{\sqrt{L^2 + H^2}}{LH} \tag{1}$$

where Δ_{SD1} is the displacement measured by displacement meter 1, Δ_{SD2} is the displacement measured by displacement meter 2, L is the width of the SD, and H is the height of the SD. The displacement meters were installed as shown in Fig.9 and Fig.10 to measure the in-plane deformation angle of the ALC panels, and the in-plane deformation angle of the ALC panels, γ_{ALC}, was calculated from the displacement data using Eq. (2) [1].

$$\gamma_{ALC} = \frac{\Delta_{ALC1} - \Delta_{ALC2}}{B} \tag{2}$$

where Δ_{ALC1} is the displacement measured by displacement meter 1, Δ_{ALC2} is the displacement measured by displacement meter 2, and B is the distance between the displacement meters. Furthermore, polyethylene vertical pipes for water supply with diameters of 50-φ and 75-φ were installed in the locations shown in Fig.2. The installation situation of the water supply vertical pipes is shown in Fig.11, whereas the installation method used for the water supply vertical pipes is shown in Fig.12 and Fig.13. Water supply vertical pipes are usually passed through the sleeves in the slab and fixed by filling with mortar. However, in this test, a stub flange was provided at the edge of the water supply vertical pipes and fixed to the slab with stainless flanges and anchor bolts. In addition, the water supply vertical pipes are provided with a fusionless joint. The strain gauges were attached to the water supply vertical pipes to assess their behavior during an earthquake. The locations of the strain gauges are shown in Fig.14. The strain gauges were placed at three locations on the pipe, and in four directions at each location.

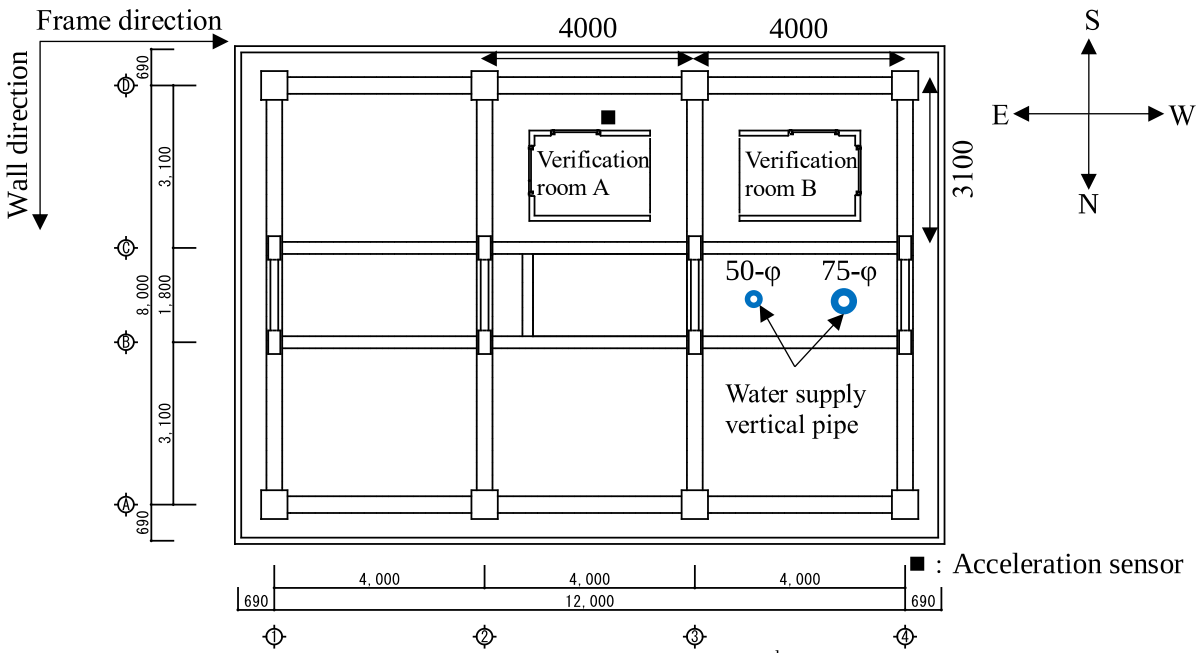


Fig. 2 – Floor plan of the 2nd story

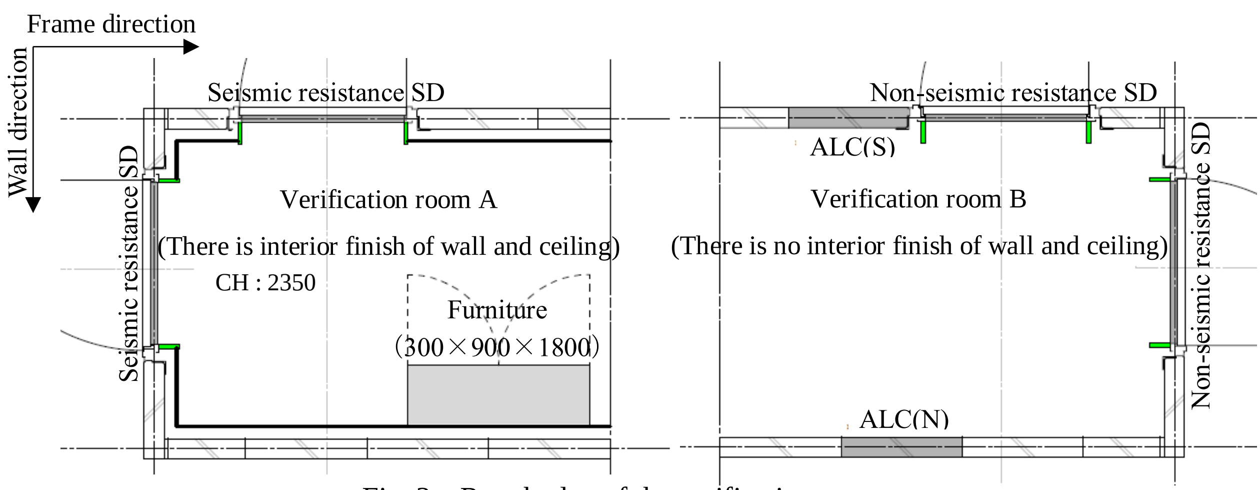
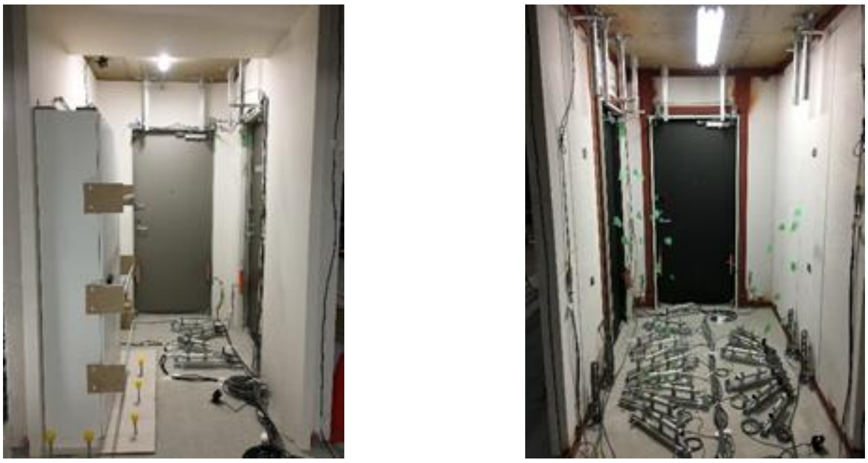
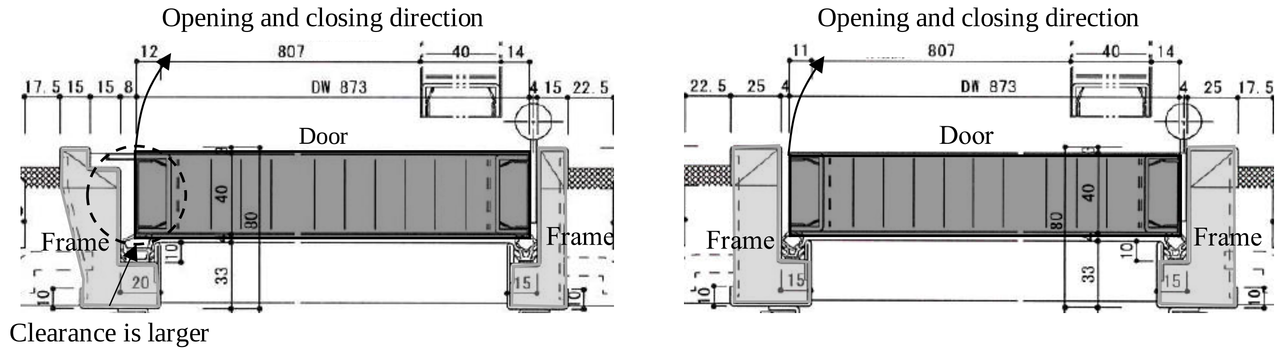


Fig. 3 – Rough plan of the verification rooms



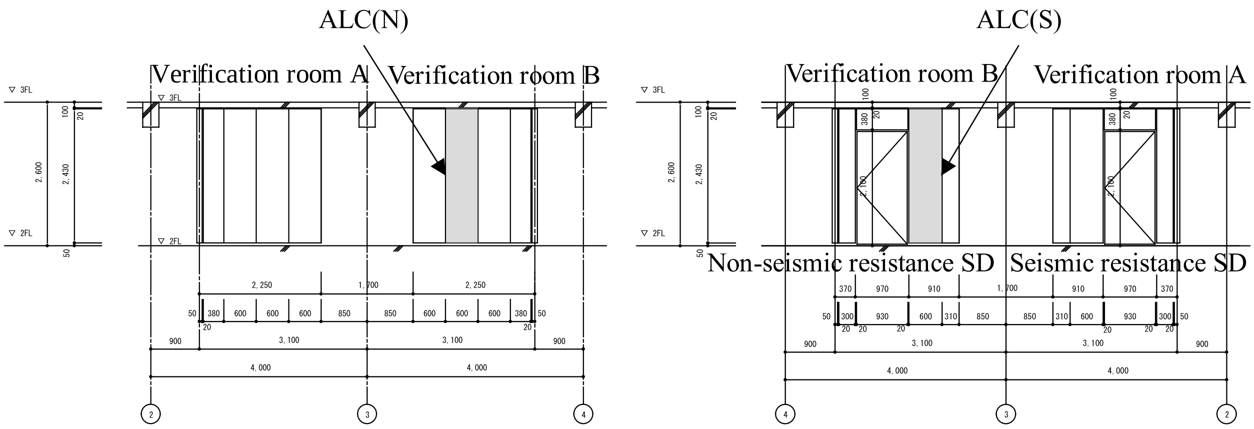
(a) Verification room A (b) Verification room B

Fig. 4 – Setup of the verification rooms



(a) Seismic resistance SD (b) Non-seismic resistance SD

Fig. 5 – Cross section of the SDs



(a) External elevation of N-side ALC panel (b) External elevation of S-side ALC panel

Fig. 6 – Elevation view of the ALC panels

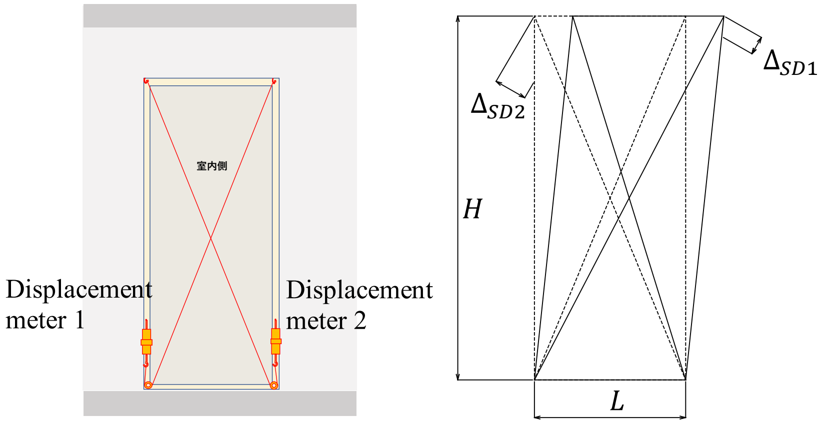


Fig. 7 – Measurement method of the in-plane deformation angle of the SD

Fig. 8 – Installation of the displacement meters on the SD

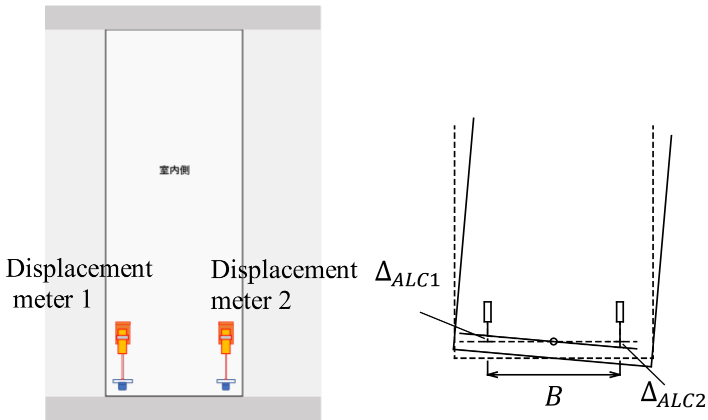


Fig. 9 – Measurement method of the in-plane deformation angle of the ALC panel

Fig. 10 – Installation of the displacement meters on the ALC panel

Fig. 11 – Installation situation of the water supply vertical pipes

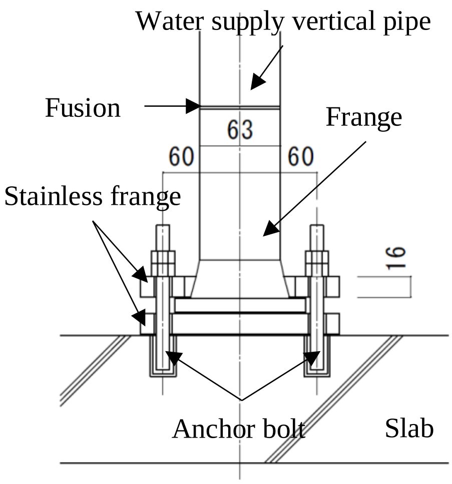


Fig. 12 – Installation method

Fig. 13 – Installation part

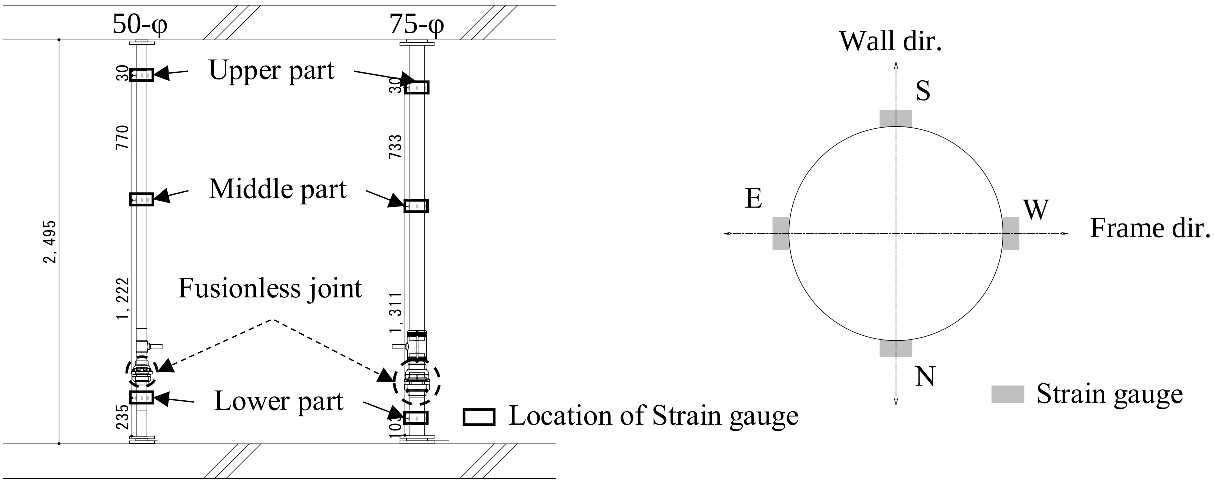


Fig. 14 – Attachment locations of strain gauges

4. Results

This paper reports the results of the first 100%-scale JMA-Kobe test with the seismic resistance system.

4.1 Floor Response Acceleration

The floor response acceleration on the 2nd story was measured by the acceleration sensor installed near the seismic resistance SD in the frame direction of verification room A (see Fig.2). The floor response acceleration on the 2nd story is shown in Fig.15. The maximum floor response acceleration on the 2nd story was 927 cm/s/s in the wall direction, 1177 cm/s/s in the frame direction, and 1562 cm/s/s in the vertical direction. The maximum acceleration of the shaking table was 862 cm/s/s in the wall direction, 1240 cm/s/s in the frame direction, and 451 cm/s/s in the vertical direction, and the maximum acceleration of the shaking table exceeded the maximum acceleration of JMA-Kobe in all directions [2]. The Fourier spectra of the data of floor vibration on the 2nd story is shown in Fig.16. A peak occurred in the wall direction at approximately 0.4 s, whereas peaks occurred in the frame direction at approximately 0.5 s and 0.7 s, as shown in Fig.16. The peak periods were different between the wall direction and the frame direction, probably because the structure was different.

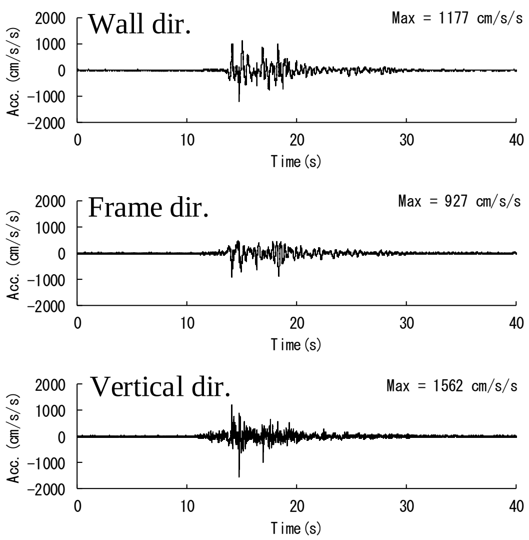


Fig. 15 – Floor response acceleration on the 2nd story

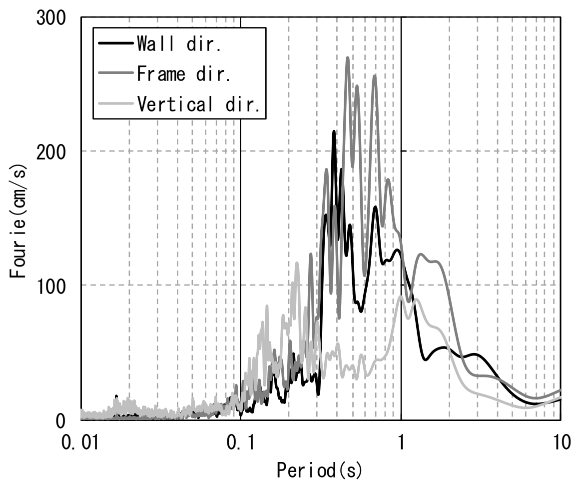


Fig. 16 – Fourier spectra of floor vibration on the 2nd story

4.2 Maximum Story Drift Angle

The maximum story drift angle of each story was measured by the displacement meters shown in Fig.17 [2]. The measured maximum values were 1/79 rad on the 4th floor in the wall direction, and 1/38 rad on the 7th floor in the frame direction (see Fig.18). The maximum story drift angles of the verified 2nd story were 1/103 rad in the wall direction, and 1/42 rad in the frame direction.

Fig. 17 – Displacement meters for measuring story drift angle

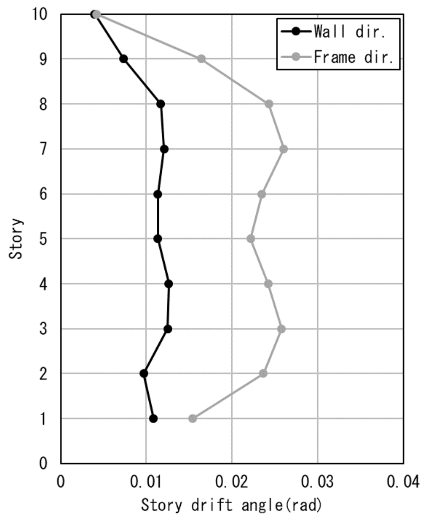


Fig. 18 – Maximum story drift angle [2]

4.3 In-Plane Deformation Angle of Entrance Steel Doors

The time histories of the in-plane deformation angle of the seismic resistance SDs and the non-seismic resistance SDs are shown in Fig.19. The maximum in-plane deformation angle was different for the seismic resistance SDs and the non-seismic resistance SDs; however, the character of the waveform of the in-plane deformation angle was almost the same. Additionally, the character of the waveform of the in-plane deformation angle of the SDs was different in the wall direction and the frame direction. This is because the behavior of the building is different in the wall direction and the frame direction.

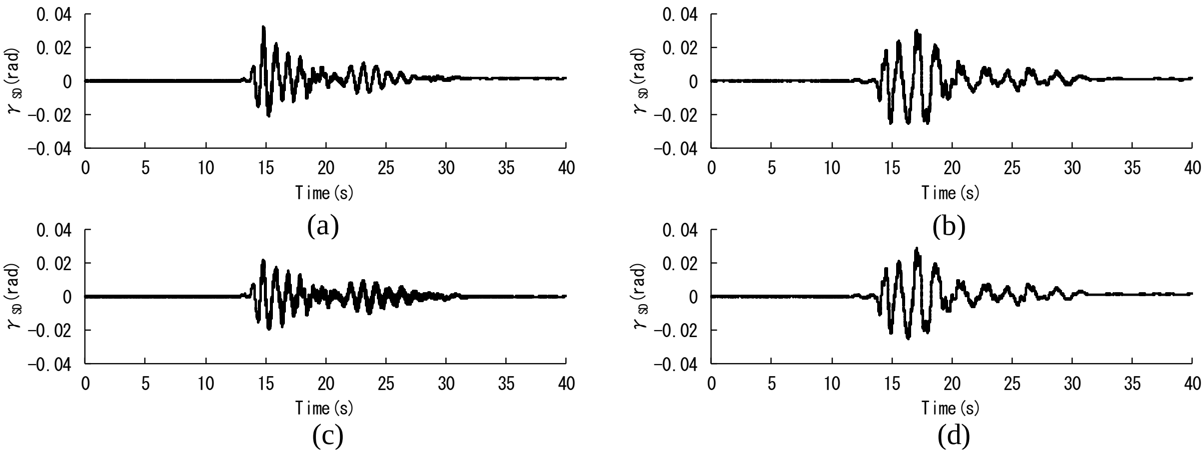
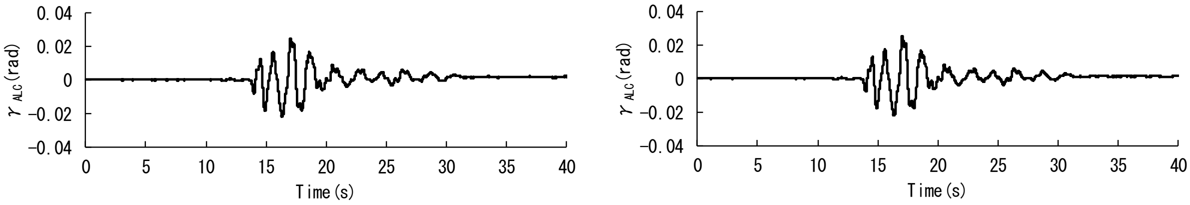


Fig. 19 – Time histories of the in-plane deformation angle of the seismic resistance SD (a) in the wall direction and (b) in the frame direction and the non-seismic resistance SD (c) in the wall direction and (d) in the frame direction

4.4 In-Plane Deformation Angle of Autoclaved Lightweight Concrete Panels

The time histories of the in-plane deformation angle of ALC (N) and ALC (S) are shown in Fig.20. The maximum in-plane deformation angle and the character of the waveform of the in-plane deformation angle were almost the same for ALC (N) and ALC (S) installation positions. Therefore, there was no difference in the behavior of the ALC panels due to the difference in the installation position.

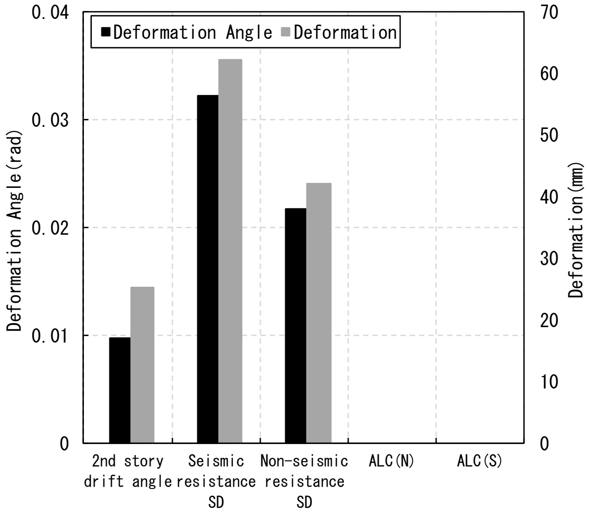


(a) ALC (N) (b) ALC (S)

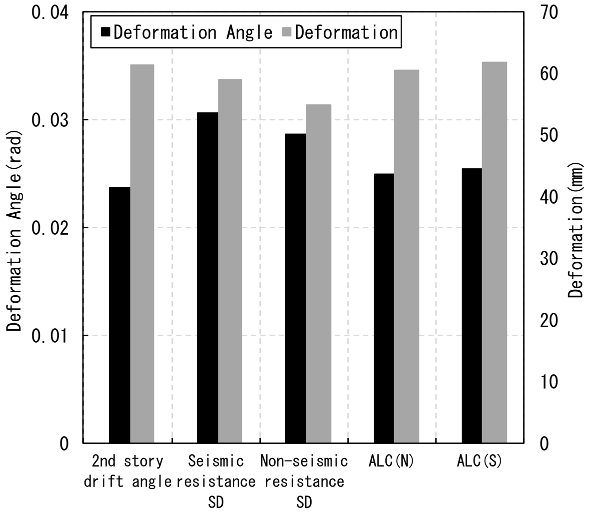
Fig. 20 – Time histories of the in-plane deformation angle of the ALC panels

4.5 Maximum Deformation of Each Component

The maximum story drift angle of the 2nd story and the maximum in-plane deformation angle of the SDs and ALC panels in each direction are shown in Fig.21, along with the overall maximum story drift and the maximum in-plane deformation. The maximum in-plane deformation angle of the seismic resistance SD was about 1.3 times, and that of the non-seismic resistance SD was about 1.2 times, the maximum story drift angle of the 2nd story in the frame direction. Additionally, the maximum in-plane deformation angle of the ALC panels and the maximum story drift angle of the 2nd story were comparable, and the rocking behavior of the ALC panels followed the behavior of the building. The maximum in-plane deformation angle of the seismic resistance SD was more than 3 times, and that of the non-seismic resistance SD was more than 2 times, the maximum story drift angle of the 2nd story in the wall direction. The maximum in-plane deformation angle of the SDs was larger than the maximum story drift angle of the 2nd story because of installation of the hanging wall on the SDs. However, comparing the maximum deformation of the SDs with the maximum story drift of the 2nd story, the maximum deformation of the SDs was larger in the wall direction, but smaller in the frame direction. The maximum in-plane deformation angle of the seismic resistance SD was larger than that of the non-seismic resistance SD in both the wall direction and the frame direction. A reason for this difference is that the seismic resistance SD has lager clearance between the door and the frame and therefore less confinement due to contact between the door and the frame. The scratches on the seismic resistance SD were larger than those on the non-seismic resistance SD [4], and the behavior of the frame was great even after the door contacted the frame. In addition, although both the seismic resistance SD and the non-seismic resistance SD sustained minor damage, as shown in Fig.22, all doors could be opened and closed after the tests. Additionally, there was some minor damage at the edges of the ALC panels, but no major damage, as shown in Fig.23.



(a)



(b)

Fig. 21 – Maximum story drift angle of the 2nd story and the maximum in-plane deformation angles of the SDs and ALC panels in the (a) wall direction and (b) frame direction

Fig. 22 – Scratches on the SDs after the test

Fig. 23 – ALC panels after the tests

4.6 Strain Measurement of Water Supply Vertical Pipes

This paper reports the results for the water supply vertical pipe of 50-φ. The time histories of the strain are shown in Fig.24. The positive side is tension and the negative side is compression. The strain in the frame direction, where the story drift angle of the 2nd story was large, was larger than the strain in the wall direction. The maximum strain of the water supply vertical pipes was approximately 2000 μ, which is less than the allowable strain of 3% (30,000 μ) for polyethylene pipe for water supply [5] against earthquakes. The strain distribution for the time of the maximum story drift angle of the 2nd story is shown in Fig.25. Tension strain occurred on both the N side and S side of the supply vertical pipes, and the strain at any location was almost the same in the wall direction. On the other hand, the strain above the joint of the water supply vertical pipe was tension on the E side and compression on the W side, and the strain was larger in compression than in tension. The strain below the joint of the water supply vertical pipe showed the opposite behavior. The water supply vertical pipe of 75-φ showed similar results. There was no damage to the water supply vertical pipes or the joints after the tests.

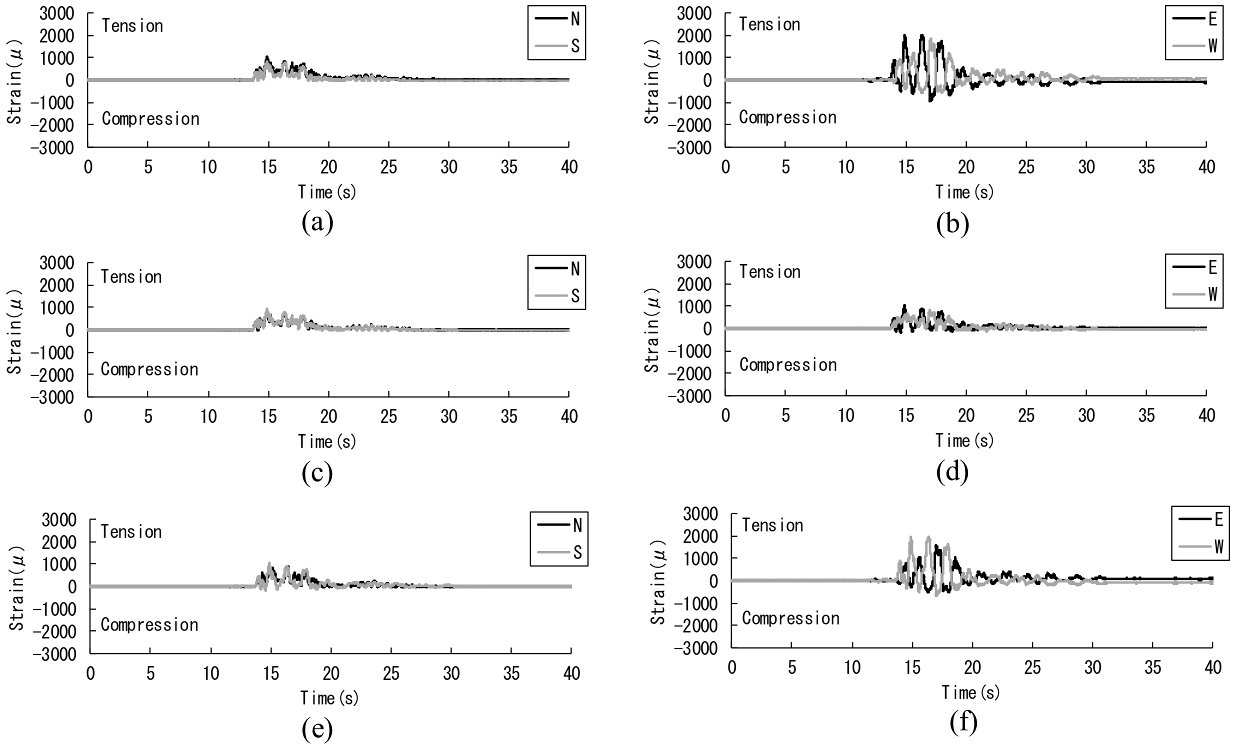


Fig. 24 – Time histories of the strain on water supply vertical pipe of 50-φ in the upper part (a) in the wall direction and (b) in the frame direction, in the middle part (c) in the wall direction and (d) in the frame direction, and in the lower part (e) in the wall direction and (f) in the frame direction

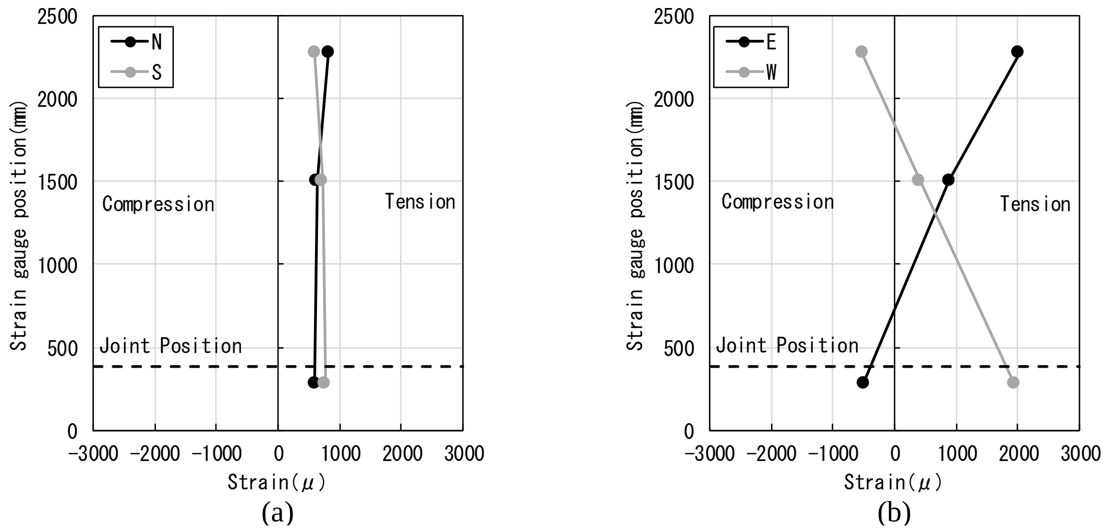


Fig. 25 – Strain distribution at the time of the maximum story drift angle of the 2nd story (a) in the wall direction and (b) in the frame direction

5. Conclusions

The seismic safety of the SDs, ALC panels, and water supply vertical pipes were verified by three-dimensional shaking table test on a full-scale ten-story RC building, and the following results were obtained.

(1) The behavior of the SDs was different between the wall direction and the frame direction. This is because the behavior of the building is different in the wall direction and the frame direction.

(2) The maximum in-plane deformation angle of the seismic resistance SD was larger than that of the non-seismic resistance SD. A reason for this difference is that the seismic resistance SD has larger clearance between the door and the frame and is less confined due to contact between the door and the frame.

(3) Although both the seismic resistance SD and the non-seismic resistance SD showed minor damage, all doors could be opened and closed after the tests.

(4) There was no difference in the behavior of the ALC panels in different installation positions

(5) The maximum in-plane deformation angle of the ALC panels and the maximum story drift angle of the 2nd story were comparable, and the rocking behavior of the ALC panels followed the behavior of the building.

(6) There was some minor damage at the edges of the ALC panels, but no major damage.

(7) The strain of the water supply vertical pipes was less than the allowable strain for polyethylene pipe for water supply against earthquakes.

(8) There was no damage in the water supply vertical pipes or the joints after the tests.

These verification results can be used as basic data for improving the seismic safety of RC residential buildings.

Acknowledgements

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