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NON-STRUCTURAL COMPONENT PERFORMANCE IN FULL-SCALE 4-STORY BUILDING

Y. Matsuoka[1], K. Suita[2], S. Yamada[3] and Y. Shimada[4]

ABSTRACT

In the shake table test conducted on a full-scale 4 story steel building at the E-Defense three-dimensional shake table facility, various non-structural components were installed to the specimen to evaluate their seismic performance. These components are ALC (autoclaved lightweight concrete) external wall cladding panels, aluminum sash, glass window, gypsum board partition walls, hanging ceiling system, and so on. Generally, non-structure components are designed to remain undamaged up to a story drift of 0.005 ~ 0.01 rad. On the other hand, by the shaking table test at the E-Defense, the 1st story was collapsed and the maximum story drift angle over 2nd story was reached to nearly 0.02 rad. So, we can observe the damage and evaluate the seismic performance for the drift angle of design level to more over.

1. Introduction

The objective of the current Japanese seismic design is to protect lives while allowing the damage to the buildings for extremely rare earthquakes. For this concept, avoiding the collapse is provided as minimum structural performance, and continuity of the building is not mentioned basically. However, from experience of the destructive earthquakes after the 1995 Hyogo-Ken Nanbu earthquake, it developed that continuity of the building after the earthquake had to be considered as the seismic performance of the building for general people who are not structural engineers such as users or owners of the buildings. This opinion is not necessarily correspondent to the idea of the experts. One of these reasons is expected to be that only the ultimate seismic performance was discussed for the structural performance but the functionality of the building was not mentioned. In this study, the functional performance of the building mainly thorough the damage to non-structural components during and after a severe earthquake is evaluated based on the result of the collapse experiments on 4-Story moment frames conducted in September 2007 at E-Defense three-dimensional shake table facility. The details of the specimen and experimental method are described in the companion paper by S. Yamada et. al. (2008), and the

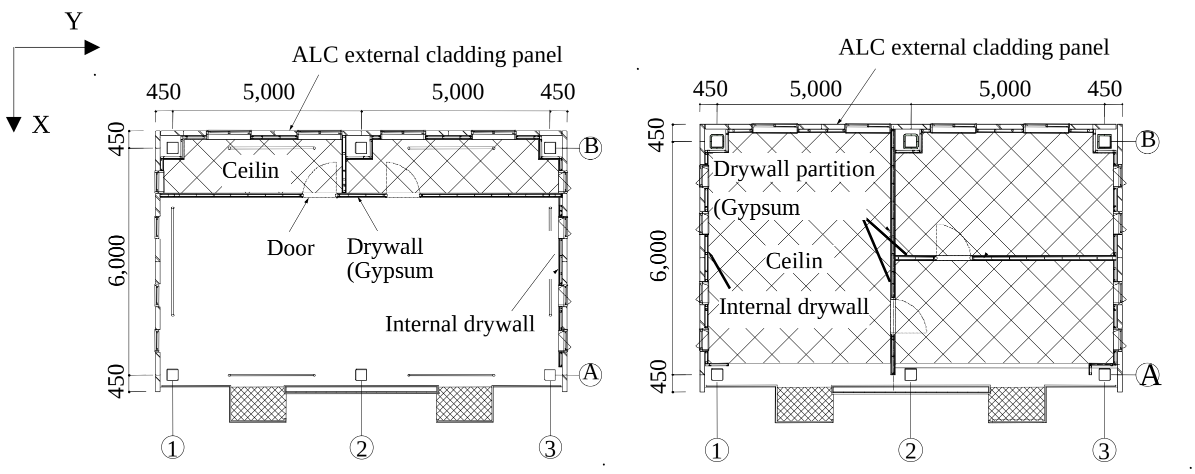
[1]Nippon Steel Engineering Co., LTD. (Former Researcher, Hyogo Earthquake Engineering Research Center, NIED), Tokyo, Japan
[2]Assoc. Professor., Dept. of Architecture and Architectural Engineering, Kyoto University, Kyoto, Japan
[3]Assoc. Professor, Structural Engineering Research Center, Tokyo Institute of Technology, Yokohama, Japan
[4]Graduate student, Tokyo Institute of Technology, Yokohama, Japan

behaviors of the specimen building are also described in the companion paper by K. Suita et. al. (2008).

2. Specifications of Non-Structural Components

Drawings of the non-structural components installed to the specimen are shown Figure 1. ALC (autoclaved lightweight concrete, designated as autoclaved aerated concrete in the US) external wall cladding panels, typically used for Japanese steel buildings of similar size and use, are placed on three sides of the specimen. Their thickness and width is 125mm and 600mm, respectively. ALC panels are fixed on to the beams at the top and bottom as to permit rocking behavior of the panels in case of an earthquake. Each external wall has the openings of the aluminum sash window. Internal drywall partitions, ceilings, steel doors are placed on the 2nd to 4th floor. The drywall partitions consist of two sheets of gypsum board whose thicknesses are 12.5mm for the inner layer and 9.5mm for the outer layer, and are attached to metal-stud framing typically used in Japanese buildings. The ceiling consists of gypsum boards bolted to cold-formed channel. These channel sections are supported by hanger bolts, which in turn connect to the bottom side of steel decks on the upper story floor slab.

The connections between the ALC panels and the drywall partitions or two drywall partitions have two kinds of details. One is the seismic type and the other is the non-seismic type. The clearance of 15mm was provided on the connection for the seismic type, and two walls contact directly for the non-seismic type. Similarly, the connections between the door (or window) frame and the internal drywall have two kinds of details. The gap of 25mm was provided on the connection for the seismic type, and the frames and the walls contact directly for the non-seismic type. On the door frames, furthermore, the top of the vertical supporting frame of the door, attaching to the bottom of the upper floor slab, had the sliding mechanism for the seismic type, so that the frame can move to horizontal way.



(a) 2nd and 3rd Floor (b) 4th Floor

Figure 1. Plan of non-structural components

3. Results for External Walls

3.1. Observations of External Walls after the Experiment

Under 0.2 times the Takatori records (maximum story drift at the 2nd story: X direction 0.0055 rad, Y direction 0.0053 rad), damage to the external wall was not observed on all façade. Under 0.6 times the Takatori records (maximum story drift at the 1st story: X direction 0.012 rad, Y direction 0.019 rad), some cracks of approximately 100mm length were observed in the corner of the ALC panels. However, the functional performance of external walls such as water-resistance, heat-insulation and sound-insulation did not spoil. Under 1.0 times the Takatori records (maximum story drift at the 1st story: X direction 0.08 rad, Y direction 0.19 rad), severe damage was observed at the 1st story. The ALC panels hatching as shown Figure 2 fell off or

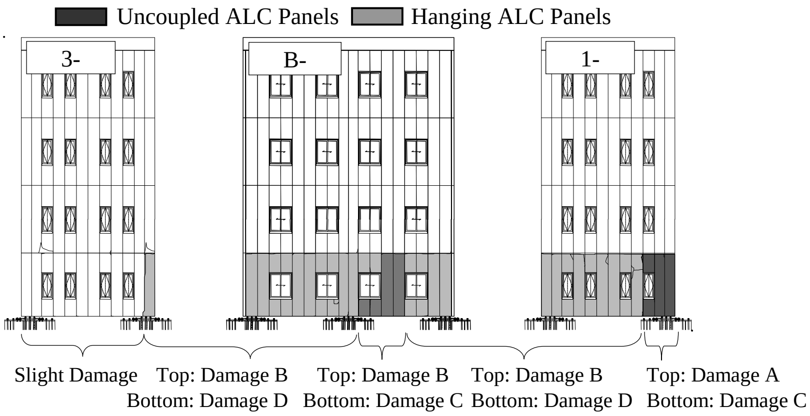


Figure 2. Damage to the ALC panels after test by1.0 Takatori records

(a) Damage to the ALC panels (b) Damage B (c) Damage C

Figure 3. ALC panels after test by 1.0 Takatori records

Table 1. Damage pattern of ALC panels

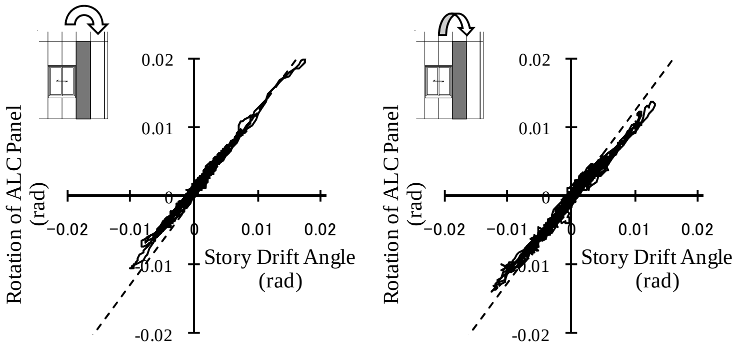
Top	Damage A	Fracture of the welding between the supporting steel angle and the attachment plate
	Damage B	Crash of the ALC panel and exposure of the reinforcing bars
Bottom	Damage C	Fracture of the O-bolt fastening the ALC panel
	Damage D	Fracture of the welding between the supporting steel angle and the main frame

hanged. Figure 3a shows the damage to the ALC panels at Line 1 of the 1st story after 1.0 times the Takatori records. In the top and bottom of these ALC panels, two kind of damage to the fastener was observed as shown Table 1. Figure 3b shows Damage B, and Figure 3c shows Damage C. On the ALC panels falling off, the top of the panel has Damage A and the bottom of the panel has Damage D. On the hanging ALC panels, the top of the panel has Damage B and the bottom of the panel has Damage C or D.

3.2. Rotation Behavior of the ALC Panels

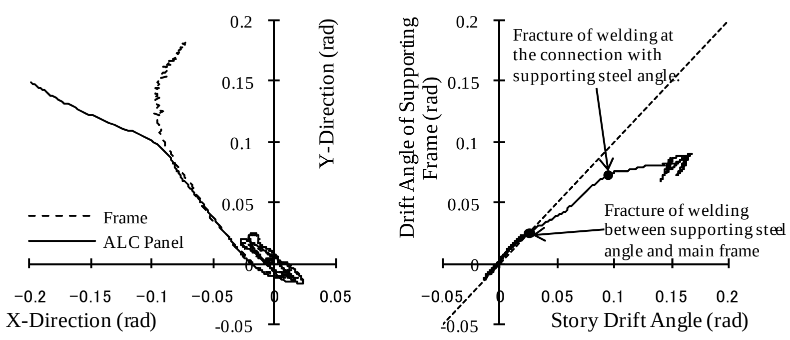
Figure 4 shows an example of rotation behavior of the ALC panels under 0.6 times the Takatori records. The dotted line in this figure indicates that the story drift corresponds to the rotation of the ALC panel. So the results of the experiment almost behaved on this dotted line, it is understood that the ALC panels were accommodated to the story drift for both in-plane rotation and out-of-plane rotation. Similar relationships are confirmed under 0.2 and 0.4 times the Takatori records. The results of Figure 4 were provided from the hatching area in the figure. Similar measurement to the openings of the window or the adjacent ALC panels was performed, so the same relationships between the story drift and the rotation were obtained.

Figure 5a shows the orbit of the story drift and the rotation of the ALC panel at the 1st story. After the story drift reached to 0.080 rad for the X direction and 0.083 rad for the Y direction, the behavior of the ALC panel was not accommodated to the story drift. It is understood that Damage D was occurred at this point and the ALC panel hanged. Figure 5b shows the relationship between the drift angle of the supporting frame of the sash and the inter-story



(a) In-plane direction (b) Out-of plane direction

Figure 4. Rotation behavior of the ALC panels at the 1st story by 0.6 Takatori records



(a) Orbit of rotation of ALC panel (b) Supporting frame of sash

Figure 5. Deformation of the external wall at 1st story by 1.0 Takatori records

drift angle. Since the drift angle of the supporting frame of the sash was not increase after the instance, it is expected that Damage D occurred at this point. In addition, it is confirmed by the video that Damage A and C occurred simultaneously.

3.3 .Damage Mechanism of the ALC Panels

In the component test to investigate the simple behavior of the ALC panel (Matsuoka, et. Al. 2007), the ALC panels did not fall when the in-plane rotation angle reached to 0.15 rad. However, in the present shake test, the some ALC panels fell off or hanged until 0.12 rad rotation in bi-axial direction during 1.0 times the Takatori records. Figure 6 shows the observed damage mechanism of the fastener of the ALC panel. On Damage A and C, the welding or the O-bolt fractured because of the shear or tensile force induced by the out-of plane rotation of the ALC panels. On Damage D, the welding fractured because of the vertical force induced by the shrinkage of the 1st story column with the local buckling. Thus, the out-of plane rotation or the vertical load which were not observed in the component test might contribute to the damage to the fastener in the present shake test.

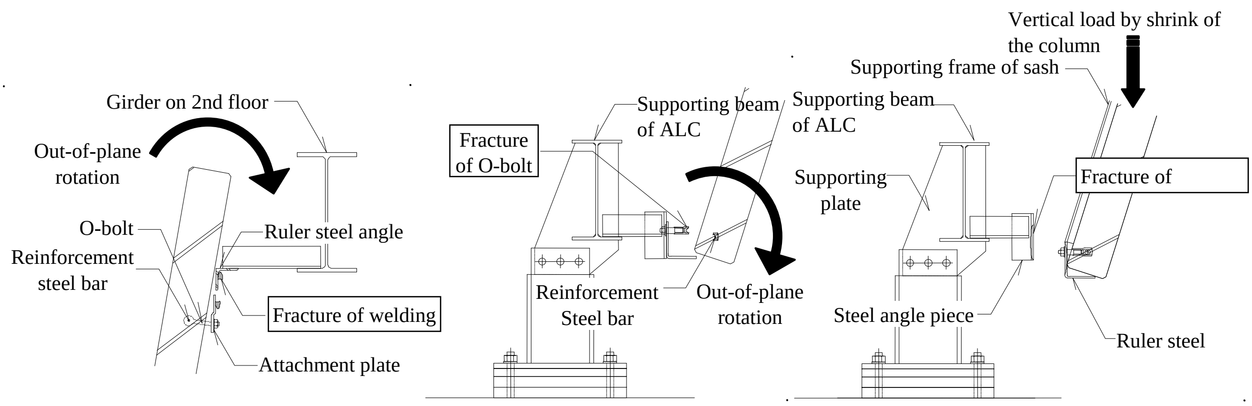


Figure 6. Damage mechanism of the ALC panels

4. Results of Internal Non-Structural Components

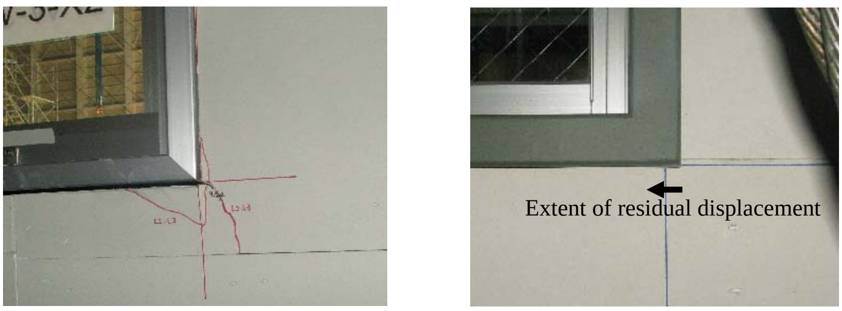
4.1. Observations of Internal Non-structural Components after the Experiment

Table 2 shows the damage to the internal non-structural components by each test. On the non-seismic type of the drywall partitions, the gypsum board met the door frame under the small story drift, and slight local crushing of the board was observed. On the seismic type of the drywall partitions, the top of the vertical supporting frame of the door could move to horizontal way until the story drift did not exceed 0.01 rad, and the door frame did not meet the gypsum board since it is mounted with gap. Consequently, damage was reduced.

On the non-seismic type of the internal finishing drywalls attached on the inside of the ALC external wall, the gypsum board met the window frame under the small story drift and some local crushing and cracks were observed as shown in Figure 7a. On the seismic type of the internal finishing drywalls, the window frame did not meet the gypsum board until 0.05 rad of the story drift because of 10.5mm gap, so no damage was observed as shown in Figure 7b. However, when the deformation exceeded the gap, the gypsum board was damaged, and the larger gap remained.

Table 2. Damage to the internal non-structural components

Scale factor of the input ground motion		**0.2**	**0.6**	**1.0**
Maximum story drift angle at 2nd story (rad)		X : 0.0054 Y : 0.0052	X : 0.012 Y : 0.017	X : 0.019 Y : 0.015
Between two drywall partitions	Non-seismic type.	No damage	Remarkable local crushing of the board in Y-direction at the 4th floor No damage at the 2nd and 3rd floor	Extent of remarkable local crushing of the board in Y-direction at the 4th floor No damage at the 2nd and 3rd floor
	Seismic Type.	No damage	No damage	No damage
Between the ALC panels and the drywall partitions	Non-seismic type.	No damage	Slight local crushing of the board at the top of wall	Slight local crushing of the board at the top of wall
	Seismic Type.	No damage	No damage	No damage
Between the door frame and the drywall partition	Non-seismic type.	Slight local crushing of the board at the 2nd and 3rd floor 1mm gap	Door frames at the 2nd and 3rd floor were deformed at a height of 100mm from the bottom Extent of remarkable local crushing of the board at the 2nd and 3rd floor	Extent of the damage on 0.6 times test
	Seismic Type.	Peeling off of the surface paper	Crack with 300mm length of the board at the top corner of the door frame No damage of the board at the other area because of the gap	Larger residual displacement among the gap
Door	Non-seismic type.	No damage	No damage	No damage
	Seismic Type.	No damage	No damage	No damage
Internal finishing drywall	Non-seismic type.	Gap with 2mm length Crack with 10mm length	Remarkable cracks and local crushing Looseness of screws between boards and light steel gages	Extent of the damage on 0.6 times test
	Seismic Type.	Slight local crushing by defective work No damage of the board at the other area	No damage because of the gap	No damage because of the gap



(a) Non-seismic type (b) Seismic type

Figure 7. Internal walls around window frame after test by 0.6 Takatori records

4.2. Sway and Deformation of Partition Walls

As shown in Figure 8, the story drift δ is expected to correspond to the summation of three kind of displacement of the drywall partition. The first one is the lateral sway at the bottom of the board δ_1, the second one is the shear deformation of the wall δ_2, and the third one is the lateral sway at the top of the board δ_3; where δ_2 contains the deformation of the board, the metal-stud and the fastener. Figure 9 shows the relationships between the story drift and the lateral sway δ_1 or the shear deformation δ_2 of the drywall partition at the 3rd story under 1.0 times the Takatori records. Significant correlation between δ_1 and δ or δ_2 and δ is observed. At the moment of reaching the maximum story drift by 1.0 times the Takatori records, δ was 36mm, δ_1 was 20mm, δ_2 was 16mm and δ_3 was 0mm in the positive direction. Similarly, δ was 30mm, δ_1 was 20mm, δ_2 was 8mm and δ_3 was 2mm in the negative direction. The ratios of these values were almost constant during the shaking tests.

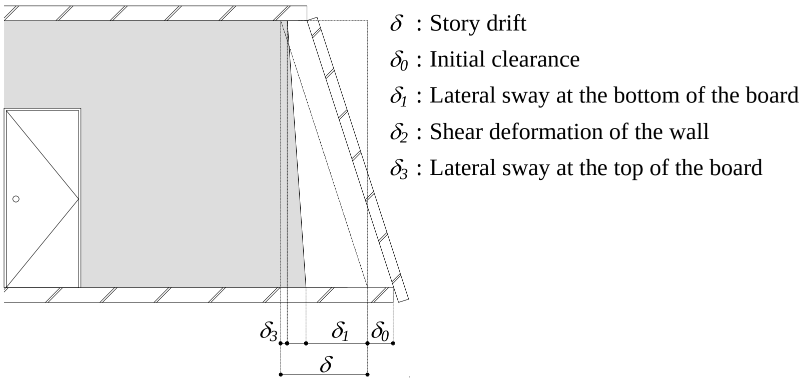
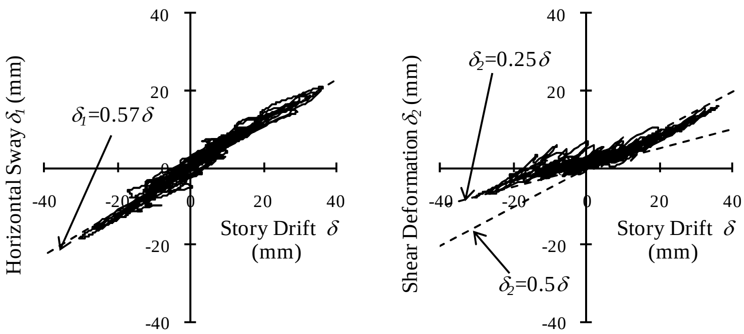


Figure 8 Sway and deformation of the drywall partition



(a) Lateral Sway (b) Shear Deformation

Figure 9. Behavior of the drywall partitions at the 3rd floor by 1.0 Takatori records

4.3. Shear Deformation of Door Frames

The shear deformation angle of the door frame, which is the non-seismic type at each floor, was measured. Figure 10 shows the time history of the story drift and the shear deformation of the door frame at the 2nd story under 0.4 times the Takatori records. The two values almost corresponded when the story drift was less than 0.005 rad. However, when the story drift exceeded 0.005 rad, the shear deformation of the door frame was not accommodated to the story drift without increasing. It is expected that the reasons of this result are loosening of the screw which fasten the vertical supporting frame of the door to the slab, and the local deformation of the reinforcing bar or the steel plates connecting the door frame and the supporting frame. Consequently, the shear deformation of the door frame did not become excessive. Despite of the maximum story drift of approximately 0.02 rad during the shake test, the door could be opened and closed.

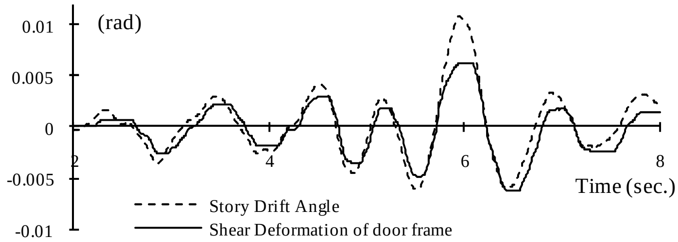
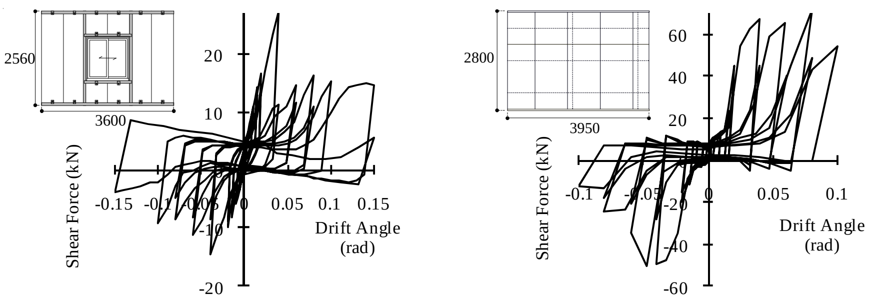


Figure 10. Shear deformation of the door frame at 2nd floor by 0.4 Takatori records

5. Effect of Non-Structual Components on Steel Structures

The lateral resistance and the stiffness of the ALC panels and the drywall partitions of the test specimen are examined through the hysteretic characteristic obtained from the component tests of ALC panels (Matsuoka, et. al. 2007) and drywall partitions (Lee, et. al. 2007). Figure 11 show the hysteretic characteristic of the ALC panels with a single window, and partition wall without opening, respectively. The hysteretic characteristic of the ALC panel consists of (1) friction of joints, (2) compressive resistance at the corner of the ALC panel, (3) stiffness of the supporting frame of the sash, and (4) initial friction. The drywall partition are expected to resist the story drift by compressive action in the diagonal direction of the wall, when the gypsum board meet the columns, beams or the supporting frame of the door. Figure 12 shows the relationships between the lateral resistance per one story and the story drift. This lateral resistance was estimated from the results of the component tests considering the difference of the size of ALC panels and the drywall partitions between the component tests and the present shake tests.



(a) ALC panel with opening (b) Drywall partition

Figure 11. Results of the element tests

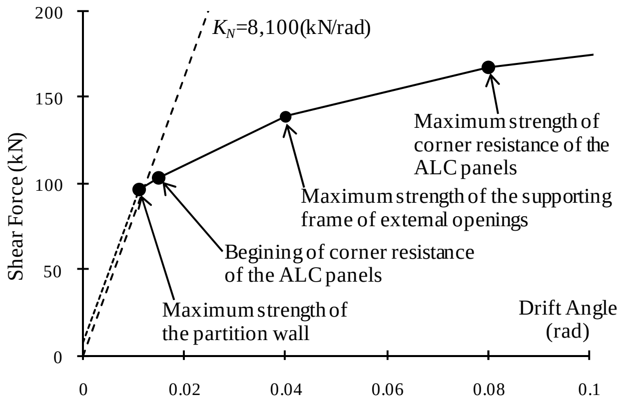


Figure 12. Story shear of ALC panels and drywall partitions versus story drift at the 2nd and 3rd story in Y-direction

Under 0.4 times the Takatori records the maximum story drift reached 0.0011 rad at the 2nd story for Y direction. Then the story shear was 1,019 kN, and the summation of the column shear forces was 812 kN, so the difference Q_n=207 kN of the two values is expected to be the lateral resistance of the non-structural components except the structural frame. It is obtained from Figure 12 that the lateral resistance of the ALC panels and the drywall partitions is 97 kN, which was 47% of Q_n. In the same way under 0.6 times the Takatori records, the maximum story drift was 0.017 rad, the story shear was 1,260 kN, the summation of the column shear force was 994kN, the difference Q_n was 266 kN, and the lateral resistance from Figure 12 was 108 kN, which was 41% of Q_n. These lateral resistances are 11 to 12% of the story shear carried by the structural frame. In the same way, the initial stiffness of the ALC panels and the drywall partitions is calculated from Figure 12. The stiffness is 8,100 kN/rad, which is 8% of the initial stiffness 100,000kN/rad at the 2nd story.

6. Conclusions

1. Damages to the ALC panels were hardly observed until 0.02 rad of the story drift, and the ALC panels fell off or hanged at 0.12 rad of the story drift.
2. Damages to the drywall partitions for the non-seismic type were observed around the door frames or the window frames at more than 0.005 rad of story drift, whereas damages for the seismic type were slight and it was confirmed that the initial gap between the drywall partition and the frame was effective to reduce the damage to gypsum boards. The sway and deformation of the drywall partitions correspond to the story drift.
3. The lateral resistance of the ALC panels and the drywall partitions were evaluated from the result of the component tests. As a result, the initial stiffness and maximum lateral resistance of non-structural components of the collapse test specimen were approximately 10 % of those of the structural frames.

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