BEHAVIOR OF EXTERIOR CURTAIN WALL OF HIGH-RISE BUILDINGS AGAINST LARGE STORY DRIFT BY LONG-PERIOD EARTHQUAKE GROUND MOTIONS

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ABSTRACT:

Recently, the possibility that a high-rise building generates the vibration with large displacement amplitude against the long-period earthquake ground motions by the ocean trench type and against the near fault earthquake ground motions has been indicated. Though an exterior curtain wall (called the following CW) of a high-rise building has been designed for various external force, the behavior and process to failure of CW with large story drift has not been clarified yet. In this paper, the dynamic behavior of CW in the large deformation was observed by the shaking table test using full-scale specimen. As a test specimen, high-rise building of 30 stories with average earthquake resistance performance is assumed. Authors built the testing system of 2 stories on, which could reproduce story drift of the high-rise building was reproduced, and the largest floor acceleration was reproduced in the 2nd floor. Dynamic behavior was similarly tracked even in full-scale shaking table test against the large deformation of story drift angle of 0.05. The response acceleration data was recorded, in- and out-plane direction which affects CW in real time. The dynamic behavior of CW in the large deformation was clarified by dynamic experimental tests with full-scale specimen.

KEYWORDS: Exterior curtain wall, full-scale shaking table test, long-period ground motions

1. INTRODUCTION

Although structural members of building have been verified to have seismic safety performance of a certain standard level, exterior materials might receive damage in response to deformation that is greater than the designed level by unexpectedly strong ground motion in the event of a large earthquake. So, exterior curtain walls might cause injury to those outside the building. In particular, high-rise buildings constructed might response with large displacement amplitude for a long time because of ground motion with a dominant long-period component, resulting from a distant inter-plate earthquake. A pulse-like ground motion with large velocity amplitude contained in a near-fault ground motion might induce a great deformation in the exterior curtain walls. Essential subjects in such a situation are to protect the neighborhood from damage from falling exterior curtain walls of high-rise buildings and to avoid the functional degradation of buildings.

2. OBJECTIVES

In order to develop the performance of exterior curtain walls and keep the function of buildings, the curtain walls are needed, which resist large horizontal deformation. So, authors built a real-scale two stories test specimen (Photo 1) with four spans knockdown curtain walls in two directions, which deform to 0.0227 (rad) of story drift angle without collision between glasses and aluminum members, as a part of ordinary high-rise building (Nagae et al. (2008)). Then, a series of shaking table tests were conducted by using the world largest shaking table "E-Defense" (http://www.bosai.go.jp/hyogo/ehyogo/index.html) at Hyogo Earthquake Engineering Research Center, National Research Institute for Earth Science and Disaster Prevention, Japan. The results of the shaking table tests shows the resisting performance of the designed curtains walls for large deformation and the process of damage occurring in the process to 0.0500 (rad) of story drift angle.

Photo 1 Test specimen for shaking table test

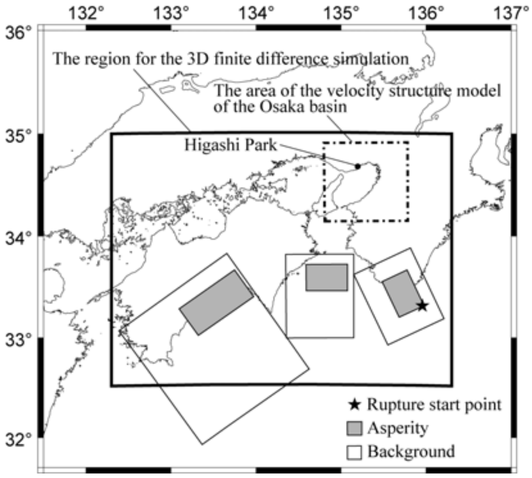


Figure 1 Hypocenter model of Future Nankai Earthquake

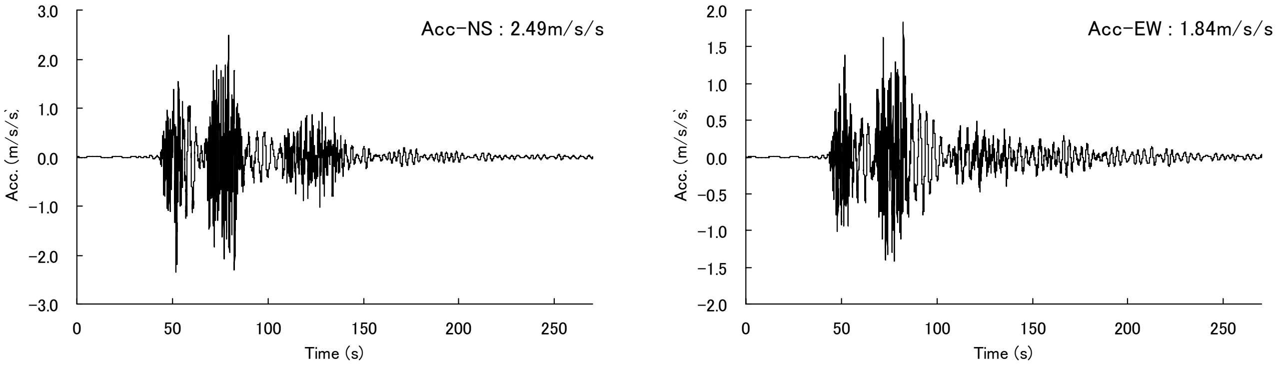
3. EARTHQUAKE GROUND MOTION

For calculation of earthquake ground motions of the Future Nankai Earthquake (Figures 1,2), hybrid techniques are used such that short period elements are calculated using Green's function, a statistical method. Long period elements are calculated using three-dimensional differential calculus, which can evaluate three-dimensional influences of the underground structure. The continued frequency of the earthquake motion calculated using Green's function and differential calculus is considered to be 2.5 s. Earthquake ground motion that occurs on the top face of an engineered foundation is calculated using the hybrid technique; amplification of earthquake motion from the engineering foundation to the foundation of the structure of assumption is calculated using an earthquake response analysis program for a one-dimensional surface based on equivalent linear method, supposing the site of Higashi-park in Kobe City.

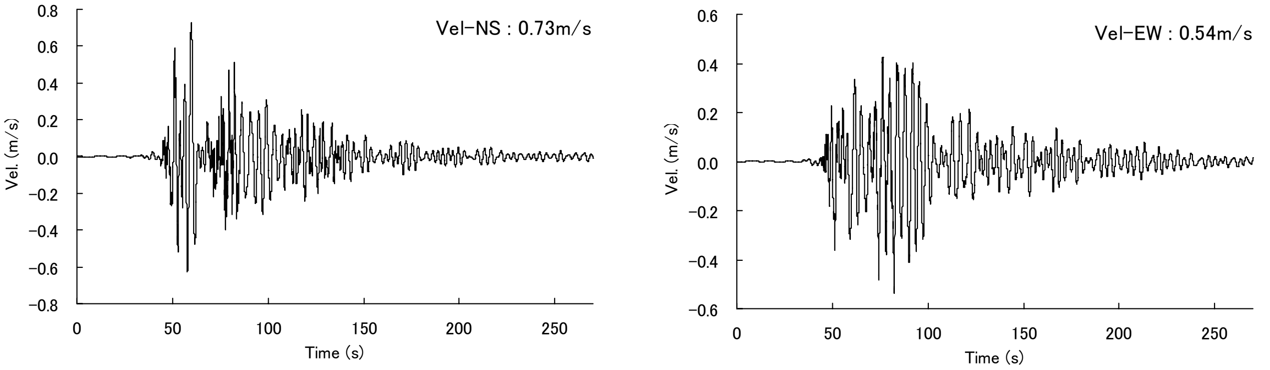
According to the observation record taken at Takatori during the Hyogoken Nanbu Earthquake (Figure 3), the dominant period is 1–2 s; the spectrum amplitude around the dominant period is about 4 (m/s). According to results of prediction at Higashi-park in Kobe City for the Nankai Earthquake scenario, the dominant period is 3–4 s; the spectrum amplitude around dominant period is about 2.5 (m/s), which reveals that both spectra are far above the El Centro, Taft, and Hachinohe spectra around the dominant period, corresponding to a level-2 earthquake ground motion (Figure 4).

It is probable that the Higashi-park wave for the Future Nankai Earthquake scenario generates a large response displacement for high-rise buildings of about 30 stories. Observation records taken at Takatori show one peak at a frequency greater than 2 (s) and one more peak at a frequency above 1 (s), which is close to the secondary natural period of high-rise buildings; the possibility of generation of a large response displacement also exists.

Therefore, these two earthquake ground motions are chosen for use as the input earthquake motion for the current shaking table experiments.

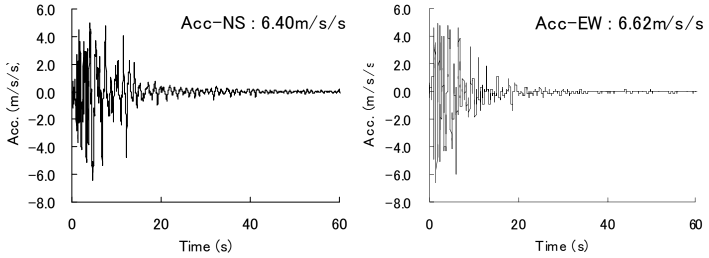


(a) Acceleration (North-South component) (b) Acceleration (East-West component)

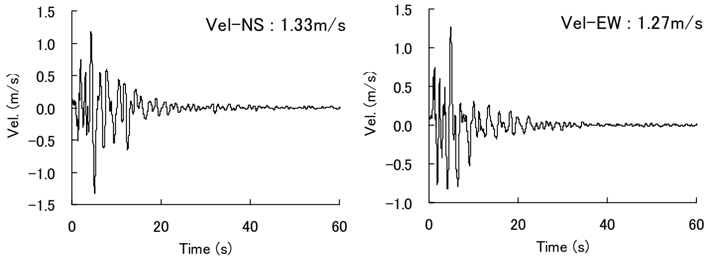


(c) Velocity (North-South component) (d) Velocity (East-West component)

Figure 2 Synthesized ground motion of the Future Nankai Earthquake



(a) Acceleration (N-S) (b) Acceleration (E-W)



(c) Velocity (N-S) (d) Velocity (E-W)

Figure 3 Observed ground motion of Hyogoken Nanbu Earthquake (1995)

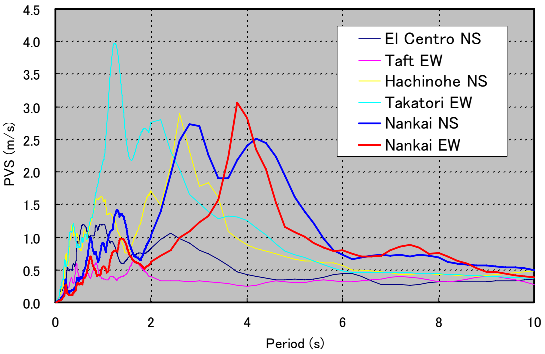


Figure 4 Pseudo velocity spectra

4. TEST RESULTS

4.1. Test schedule

The shaking table tests were conducted five times as shown below.

Case 1) Future Nankai earthquake ground motion at Higashi park in Kobe City (horizontal two directions)
Case 2) Hyogoken Nanbu earthquake ground motion at JR Takatori in Kobe City (100%, three directions)
Case 3) Hyogoken Nanbu earthquake ground motion at JR Takatori in Kobe City (108%, horizontal two directions)
Case 4) Same as Case 3)
Case 5) Same as Case 3) and case 4)

4.2. Response values

Tables 1 and 2 show the absolute acceleration of the test specimen. Table 1 shows the values in north-south (N-S) direction, and Table 2 shows the values in east-west (E-W) direction. Tables 3 and 4 show the absolute acceleration, horizontal deformation of the point of mid-height level in the curtain wall, and story drift angle. Table 3 shows the values in the north face, and Table 4 shows the values in the west face.

Table 1 Observed maximum absolute acceleration of the test specimen (N-S) direction

		Case 1	Case 2	Case 3	Case 4
Acceleration (m/s^2)	1F	4.24	2.65	3.64	4.66
	2F	4.27	2.70	7.22	4.32
	RF	4.29	4.34	4.42	4.98

Table 2 Observed maximum absolute acceleration of the test specimen (E-W) direction

		Case 1	Case 2	Case 3	Case 4
Acceleration (m/s^2)	1F	3.21	2.85	3.90	5.15
	2F	3.69	3.63	3.49	4.41
	RF	3.72	4.20	4.81	4.68

Table 3 Observed maximum absolute acceleration, relative displacement and story drift angle of curtain wall (North face)

	Direction	Case 1	Case 2	Case 3	Case 4
Acceleration (m/s^2)	in-plane	4.56	3.03	6.80	8.48
	out-plane	4.98	8.75	5.46	11.92
Displacement (mm)	in-plane	58.4	64.4	115.2	172.8
	out-plane	45.4	53.0	86.2	314.2
Story drift angle (rad)	in-plane	0.0172	0.0189	0.0339	0.0508
	out-plane	0.0134	0.0156	0.0254	0.0926

Table 3 Observed maximum absolute acceleration, relative displacement and story drift angle of curtain wall (West face)

	Direction	Case 1	Case 2	Case 3	Case 4
Acceleration (m/s^2)	in-plane	4.31	2.91	6.04	36.79
	out-plane	4.69	10.18	6.52	20.94
Displacement (mm)	in-plane	59.4	56.0	106.4	176.4
	out-plane	52.0	50.6	98.0	163.8
Story drift angle (rad)	in-plane	0.0175	0.0165	0.0313	0.0518
	out-plane	0.0153	0.0149	0.0288	0.0481

4.3. Damage of curtain wall

Damage of curtain wall is shown in Figures 5-7 and Tables 5-7. Figure 5 and table 5 show damage in test of Case 1 and Case 2. Figure 6 and table 6 show damage in test of Case 3, Case 4 and Case 5. Figure 7 and table 7 show damage observed by investigation after dismantle the glasses from aluminum members after all tests. Figures 5-7 show the place of the damage occurred, and Table 5-7 show the contents of the damage.

Case 1) Although small, a slippage was generated in the lowermost fastener for both the north and the west face (Photo 2 (a)). No deformation was observed around glass.
Case 2) Washer slippage (Photo 2 (b)) was observed at the lowest part of the north face. Separation of a sealing member (Photo 2 (c)) was noted at the lowest part of the west face. Residual deformation was not observed around glass, as in case 1.

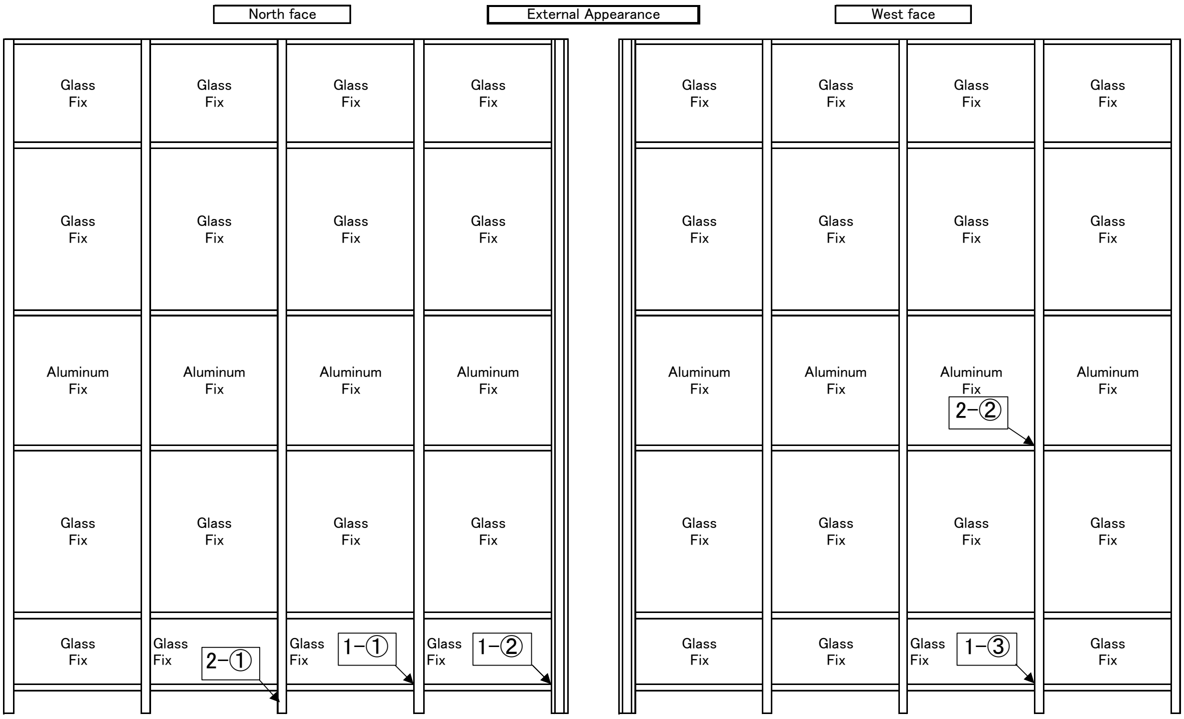


Figure 5 Place of damage of curtain wall in the test of Case1) and Case 2)

Table 5 Damage of curtain wall in the test of Case1) and Case 2)

Place	Damage
Case 1−①, 1−②, 1−③	Fastener slippage
Case 2−①	Washer slippage
Case 2−②	Separation of a sealing member

(a) Fastener slippage (b) Washer slippage (c) Separation of a sealing member

Photo 2 Damage of curtain wall in Case 1) and Case 2)

Case 3: Washer slippage was observed at the lowest part of the north face, and washer slippage, bead slippage, mullion slippage and bracket slippage (Photo 3(a)) were observed at the lowest part of the west face. Furthermore, at the end of center part of the west face, disengagement of a machine screw from the blind box (Photo 3(b)), and drops of machine screws of the fanlight receiver bracket were noticed in a couple of places.

Case 4) and 5) Bracket slippage was observed at the lowest part of the north face. Bead slippage (Photo 4 (a)) was observed at one location. Bracket slippage was also apparent at the lowest part of the west face, and bead disengagement was observed. Residual deformation was apparent around glass (Photo 4(c)), and rise up of height adjust bolt (about 1.5 mm) was observed at the south end center area (Photo 4(b)).

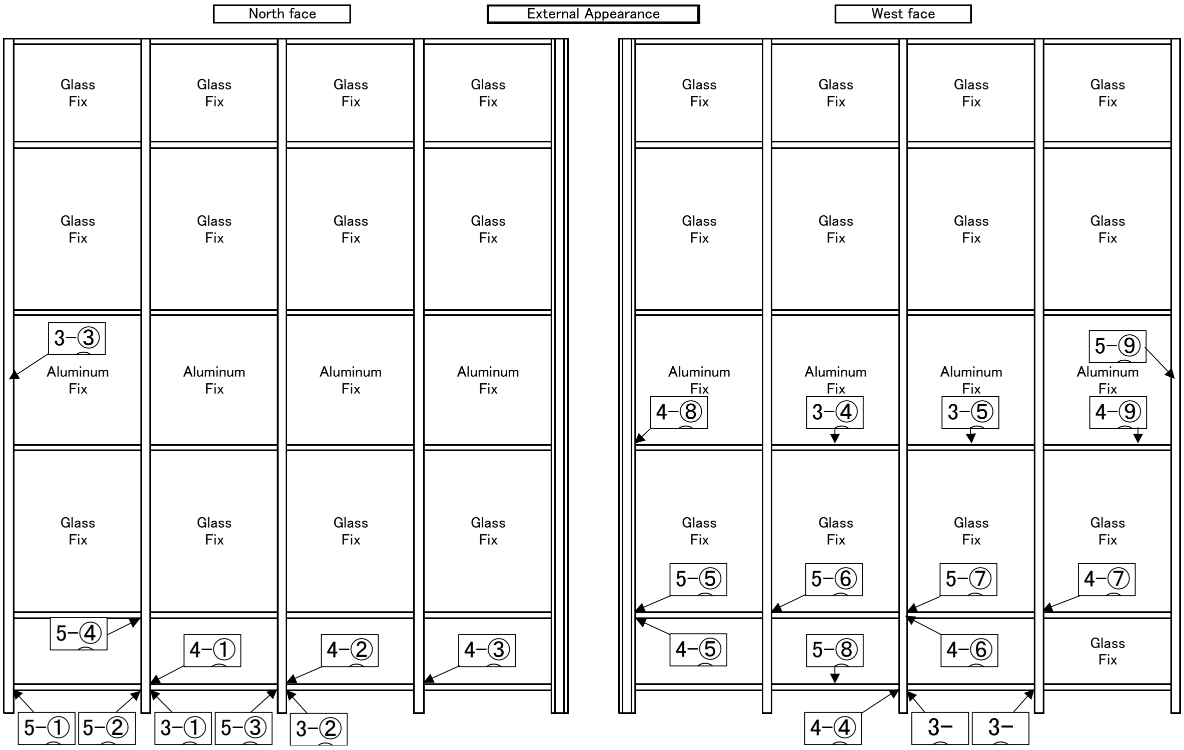


Figure 6 Place of damage of curtain wall in the test of Case3) Case 4) and Case 5)

Table 6 Damage of curtain wall in the test of Case3) Case 4) and Case 5)

Place	Damage
Case 3-①	Washer slippage, Horizontal gap of fastener bracket
Case 3-②, 3-⑦	Washer slippage
Case 3-③	Rise up of height adjust bolt
Case 3-③, 3-④	Disengagement of a machine screw at the blind box
Case 3-⑥	Rotation of fastener bracket
Case 4-①, 4-②, 4-③, 4-④	Washer slippage
Case 4-⑤, 4-⑥	Bead slippage
Case 4-⑦	Slippage of mullion component, bracket slippage
Case 4-⑧, 4-⑨	Disengagement of a machine screw at the blind box
Case 5-①, 5-②, 5-③	Bracket slippage
Case 5-④	Slippage of glazing bead
Case 5-⑤, 5-⑥, 5-⑦	Disengagement of glazing bead
Case 5-⑧	Bracket slippage
Case 5-⑨	Rise up of height adjust bolt (about 1.5 mm)

By investigation after dismantle of Glasses from aluminum members after test, some defects at glass corner (Photo 5 (a)), some dent at glass pocket of transom (Photo 5 (b)) and defect at glass corner (Photo 5(c)) were observed.

CONCLUSIONS

In the present tests, damage of CW of standard knockdown construction that occurred during large deformation (maximum story drift angle: 0.0508) was observed. The destructive damage did not occurred, because the curtain wall had a sufficient performance for large deformation, However, partial damage was observed in each case. Furthermore, acceleration on the curtain wall was recorded.

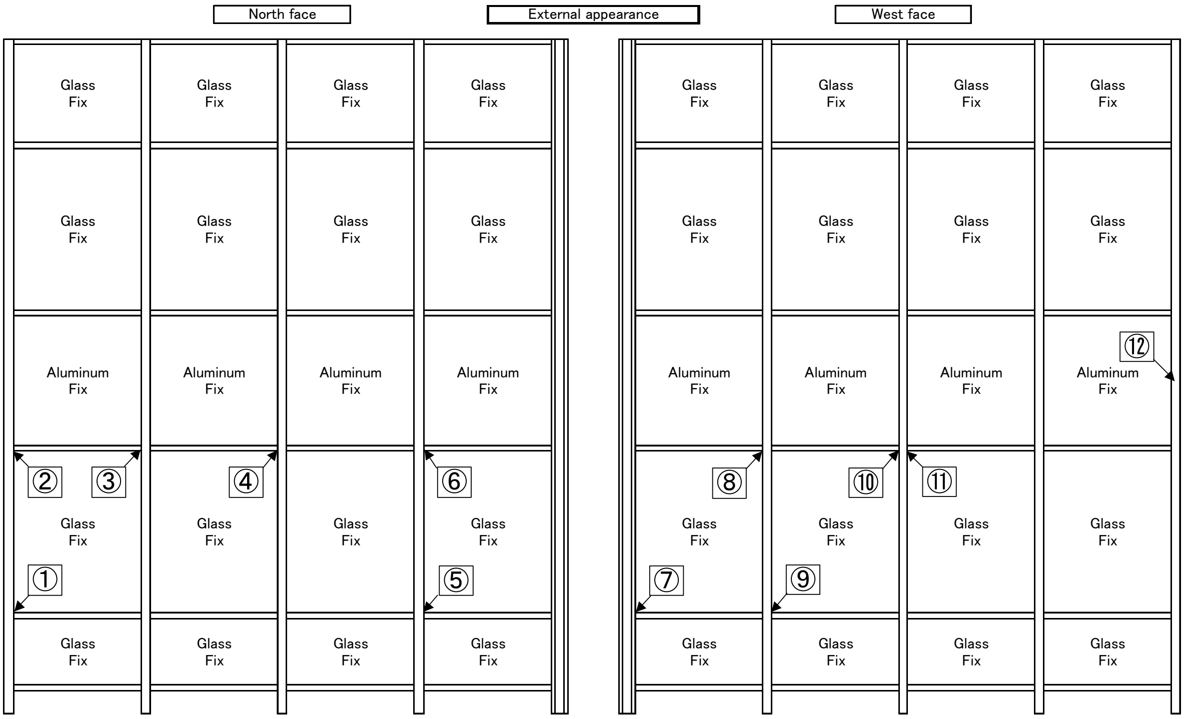


Figure 7 Place of damage observed by investigation after dismantle of Glasses after test

Table 7 Damage of curtain wall observed by investigation after dismantle of Glasses after test

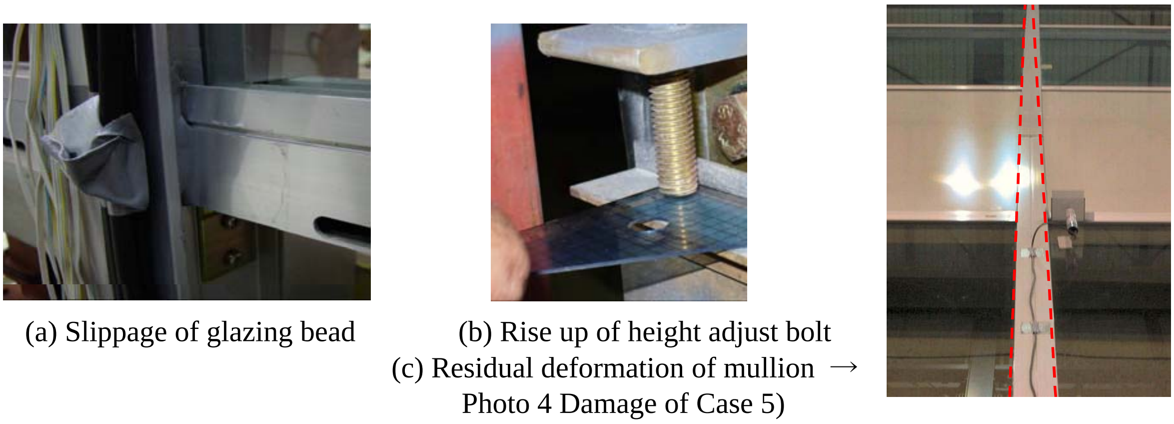
Place	Damage
①	Dent closing plate at transom end
②	Dent at glass pocket of transom
③	Some defect at glass corner and dent at glass pocket of transom
④	Rise up of transom (residual displacement with 3mm) no dent, nor damage
⑤	Some defects observed at glass corner
⑥	Some defects at glass corner and slight dent at glass pocket of mullion
⑦	Unable to take off glazing bead due to deformation of mullion component
⑧	Some defect at glass corner and slight dent at glass pocket of mullion
⑨	Damage at pre-sealant at transom edge (no adhesion to substance)
⑩	Some defect (crack) at glass corner and dent at glass of transom
⑪	Slight defect at glass pocket of transom
⑫	Rise up of height adjust bolt(residual displacement with 2mm)

(a) Rotation of fastener bracket (b) Disengagement of a screw at the blind box

Photo 3 Damage of Case 3)

(a) Bead slippage (b) Disengagement of height adjust bolt of transom

Photo 4 Damage of Case 4)



(a) Slippage of glazing bead (b) Rise up of height adjust bolt

(c) Residual deformation of mullion →

Photo 4 Damage of Case 5)

(a) Some defects at glass corner (b) Dent at glass pocket of transom (c) Defect at glass corner

Photo 5 Damage observed after dismantle of glasses

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