FAILURE OF CEILINGS IN AN AIRPORT BUILDING DURING THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE AND ESTIMATION OF ITS IMPACT

Yasushi OBA[1], Yosuke NAKASO[2] and Ken'ichi KAWAGUCHI[3]

ABSTRACT: This is an investigation report on the failure of ceilings at the entrance hall of an airport building with well space during the "2011 off the Pacific Coast of Tohoku Earthquake". Although nobody was injured by the accident, the height of the ceilings was so high that the estimation of the extent of possible damage to human body is worth to understand the risk of such failure. The impact estimation was carried out by using a broadcasting video record taken accidentally during the earthquake and the results of ceiling dropping test to a dummy head.

***Key Words**: the 2011 off the Pacific Coast of Tohoku Earthquake, Suspended ceiling, Impact estimation*

INTRODUCTION

This is an investigation report on the failure of ceilings at entrance hall with well space of an airport building during the "2011 off the Pacific Coast of Tohoku Earthquake". Luckily, nobody was injured by the accident, however the height of the ceilings was so high and it is worth to estimate impact of the failure and possible danger to human body for better understanding of the risk of such failure. The impact estimation was carried out by reference to the news video taken during the accident and by comparing to the experimental results of dummy head test. The building has restored its function in a short period, ensuring the safety after the inspection and removal of the ceiling.

INVESTIGATION REPORT

Overview of damage

Details of the building and its damage, the building's site plan, and acceleration observed 12 km away from the airport are shown respectively in **Tables 1** and **2** and **Figures 1** and **2**. The seismic intensity of 6-Lower on the JMA scale was observed near the location. This report focuses on failure of ceilings in large well space (area: 25.8 × 11.2 m, ceiling height: 8.3 m) served as an entrance hall and a lobby. At the well space, ceilings were separated into five rows among which lightings are located. The northernmost row (11.2 m × 3.0 m) fell in whole during the main shock. (**Figures 3** to **6**)

[1] Predoctoral fellow, Institute of Industrial Science, The University of Tokyo
[2] Graduate student, Department of Architecture, The University of Tokyo
[3] Professor, Institute of Industrial Science, The University of Tokyo

Table 1. Details of building

Structure	Steel
Scale	2 stories (partially 3 stories) Long side 120 m (north to south), Short side 42 m Total floor area 7,800 m^2
Open	March 11, 2010 (1st anniversary)

Table 2. Details of damage to ceilings

Space	Details of damage
Lobby at the 1st fl.	Failure of ceilings (Figure 5, row①) Failure of ceilings at stepped part (Figure 5, row①~⑤) Deformation of ceilings like hanging (Figure 5, row③)
Gallery at the 2nd fl.	Failure of indirect lightings and ceilings over 11 m long
Shop at the 2nd fl.	Hanging of duct vents

Table 3. Details of fallen ceiling

Ceiling furrings	Light gage steel furring (details in text)
Ceiling panels	Plaster board (underlayer) of 9.5 mm thick + Decorated acoustic rock wool board of 15 mm thick
Ceiling height / Suspension length	8.3 m / 1.6 m

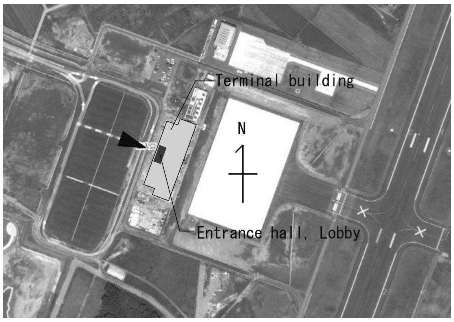

Figure 1. Site plan of airport

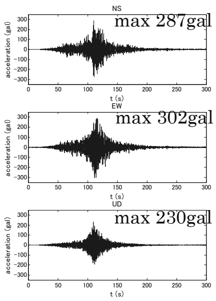

Figure 2. Observed acceleration

Figure 3. Internal view of lobby

Figure 4. Failure of ceiling

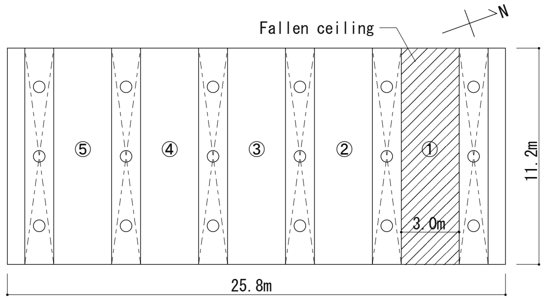

Figure 5. Reflected ceiling plan of lobby

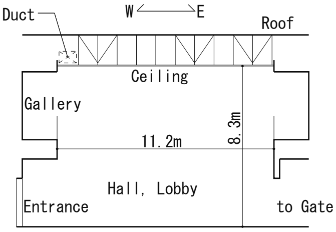

Figure 6. Section of lobby

Details of fallen ceiling （reference to Table 3）

As illustrated in **Figures 7** and **9**, a gap was observed between arrangement of ceiling and one of inserts on roof side and the ceiling was put to one side against arrangement of hanger bolts along the direction of ceiling width (there was no hanger bolt around the bottom of ceiling plan in **Figure 7**). Therefore, there was no hanger bolt to hang panels and furrings on the southern part of the ceiling and they cantilevered. Channels and hanger braces seemed to be reinforcement for that was set only at the southern part of the ceiling (right side in **Figure 9**). These hanger braces was set at each ceiling runners but they had little effect to reduce horizontal motion of the ceiling because of absence of hangar bolt at the end. Braces, which composed triangles with hanger braces, was set only at three points. The arrangement of hanger bolts along the longitudinal direction was uniform, except in west end with air conditioning ducts, but three pairs of braces was set to southern side (braces seen in **Figure 8** was set only at most southern row of hanger bolts in **Figure 7**). Upper ends of braces was fastened to hanger bolts around their roots with metal fittings, on the other hand, lower ends was fastened to furrings and hanger bolts mainly by spot welding (it seemed). Longitudinal end of the ceiling butted against stepped parts of surrounding ceiling without clearance. Finishing panels at the parts also fell off by collision.

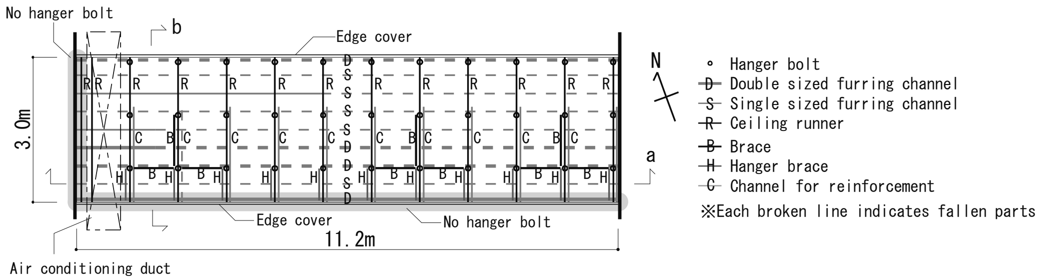

Figure 7. Reflected plan of fallen ceiling

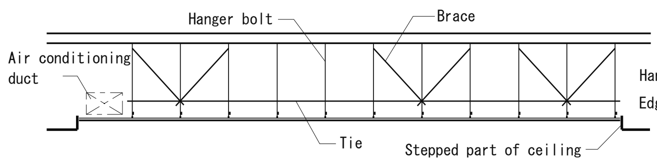

Figure 8. Longitudinal section of ceiling (b-b)

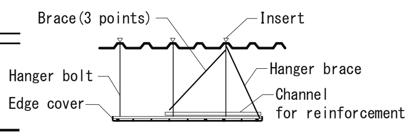

Figure 9. Lateral section of ceiling (a-a)

Discussion on cause of the failure

Almost all furring channel (**Figure 7**) and many deformed clips fell (**Figure 10**), therefore, it is suggested that direct cause of the failure was coming off of clips. First, there was strong possibility that eccentricity caused by the arrangement of braces mentioned above caused larger deformation on northern side of the ceiling than on the other parts. Actually large deformation was found only at northern edge cover, which was set at both of southern and northern longitudinal edges, at contact point with stepped ceiling (**Figure 11**). All ceiling runners were fastened to the edge covers in southern and northern edges with fitting members like pin. Therefore, it seems that assembly of the edge covers and the ceiling runners as a whole could move like parallel crank and the degree of freedom of the motion was constrained by ceiling panels through clips and screws. For that reason it is suggested that large force caused by the eccentricity acted on the clips. On the day, a TV interview for NHK (Japan Broadcasting Corporation) about the airport's first anniversary was assigned. The camera crew happened to video during the failure of ceiling on TV camera, and the video was broadcasted as news. It is confirmed that the failure began at northeastern corner of the ceiling in the video and it corresponded with the phenomena as discussed above (**Figure 12**).

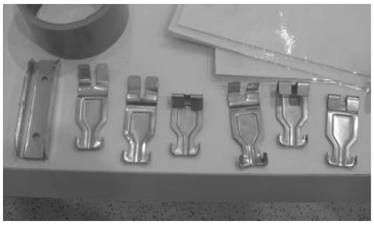

Figure 10. Fallen clips

Figure 11. Deformation at northeastern corner

Figure 12. Ceiling just before failure (from NHK TV news)

Estimation of impact of failure

The accident occurred at highly public and important building such as airport terminal. Furthermore, although similar accidents had been reported, in Kushiro airport for example, the experiences had not been used effectively. Therefore, there are many points to be inspected seriously. These points considered, in this report we estimate influence on human bodies that impact of the failure of the ceiling might have for understanding of the risk of the accident.

Method of estimation
We estimate falling velocity of the ceiling from TV news video mentioned above and comparing it to test result of falling velocity just before impact of similar material in **Ref. 3** we estimate impact and degree of injury in case that a man stands just under ceiling and is hit directly by it.

Estimation of falling velocity from video
First, for preparation to make the estimation we discuss precision of falling velocity estimated from video by reference to results of former tests. In **Refs. 1~3**, ceilings of various materials were dropped onto dummy head in free fall from a height of 1~20m in the range and the impacts were measured in its moment. In the test that underlayered ceiling with furring channels was dropped from a height of 8 m we compare velocity measured by speed gun with one estimated from video.

Figure 13. Video of test (dt=0.034sec)

Table 4. Velocity measured by speed gun in test

Height from GL [m]	Falling velocity [m/s]
1.34	9.16
1.26	9.24
1.16	9.10
1.07	9.30
0.98	9.10

Falling velocity estimated from video

We attempt to estimate falling velocity from video of the test. It is estimated about 10m/s in **Figure 13**.

$0.35 / 0.034 \approx 10$ [m/s]

Falling velocity measured by speed gun

The estimation above is made at 0.95 m~1.35 m height from GL. Velocity measured by speed gun at the height is about 9 m/s (**Table 4**).

Therefore, in the case of fall from the height of 8m it is suggested that the falling velocity can be estimated with error of about a tenth.

Differences between the accident and the test

Conditions are different between the actual accident and the test in **Ref. 3**. The most different condition is the size of ceiling at its fall. In the accident suspended ceiling the size of 11.2 m×3.0 m fell almost together (total weight of the ceiling with furring channels was about 4.0 kN). On the other hand, in the test boards about the size of one sheet on the market (mainly 910 mm square) were dropped with their bodies horizontally. However, based on observation of modes of the ceiling's failure in the test, in the case that fragile materials such as rock wool board and plaster board impact onto human head with their planes horizontal and with a certain velocity it is found that failure caused at impact point is very local and like punching. Therefore, it can be suggested that in the case that ceilings impact onto human head with their planes horizontal the failure phenomenon concerned with the impact occurs within small area (about a sheet of board). For that reason it is supposed that in the case that falling velocity just before impact is equal to one in the test the size of ceiling has little influence and impact nearly equal to one in the test is caused. The inclination of the ceiling during fall in the news video seemed different locally inside the ceiling the size of 11.2×3.0 m. However, the part of the ceiling that fell to the floor first, focused in the following, seemed falling with its plane roughly horizontal at the height of 170 cm above the floor. From specimens of various materials tested in **Refs. 1~3**, the underlayered one (8 mm thick calcium silicate board and 12 mm thick acoustic rock wool board) with furring channels is most similar to the fallen ceiling in the accident (**Tables 5** and **6**). The ceiling dropped in the test is 910 mm×910 mm in size and weights 105 N. Its data is used in the following.

Table 5. Materials of fallen ceiling in the airport

Material name	Unit weight	Size (mm)	Weight (N)
Plaster board	60 [N/m^2]	11200×3000×9.5	4027
Acoustic rock wool board	51 [N/m^2]	11200×3000×15	
Single-sized furring channel	3.3 [N/m]	49400	
Double-sized furring channel	4.2 [N/m]	32000	

Table 6. Materials of ceiling in the dropping test

Specimen	Material	Size (mm)	Weight (N)
Underlayered ceiling with furring channels	Calcium silicate board	910×910×8	105
	Rock wool board	300×600×12	
	Single-sized furring channel	17×25×0.8	
	Double-sized furring channel	17×50×0.8	

Discussion of velocity just before impact

It is assumed that a man of 170 cm tall stands just under the ceiling in the accident. Estimated from the TV video, falling velocity of the ceiling at the height of 170 cm above the floor is approximately 8.5 m/s. Since the ceiling height is 8.3 m, the velocity may be equal to one in condition that falling height is 6.6 m. Here the estimated velocity is verified with relation between falling height and velocity tested in **Ref. 3** (**Figure 17**). The falling velocity of underlayered ceiling with furring channels to falling height of 6.6 m is 8.7 m/s. It agrees approximately with 8.5 m/s estimated above. Therefore, in this case it is assumed that the velocity just before impact of the ceiling falling in a body and one of ceiling the size of 910 mm×910 mm in the test are approximately equivalent for same falling height.

Figure 14. Video of falling ceiling (NHK)

Figure 15. Video at 0.029 s after Figure 14 (NHK)

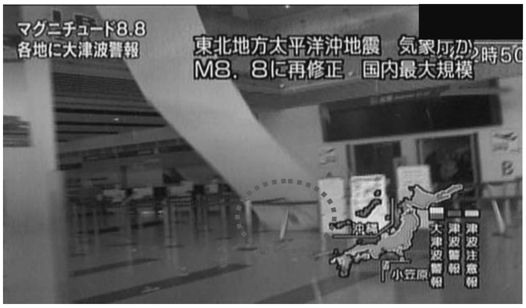

Figure 16. The first landed part of ceiling

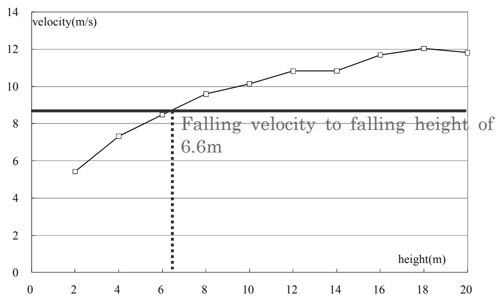

Figure 17. Velocity of the underlayered ceiling

Comparison of impacts to human head

For the reasons mentioned above, it is assumed that impact of the actual fallen ceiling is approximately equal to one of underlayered ceiling with furring channels in the test (similar material is substituted because of absence of completely same one). The figure of relation between falling height and impact on dummy head by the reference is shown below.

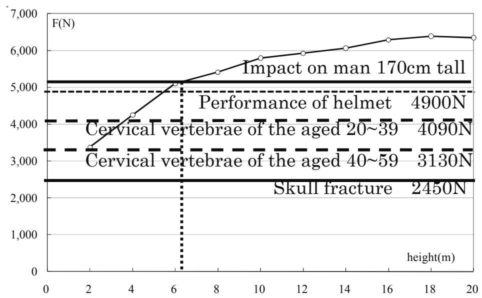

Figure 18. Impact of the underlayered ceiling

According to this, the impact on human head is estimated at 5100 N. In the figure thick solid line indicates the limit of skull (temporoparietal bones) fracture by Nahum. Thick broken lines indicate the limits of cervical fracture for men aged 20~39 and 40~59. Thin broken line indicates the limit used in performance regulation of helmets. It is confirmed that the impact estimated from the test data exceeds the limit of skull fracture. As mentioned above, if a man had stood just under the falling ceiling there might have been possibility that the impact led to critical injury such as brain contusion and injury of cervical vertebrae.

CONCLUSIONS

Airports are used by large numbers of people usually and should function as important base in disasters. For these buildings the situation that they lose safety and function by failure of ceilings should be avoided the most. It is well known that damage by earthquake at Kushiro airport terminal in September 2003 has been a good lesson as a precedent. In the accident as reported here luckily nobody was injured, but the seriousness of danger of ceilings with high ceiling height such as the lobby is proved in the estimation of impact in this report. Care to safety is required at architectural planning and design including select of the ceiling material.

ACKNOWLEDGMENT

We are grateful to kind cooperation of people in charge of the airport. This research is supported by grant from the Ministry of Land, Infrastructure, Transport and Tourism. Furthermore, we are grateful to the National Research Institute for Earth Science and Disaster Prevention for publishing strong-motion data.

REFERENCES

[1] Uchida, T., Kawaguchi, K. and Katayama, S. (2009) “Fundamental research on the safety of non-structural components, using human tolerance index, in large enclosures criteria: Part1: Human tolerance indexes.” *Summaries of technical papers of annual meeting Architectural Institute of Japan*, A-1, 1081-1082.

[2] Katayama, S., Kawaguchi, K. and Uchida, T. (2009) “Fundamental research on the safety of non-structural components in large enclosures using human tolerance index: Part2: Results of the experiments.” *Summaries of technical papers of annual meeting Architectural Institute of Japan*, A-1, 1083-1084.
[3] Uchida, T., Kawaguchi, K., Ogi, Y. and Ohya, S. (2010) “Fundamental research on the safety of non-structural components in large enclosures using human tolerance index: Part3: Results of the experiments 2.” *Summaries of technical papers of annual meeting Architectural Institute of Japan*, B-1, 881-882.