PRELIMINARY STUDY OF OBSERVED RESPONSE OF SUSPENDED CEILING DURING AFTERSHOCKS IN A LARGE ROOF BUILDING

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ABSTRACT: This paper reports results of dynamic characteristics of damaged suspended ceiling in the "National Museum of Emerging Science and Innovation (Miraikan)," Tokyo, Japan, by using observed motion data during aftershocks of the "2011 off the Pacific Coast of Tohoku Earthquake." Analyses of horizontal motion data for the ceiling, the building structure, and the ground next to Miraikan recorded during aftershocks showed that the natural frequency of the ceiling was lower than that of the building structure. However, the structural characteristics of the building strongly affected the ceiling's response.

***Key Words**: Large roof building, Non-structural component, Ceiling, Earthquake, Vibration, Observation*

INTRODUCTION

Due to the "2011 off the Pacific Coast of Tohoku Earthquake" on March 11, 2011 and its aftershocks (Japan Meteorological Agency 2011), the "National Museum of Emerging Science and Innovation (Miraikan)" built on a landfill of Tokyo, Japan suffered damage to non-structural components such as falling of ceiling panels. Because aftershocks were occurring a number of times during the investigation of damage on March 22 as reported in (Kawaguchi et al. 2012), we observed the ceiling motion during aftershocks, using five tri-axial accelerometer for about two weeks from March 24. This paper reports analyzed results of ceiling response against its building structure and ground motion.

OBSERVATION METHOD

Overview of the investigated ceiling

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. Because the plan is asymmetric and open spaces exist in Miraikan, it is estimated that the response of the building structure against ground motions might be

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Figure 1. External view of Miraikan

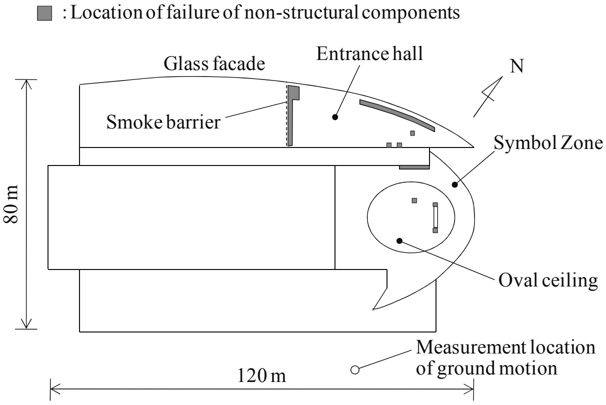


Figure 2. Plan view of Miraikan

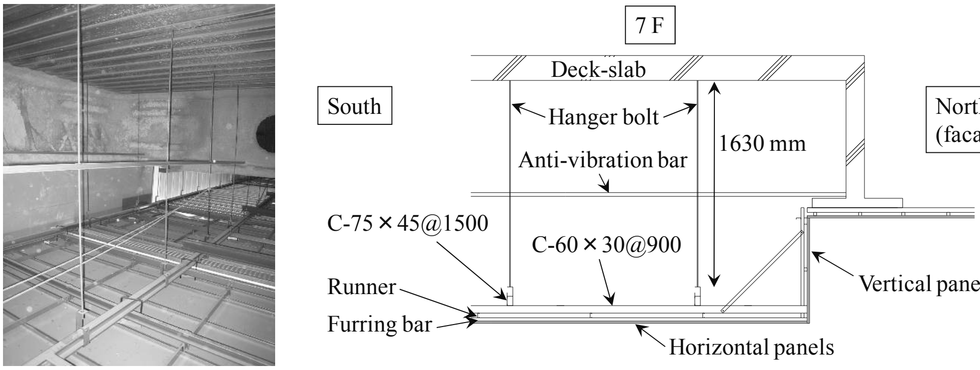
Table 1. Summary of Miraikan

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

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

complex as well as the ceiling response.

The observed ceiling is located at an entrance hall (**Figure 3**). 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. The observed ceiling is eastern one which is split by a smoke barrier. Its area is about 500 m^2. It is hanging from the floor of the 7th story through heavy frame structure as shown in **Figure 4**. 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. 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.



(a) Ceiling space (b) Cross section

Figure 4. Eastern ceiling at the entrance hall

Table 2. Specifications of tri-axial capacitive accelerometer (Colibrys/SF3000L)

Item	Specification
Size	75 mm×80 mm×57 mm
Mass	500 g
Output range	±3 G
Sensitivity	1.2 V/G
Frequency response	DC to 1000 Hz
Dynamic range	120 dB (100 Hz BW)
Noize	300 to 500 nGrms/Hz$^{0.5}$ (10 to 1000 Hz)

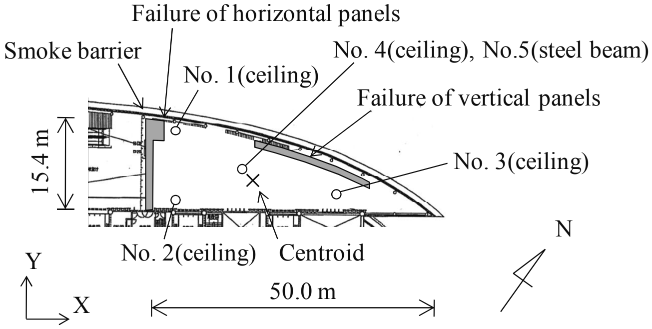


Figure 5. Location of accelerometers at the entrance hall

The ceiling suffered damage during the main shock and following aftershocks. Details of the damage and its recovery are described in (Kawaguchi et al. 2012).

The recovery of the ceiling began soon after the disaster. In the recovery, all the hanging art objects and all the panels with furring bars and runners were removed, but the frame structure remained onto which many new braces were placed among hanger bolts. The ceiling was renovated to membrane materials conclusively. However, the ceiling during the observation was a particular condition: no hanging art objects, no preexisting braces, no vertical panels shown in **Figure 4**, and no obstacles to be collided around the ceiling. In this study, the ceiling panels with the frame structure are regarded as a whole suspended ceiling. Therefore, the weight of the suspended ceiling is 294 N/m^2, which is two to three times of the conventional ceiling.

Measurement system

We used wireless measurement system with capacitive tri-axial accelerometers (**Table 2**). As illustrated in **Figure 5**, four accelerometers (No. 1 to 4) were put on the upper side of the ceiling, and one accelerometer (No. 5) was put on a steel beam (H-1200×300) of the building structure just above the No. 4 point.

The accelerometers directly measure absolute acceleration in the inertial space. In this report, motion data concerning the vibration source of the ceiling, namely data at the No. 5 point, are absolute ones. On the other hand, motion data concerning the ceiling, namely data at the No. 1 to 4 points, are relative ones against the No. 5 point; the absolute acceleration at the No. 5 point is subtracted from the absolute acceleration at each point.

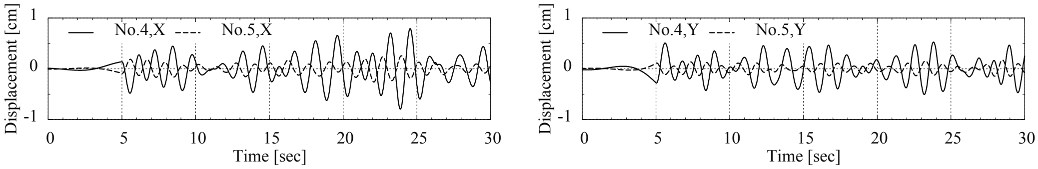
VIBRATION CHARACTERISTICS

Ceiling response against motion of the building structure

During about two weeks, we could observe the behavior during aftershocks several times. The analyzed characteristics will be explained by using representative data recorded during an aftershock at around 7:25 on March 28, 2011. The aftershock occurred in the coast of Miyagi prefecture (38.4° N, 142.3° E, focal depth 31 km), and its magnitude is 6.5 on the Japan Meteorological Agency scale. In this report, only horizontal translational motion will be discussed.

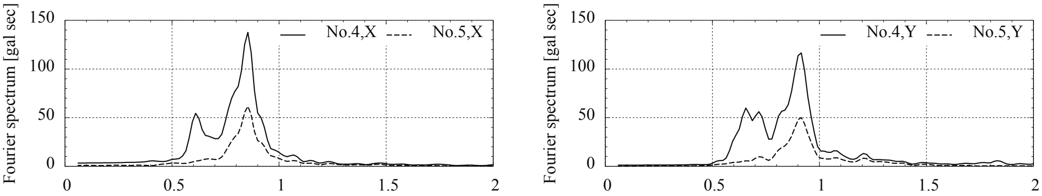
Time history of displacement of the building structure (No. 5) and the ceiling (No. 4) is illustrated in **Figure 6**. The data are numerically processed and integrated from originally recorded ones. Directions X and Y are defined in **Figure 5**. From **Figure 6**, it is observed that the motion of the ceiling is magnified in its vibration amplitude, transmitted through the steel beam from which the ceiling is hanging.

As for acceleration Fourier spectrum (**Figure 7**), the predominant frequencies of the building structure and the ceiling are nearly identical as 0.82 to 0.85 Hz in the X-direction and 0.90 to 0.93 Hz in the Y-direction. However, as for the amplification ratio of the ceiling to the building structure (**Figure 8**), the predominant frequencies are 0.61 to 0.66 Hz, which are lower than those of the acceleration Fourier spectrum. In this study, the lower predominant frequencies should be regarded as the 1st natural frequencies of the suspended ceiling in the X and Y directions. The amplification ratio at around the ceiling's natural frequency is 4.0 to 11.1. Although the ratio decreases with distance from the natural frequency, it is 1.7 to 3.2 at around the predominant frequency of the building structure. The reason can be considered that the ceiling is heavy.



(a) X-direction (b) Y-direction

Figure 6. Time history of displacement of the building structure (No. 5) and the ceiling (No. 4)



(a) X-direction (b) Y-direction

Figure 7. Acceleration Fourier spectrum of the building structure (No. 5) and the ceiling (No. 4)

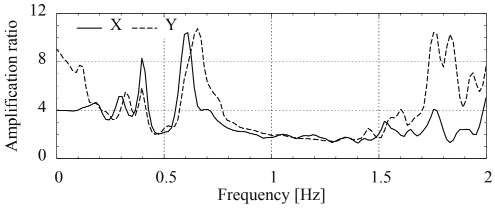


Figure 8. Amplification ratio of the ceiling (No. 4) to the building structure (No. 5) in acceleration Fourier spectrum

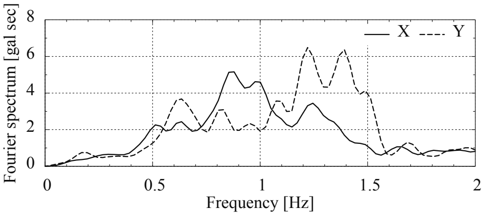
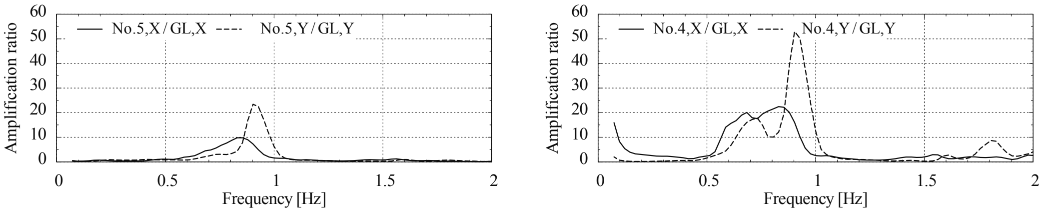


Figure 9. Acceleration Fourier spectrum of the ground in the vicinity of Miraikan



(a) Building structure (No. 5)

(b) Ceiling (No. 4)

Figure 10. Amplification ratio of acceleration Fourier spectrum against the ground

Ceiling response against ground motion

By using observed ground motion, it is examined how earthquakes are transmitted to the ceiling through the building structure. The used ground motion data is recorded at surface on which a building of the National Institute of Advanced Industrial Science and Technology is standing next to Miraikan (**Figure 2**). The original ground motion data is numerically processed including transformation of horizontal directions. Furthermore, because the ground motion data were recorded by another measurement system, the time synchronization is performed by inspection.

Acceleration Fourier spectrum of the ground motion is illustrated in **Figure 9**. Several peaks can be observed, but the spectrum is distributed in a wide frequency range. The predominant frequencies of the amplification ratio of the building structure to the ground (**Figure 10(a)**) are nearly identical to the ones of acceleration Fourier spectrum of the building structure (**Figure 7**), which indicates the resonance of the building structure at its natural frequency. On the other hand, the amplification ratio of the ceiling to the ground (**Figure 10(b)**) also shows predominant frequencies at the building structure's natural frequency, while small peaks can be observed at the ceiling's natural frequency. Therefore, it can be concluded that the structural characteristics of the building strongly affected the ceiling's response.

CONCLUSIONS

Generally, with the increase of suspended ceiling's weight, the exciting force becomes large. This may cause large response of the ceiling during earthquakes, even if the ceiling's natural frequency is not close to the one of the building structure. Suspended ceilings in large roof buildings should be designed carefully, with the consideration of usage of light-weight materials such as a membrane.

ACKNOWLEDGMENT

We are grateful to the staff of Miraikan for kind cooperation. The part of this research is supported by grant from the Ministry of Land, Infrastructure, Transport and Tourism. Furthermore, we are grateful to the Active Fault and Earthquake Research Center, the National Institute of Advanced Industrial Science and Technology for offering strong-motion data.

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