DAMAGE TO NON-STRUCTURAL COMPONENTS IN A LARGE ROOF BUILDING DURING THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE AND ITS AFTERSHOCKS AND RECOVERY OF CEILING USING MEMBRANE MATERIALS

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ABSTRACT: This paper reports damage to non-structural components in the "National Museum of Emerging Science and Innovation (Miraikan)," Tokyo, Japan during the "2011 off the Pacific Coast of Tohoku Earthquake" and its aftershocks. While damage to the building skeleton was not observed, an entrance hall and a 6-strory hall suffered damage to non-structural components. During the earthquakes, no one was harmed because of adequate evacuation guidance. After the disaster, based on thought not to repeat similar failures by future possible earthquakes, the ceiling at the entrance hall was renovated from suspended panels with conventional method of construction to membrane materials. This paper reports investigation results of the damage and outline of the recovery.

***Key Words**: Large roof building, Non-structural component, Ceiling, Earthquake, Membrane, Recovery*

INTRODUCTION

Due to the "2011 off the Pacific Coast of Tohoku Earthquake" on March 11, 2011 and its aftershocks (Japan Meteorological Agency 2011), falling of non-structural components such as ceilings and lightings in large roof buildings has occurred in the Kanto region as well as the northeastern region in Japan. Miraikan which is located in a landfill of Tokyo is one of such buildings. As for Miraikan, while damage to the building skeleton was not observed, an entrance hall and a 6-strory hall called "Symbol Zone" suffered damage to non-structural components. An external view and a plan view of Miraikan are shown in **Figures 1** and **2**, and summary of the building is shown in **Table 1**, respectively. During the earthquakes, no one was harmed because of adequate evacuation guidance. After the disaster, based on thought not to repeat similar failures by future possible earthquakes, the ceiling at the entrance hall was renovated from panels with conventional method of construction to membrane materials. This paper reports investigation results of the damage and outline of the recovery.

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Figure 1. External view of Miraikan

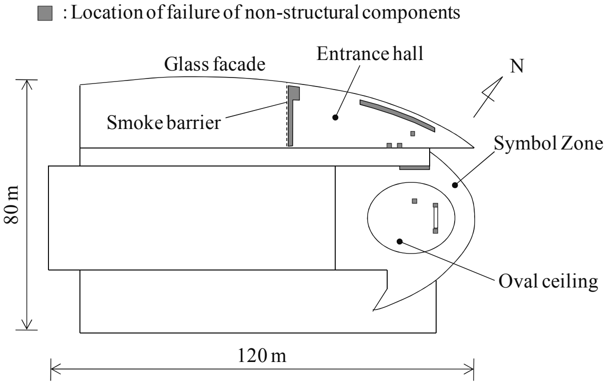


Figure 2. Plan view of Miraikan

Table 1. Summary of Miraikan

Location	Landfill in Koto-ku, Tokyo
Building structure	Steel (partially RC) with dampers 8 ground, 1 underground, and 1 penthouse stories Total floor space of approximately 40,600 m^2
Completion year	March 2001

(a) Ceiling

(b) Ceiling and hanging art objects

Figure 3. Internal view of the entrance hall before the disaster

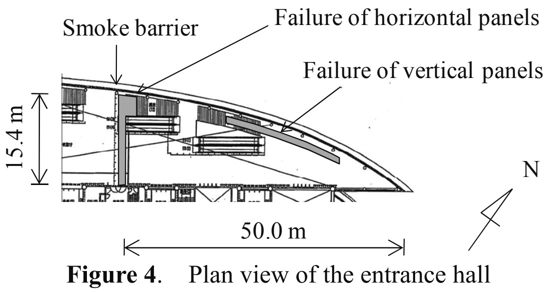


Figure 4. Plan view of the entrance hall

CEILING DAMAGE AT THE ENTRANCE HALL

Overview of the ceiling and its damage

An internal view of the entrance hall before the disaster and its plan view are shown in **Figures 3** and **4**. The hall is an open space of seven stories with a partially cylindrical glass facade, and the maximum height to the ceiling from the ground floor is 25.6 m. A smoke barrier of 15.6-m height across the ceiling splits the ceiling into eastern and western parts. The ceiling is constructed by a conventional method with metallic furring bars, clips, and runners. The ceiling panel is a set of a 9.5-mm-thick plaster board as a base layer and a 9.5-mm-thick rock-wool board as a finishing layer. The ceiling is uneven in the vicinity of the facade (**Figure 5**). The vertical panel is a set of two 9.5-mm-thick plaster boards. One hundred and seven art objects (weight: 100 to 200 N) were hanging from the ceiling.

As shown in **Figure 6**, panels of the eastern ceiling failed and fell off with furring bars in a long and thin area next to the smoke barrier. Glass panels of the smoke barrier also broke. And about 30 vertical panels (approximately 0.8 m by 0.9 m) in the vicinity of the facade failed with furring bars in several regions along 25-m length (**Figure 7**). Several small parts of the ceiling next to walls also failed. Two hardened glass panels of the facade broken. One of the hanging art objects also fell off.

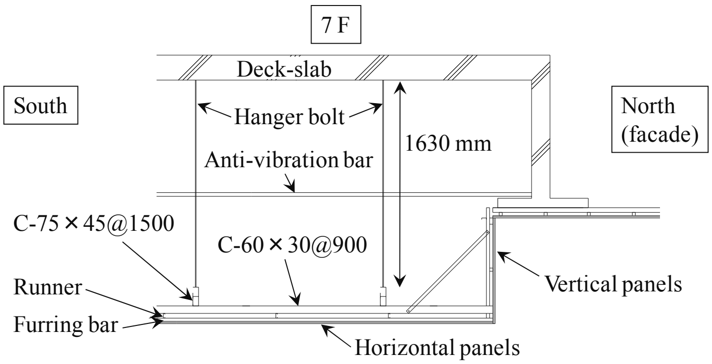


Figure 5. Cross section of the eastern ceiling at the entrance hall

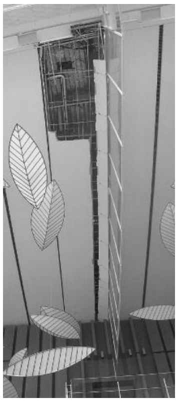


Figure 6. Failure of horizontal ceiling panels next to the smoke barrier at the entrance hall

Figure 7. Internal view of the entrance hall after the disaster

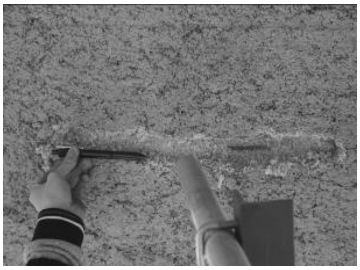
Observation of the ceiling space

The ceiling system is hanging from the floor of the 7th story through heavy frame structure as shown in **Figure 8(a)**. The frame is composed of hanger bolts of 1630-mm length and 1500-mm pitch whose one edge is inserted into the deck-slab of the floor, upper runners (C-75×45), and orthogonally intersecting lower runners (C-60×30). The frame is used to support catwalk and hanging art objects. The ceiling panels are hanging of 5-cm hanging length from the frame.

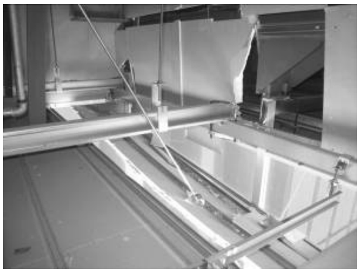
Although horizontal anti-vibration bars and braces (C-60×30) had been placed among hanger bolts, they failed or dislocated due to buckling deformation of the members or fracture of their clasps. As shown in **Figure 8(b)**, a print on fire resistive covering of a steel beam scraped by the handrail was observed, which indicated that, during the earthquake, relative displacement in vibration amplitude between the building skeleton and the ceiling is over 20 cm in east-west direction. Because the duration of the main shock was so long, the circumstances can be estimated that many braces failed during the early part of the earthquake, inducing subsequent large horizontal motion of the ceiling.

The reason for the failure of the panels next to the smoke barrier (**Figure 8(c)**) can be considered that collision between the barrier and panels due to motions in east-west direction. And the reason for the failure of the vertical panels in the vicinity of the facade (**Figure 8(d)**) can be considered that furring bars deformed and clips were dislocated during motions of lower panels pushing lower edges of the vertical panels.

(a) Ceiling system



(b) Print on fire resistive covering



(c) Failure of the panels next to the smoke barrier

(d) Failure of the vertical panels in the vicinity of the facade

Figure 8. Ceiling space at the entrance hall

SYMBOL ZONE

Symbol Zone (**Figure 9**) is a 6-story hall located in the middle and eastern area of the building. On the east side of the hall, there was a partially inverted-conical glass wall. A spiral ramp is surrounding inside the hall. An Earth-like object called "Geo-cosmos" of approximately 6-m diameter and 130-kN weight is hanging from a steel beam of 7-m hanging length at the center of the hall. Above Geo-cosmos, a convex oval ceiling of 35-m long and 26-m short spans is hanging from the deck-slab of 2.8-m hanging length. The height of the ceiling from the ground floor is 24 m. The ceiling panel is a set of two 23.5-mm-thick plaster boards. On northern and southern walls, finishing metal plates are arranged.

As shown in **Figure 10(a)**, panels of the oval ceiling around the hanging cable of Geo-cosmos had failed. Because hanging lengths of the ceiling and Geo-cosmos are different, the reason is estimated that two of them were oscillating at different phases during the earthquake.

Above the oval ceiling and just below the catwalk, punching metal panels (1.3 m × 0.8 m, 40-N weight) were used to blind the catwalk, and 29 panels had fallen off to the oval ceiling and the ramp (**Figure 10(b)**). Furthermore, at around the height of the 6th story, finishing metal plates deformed and about to be dislocated (**Figure 10(c)**).

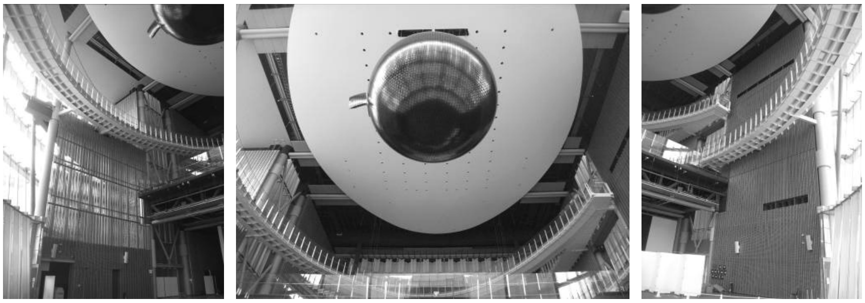
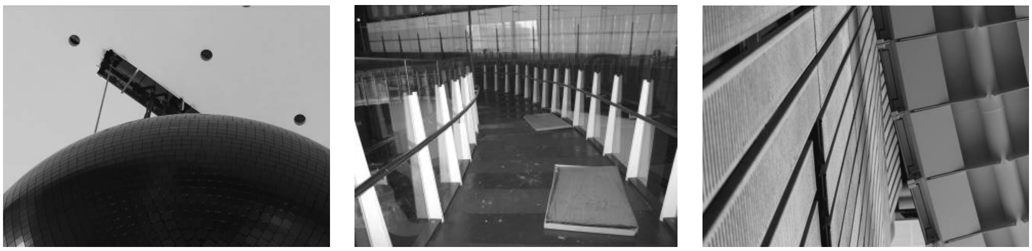


Figure 9. Internal view of Symbol Zone



(a) Failure of ceiling panel (b) Fallen punching metal panels (c) Deformed finishing metal plates

Figure 10. Damage to non-structural components at Symbol Zone

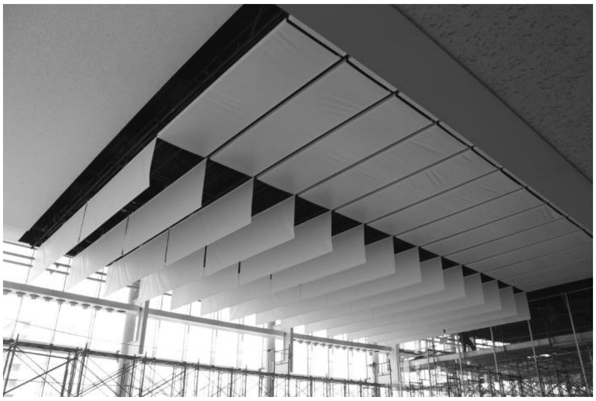


Figure 11. Recovery of the eastern ceiling at the entrance hall by membrane materials

RECOVERY BY MEMBRANE MATERLAS AT THE ENTRANCE HALL

As Miraikan considered becoming a good model to realize safety and reassuring of ceiling system, the recovery was planned with the authors. As a result, at the eastern part of the ceiling at the entrance hall (approximately 500 m^2), all the panels with conventional method of construction were removed and recovered by membrane sheets. The duration of the recovery including the design was about 2.5 month. The thickness of the sheet is 0.28 mm, and the material is glass woven fabric coated with vinyl chloride on both sides. As shown in **Figure 11**, the sheets were directly attached to the hanging frame structure in two ways, horizontally and vertically.

CONCLUSIONS

With increasing aseismic performance of building skeletons, damage to non-structural components such as interior finishing is becoming to stand out. During the "2011 off the Pacific Coast of Tohoku Earthquake" and its aftershocks, failures of ceilings occurred in many buildings. However, it should be noticed that aseismic reinforcement of ceiling is not an essential solution. A direct factor of ceiling panels' falling is not seismic force but gravity. As opposed to structural members of building skeletons, non-structural components can save self-weight by selecting proper materials, drastically reducing the seismic force. The authors hope that the renovation of the ceiling at Miraikan becomes a good example.

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