7th International Conference on
Protection of Structures against Hazards
30-31 October 2018, Hanoi, Vietnam

MOTION ANALYSIS OF EARTHQUAKE-RESISTANT AND NON-RESISTANT CEILINGS UNDER SEISMIC EXCITATION

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Keywords: Ceiling collapse, gymnasium ceiling, earthquake-resistant measures, Adaptively shifted integration (ASI) - Gauss technique, motion analysis, finite element method

Abstract. *As buildings with large-scale spaces such as school gymnasiums are used as refuge bases during earthquakes, they are required to be subsequently usable and to resist aftershocks. However, in the 2011 Great East Japan Earthquake, cases had been reported in which gymnasiums did not satisfy this function as refuge bases owing to fallen ceilings and lightings. Therefore, measures to prevent ceilings from falling must be considered; in order to achieve that, it is necessary, first, to understand the collapse mechanisms of the ceilings.*

In this study, the difference in behaviors under seismic excitations is confirmed via several motion analyses of earthquake-resistant and non-resistant ceilings. Two types of numerical models representing the ceilings are constructed. The non-resistant ceiling is composed of hanging bolts, ceiling joist receivers, ceiling joists and plaster boards. The components are connected with metal fittings. For example, hanging bolts and ceiling joist receivers are connected with hangers, and ceiling joist receivers and ceiling joists are connected with clips. Furthermore, ceiling joists and plaster boards are connected with screws. Meanwhile, the earthquake-resistant ceiling is supported with additional braces to suppress the motion. Clearance is provided between the ceiling and the side walls. Furthermore, clips used for the earthquake-resistant ceilings have stronger connections than those used for non-resistant ceilings. For the numerical analysis, all the members are modeled using linear Timoshenko beam elements, and the adaptively shifted integration (ASI) - Gauss code is applied. The detachment and collapse of the ceilings are considered by introducing detachment conditions into the metal fittings that were obtained from preliminary tests.

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Simulation is performed by applying a seismic wave, observed during the 2011 Great East Japan Earthquake, to the ceiling models. According to the numerical results, the non-resistant ceilings sway greatly and collide with the walls. The metal fittings detach occasionally during the impact. The ceilings collapse at the parts where numerous metal fittings detach. Meanwhile, none of the metal fittings detach and the ceilings are safely installed in the case of the earthquake-resistant ceilings.

1 INTRODUCTION

As buildings with large-scale spaces such as school gymnasiums are used as refuge bases during earthquakes, they are required to be subsequently usable, and to resist aftershocks. In the 2011 Great East Japan Earthquake, aftershocks of seismic intensity 6 or more occurred multiple times following the main shock with a maximum seismic intensity of 7. Cases had been reported in which gymnasiums did not satisfy the function as refuge bases owing to fallen ceilings and lightings (Figure 1)[1]. Because of numerous damages related to the ceilings, the Building Standard Law was revised after the 2011 Great East Japan Earthquake[2,3].

According to the new Building Standard[4], "a ceiling over 6 m high, with a projected area of more than 200 m^2, and a unit area weight of more than 2 kg/m^2, installed in places of daily use" is defined as "a ceiling that may cause serious harm." Measures to prevent these ceilings from falling should be performed. To apply effective earthquake-resistant measures, it is necessary to understand the collapse mechanisms of the ceilings. Recently, experiments on the collapse damage of suspended ceilings were conducted at the E-Defense shaking table facility in 2014[5]. Experiments with two types of ceilings were conducted. One was a ceiling that was not provided with measures to prevent a collapse. The other was a ceiling that was subjected to collapse prevention measures based on building standards. In the experiment where a non-resistant ceiling was installed, the collapse mechanism of the ceilings was investigated. In the experiments with earthquake-resistant ceilings, the seismic resistance behavior of the ceiling was investigated. Useful knowledge was gained through these experiments. However, detailed investigation under various conditions is required to obtain more general findings on the collapse mechanisms of ceilings because the ceilings used in facilities have various kinds of shapes and characteristics. Meanwhile, it is typically costly to perform large-scale experiments repeatedly under various conditions.

The purpose of this research is to investigate the motion behaviors of non-resistant ceilings and earthquake-resistant ceilings under seismic excitation using numerical simulations, where the conditions and parameters can be easily changed, and to obtain the findings to clarify the mechanisms of collapse and damage. We used the adaptively shifted integration (ASI) - Gauss code[6,7,8] that can stably perform highly nonlinear analysis including seismic motion, elasto-plasticity and fracture.

Figure 1: Ceiling collapse that occurred during the 2011 Great East Japan Earthquake[1]

2 OUTLINE OF GYMNASIUM CEILING

In gymnasiums, ceilings with steel furrings are generally installed (Figure 2). The ceilings are composed of hanging bolts, ceiling joist receivers, ceiling joists and plaster boards. The components are connected with metal fittings. For example, hanging bolts and ceiling joist receivers are connected with hangers, and ceiling joist receivers and ceiling joists are connected with clips. Furthermore, ceiling joists and plaster boards are connected with screws.

In this study, we focused on two types of ceilings used in the experiments conducted by E-Defense. Table 1 shows the specifications of a non-resistant ceiling without specific earthquake-resistant measures and an earthquake-resistant ceiling with several measures to prevent instant detachments.

The length of all the hanging bolts in the non-resistant ceiling is 1.5 m such that the slope of the ceilings is the same as that of the roof of the gymnasium. Besides, the lengths of the hanging bolts are required to be uniform in the new building standards. Therefore, the earthquake-resistant ceiling is also slanted with the same slope as that of the roof (Figure 3).

Herein, different points between the non-resistant ceiling and the earthquake-resistant ceiling are described. First, the spacing of the hanging bolts of the non-resistant ceiling is 1,000 mm × 1,147 mm, whereas that of the earthquake-resistant ceiling is 1,000 mm × 860 mm. Clips that connect the ceiling joist receivers and the ceiling joists are also different. The clips used in the earthquake-resistant ceiling are attached between the joists and receivers with screws, and are stronger than the clips used in the non-resistant ceiling, which are simply bended and attached to the receivers (Figure 4). Furthermore, some braces are additionally installed in the earthquake-resistant ceilings. In addition, there is no clearance in the non-resistant ceilings, but the earthquake-resistant ceilings have a clearance of 60 mm beside the wall.

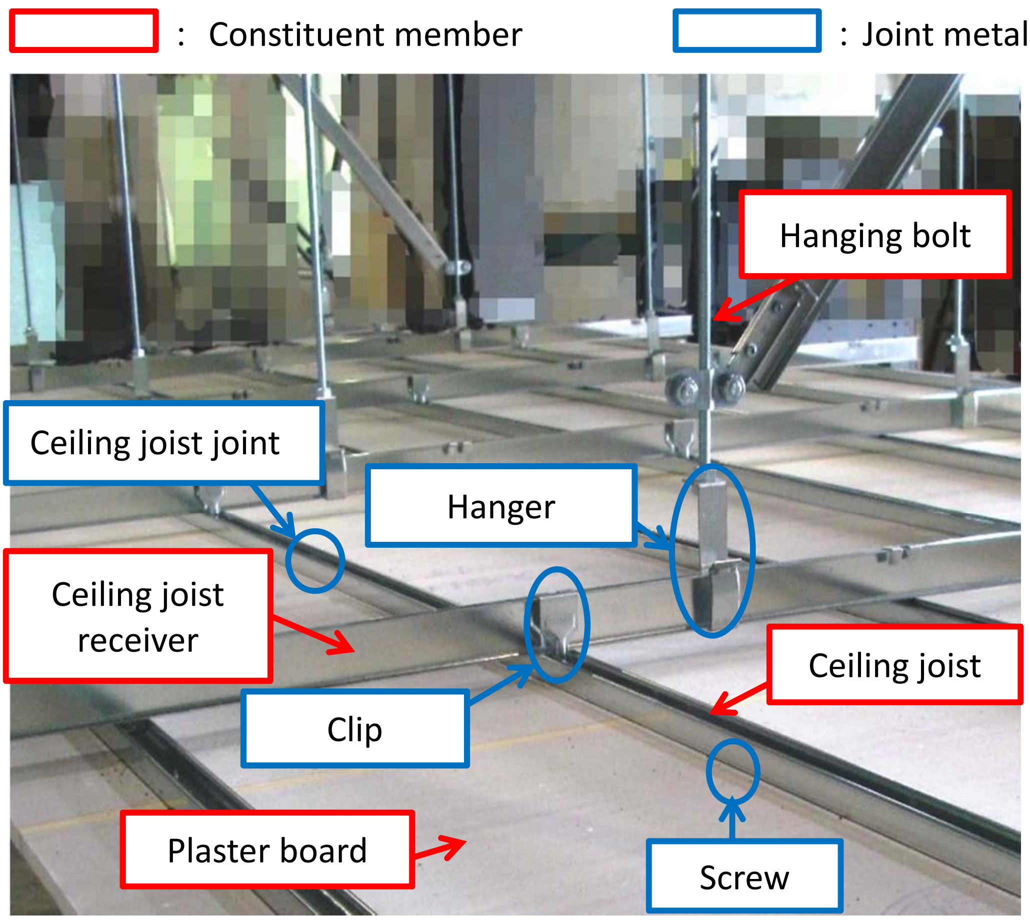


Figure 2: Components of conventional type ceiling with steel furrings

Table 1: Specifications of non-resistant ceiling and earthquake-resistant ceiling used in the experiment

Item	Specification	
	Non-resistant ceiling	Earthquake-resistant ceiling
Horizontal design load	None	1.1 [G]
Area mass	13.1 [kg/m^2]	13.8 [kg/m^2]
Clearance	None	60 [mm]
Hanger length	1,500 [mm]	
Interval of hangers	1,147 × 1,000 [mm]	860 × 1,000 [mm]
Hanging bolt	W3/8 hanging bolt	
Hanger	Free hanger	Earthquake-resistant free hanger
Single ceiling joist	JIS19 type @364 [mm]	JIS19 type @303 [mm]
Double ceiling joist	JIS19 type @1,820 [mm]	JIS19 type @910 [mm]
Ceiling joist receiver	JIS19 type @1,000 [mm]	JIS19 type @1,000 [mm]
Clip	JIS19 one-touch type clip	Earthquake-resistant clip Wind pressure resistant clip
Brace	None	Establishment
Finishing material	Plaster board 9.5 [mm] +rockwool absorber 9 [mm]	

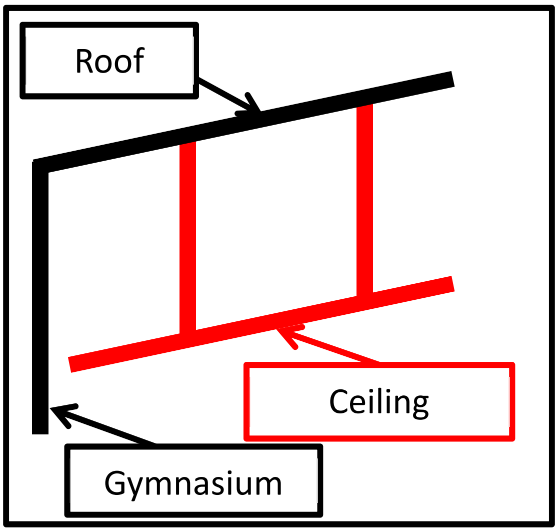
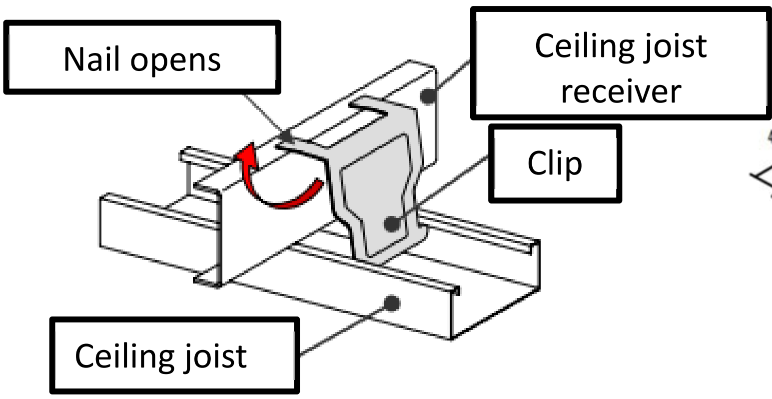
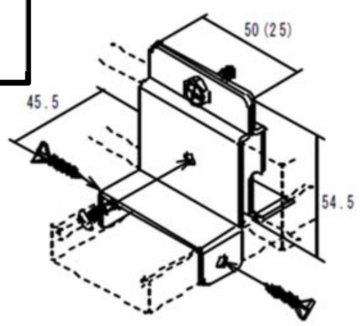


Figure 3: Locations of roof and ceiling in a gymnasium



(a) Clip used in non-resistant ceiling



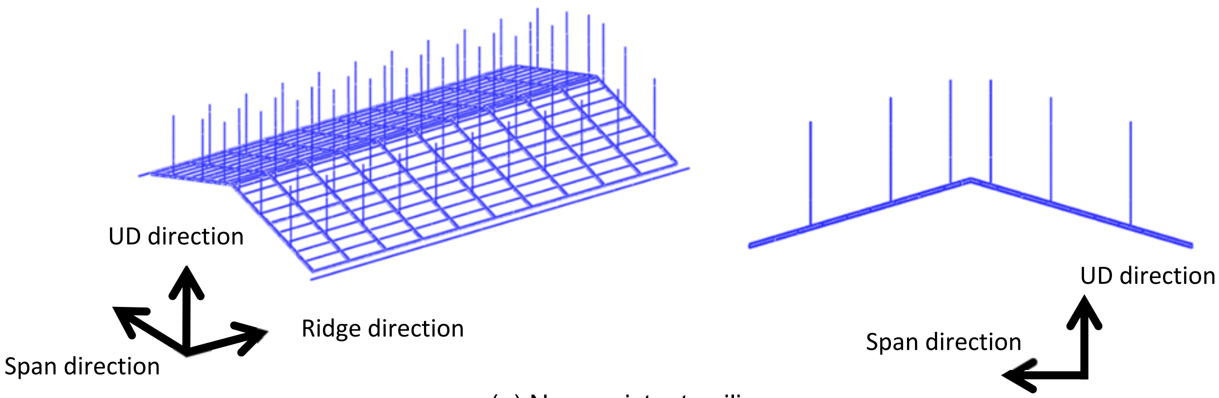
(b) Clip used in earthquake-resistant ceiling

Figure 4: Clips used in the ceilings

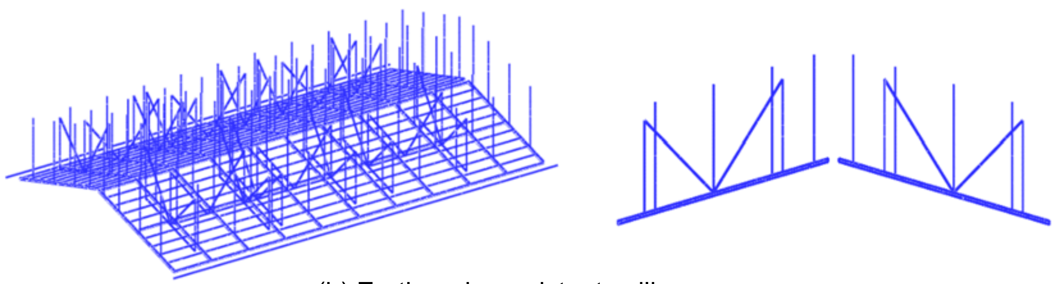
3 NUMERICAL MODELS AND CONDITIONS

Two types of partial ceiling models (non-resistant ceiling and earthquake-resistant ceiling) were prepared (Figure 5). The partial ceiling model is 1/9th the size of the ceiling used in the experiment conducted by E-Defense, and the dimensions are 10 m × 6.2 m. Figure 6 is a simplified drawing showing an outline of the ceiling model. In the analysis, the clearance of the non-resistant ceiling was set to 1 mm, and the clearance of the earthquake-resistant ceiling was set to 60 mm as in the experiment. Because the ASI-Gauss code was used for the analysis, all the ceilings and walls were modeled using linear Timoshenko beam elements. The total number of elements and the total number of nodes for the non-resistant ceiling are 4,272 and 3,465, respectively, and those for the earthquake-resistant ceiling are 7,404 and 6,610, respectively.

The detachment conditions shown in Table 2 were introduced to the hangers, clips, screws, and ceiling joist joints; if the conditions were satisfied, the elements were considered to be



(a) Non-resistant ceiling



(b) Earthquake-resistant ceiling

Figure 5: Numerical models of suspended ceilings

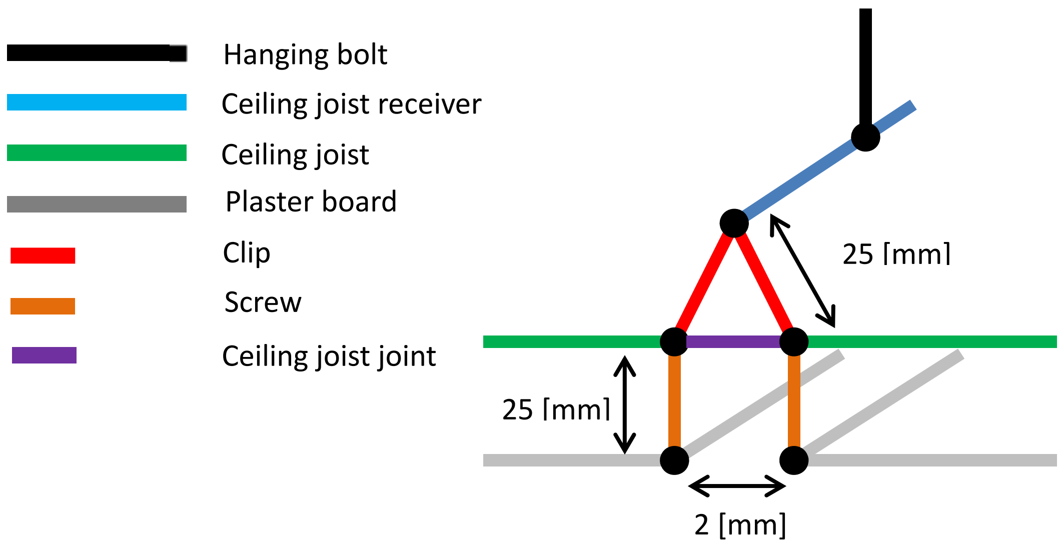


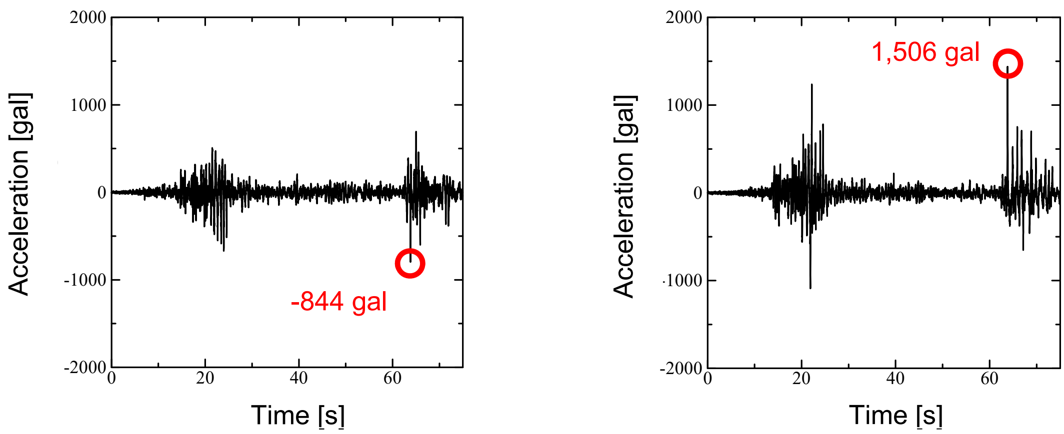
Figure 6: Outline of suspended ceiling model

fractured according to the flow of the numerical code[6,7,8]. A loading condition was set for the detachment condition of the hangers; they were detached when a tensile force of 2.8 kN acted in the axial direction of the hanger element. Different detachment conditions were set for those clips used in the non-resistant ceiling and the earthquake-resistant ceiling. For the non-resistant ceiling, three types of detachment conditions for the clips were set as shown in the table. For example, a front cover single clip was detached when a tensile force in the axial direction of the element exceeds 0.35 kN. For the earthquake-resistant ceiling, two types of detachment conditions for the clips were set. For example, an earthquake-resistant clip was detached when a tensile force in the axial direction of the element exceeds 2.50 kN. For the hangers and screws, the same conditions are set for the non-resistant and earthquake-resistant ceilings. To prevent the detachment of ceiling joist joints caused by instantaneous impact, the axial strain, generated under a static tensile axial force of 0.29 kN, was set as a detachment condition in addition to the loading condition. The ceiling joist joints were detached when two conditions shown in the table are satisfied.

The K-NET Sendai wave 200% (Figure 7) was applied to all nodes at the upper end of the hanger bolt. The time increment of the analysis was 0.001 s, and the time duration of the analysis was 75 s.

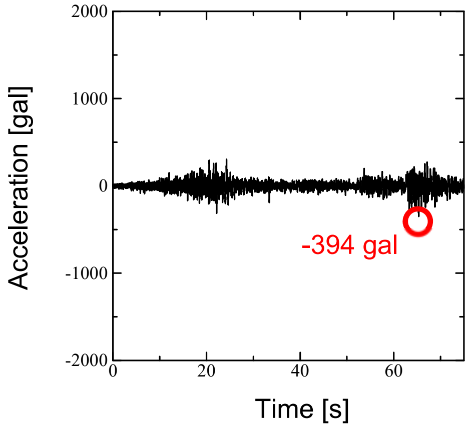
Table 2: Detachment conditions for the joint components

	Non-resistant ceiling	Earthquake-resistant ceiling
Hanger	[5]Tensile axial force≧2.80 kN	
Screw	[9]Tensile axial force≧0.40 kN and axial displacement≧3 mm	
	or	
	[10]Shear force≧0.30 kN and shear displacement≧18 mm	
Clip	Single(front cover) : [5]tensile axial force≧0.35 kN	Earthquake-resistant clip : tensile axial force≧2.50 kN
	Single(back cover) : [5]tensile axial force≧0.70 kN	Wind pressure resistant clip : tensile axial force≧2.0 kN
	Double : [5]tensile axial force≧0.80 kN	
Ceiling joist joint	Tensile axial force≧0.29 kN and axial strain≧4.93×10^{-5}	



(a) Ridge direction (b) Span direction

Figure 7: Input wave (K-NET Sendai wave 200%) (continued)



(c) UD direction

Figure 7: Input wave (K-NET Sendai wave 200%)

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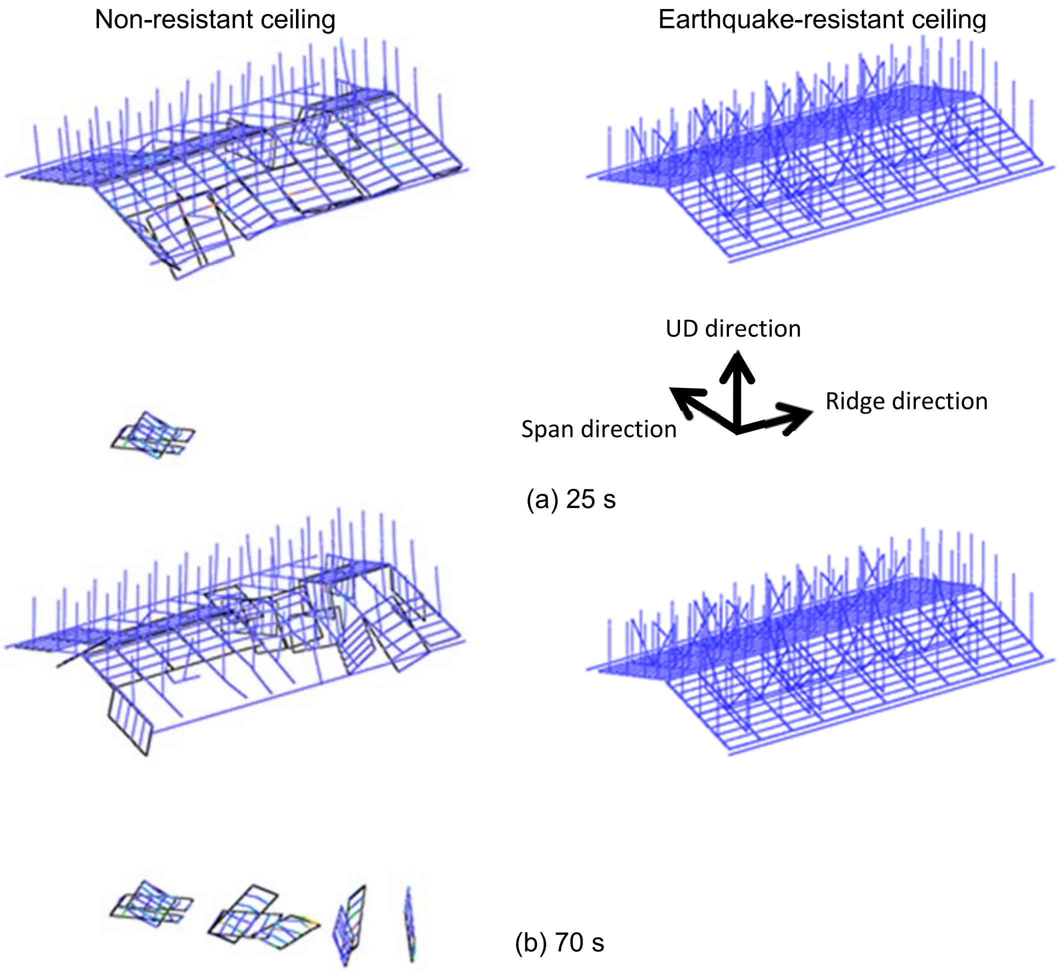
Figure 8 shows the snapshots of the non-resistant and earthquake-resistant ceilings at 25 s and 70 s. At the first peak of the K-NET Sendai wave, numerous clips and ceiling joist joints became detached and the ceilings started falling in the case of the non-resistant ceiling. And at the second peak of the K-NET Sendai wave, the ceilings fell in a wide range. Meanwhile, the earthquake-resistant ceiling did not fall at all. Next, Figure 9 shows the locations of the detached

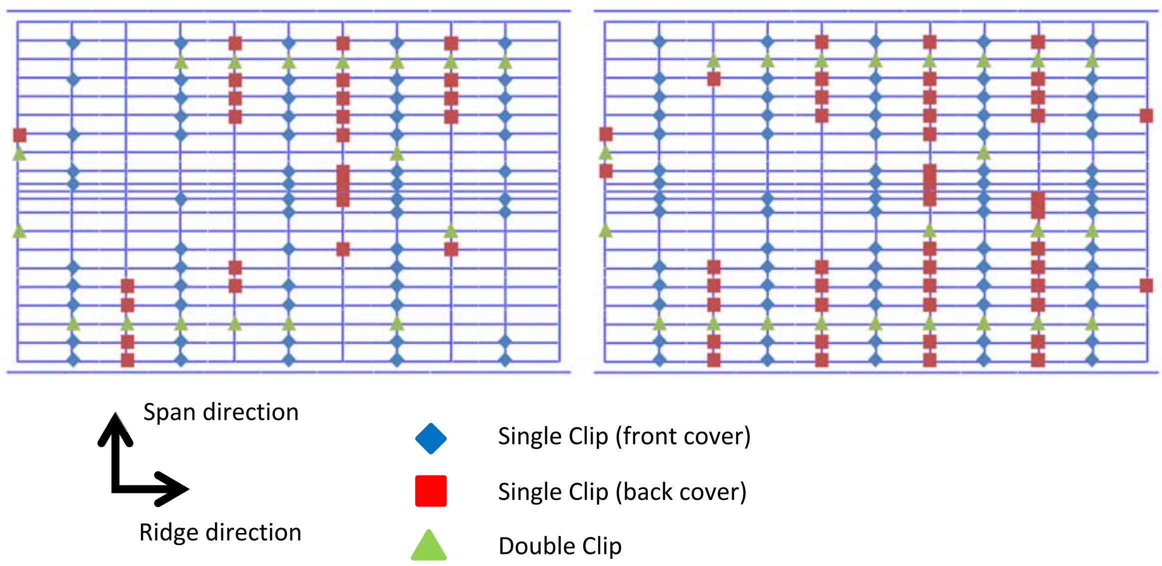


(a) 25 s

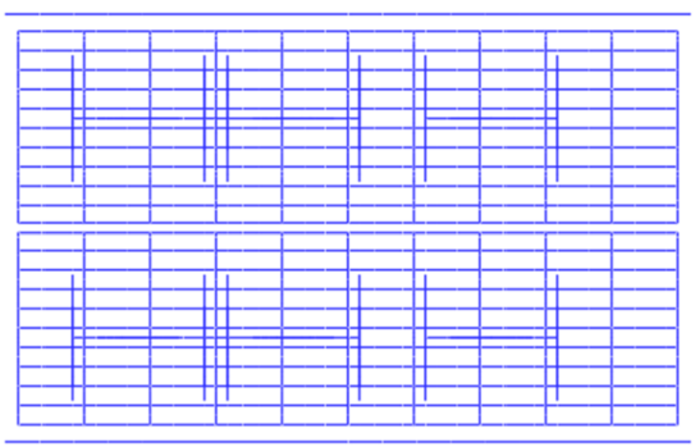
(b) 70 s

Figure 8: Collapse sequence of ceilings

clip elements at 25 s and 70 s. In the non-resistant ceiling, both single clips and double clips are detached in large quantities at the peak of the K-NET Sendai wave. Further, by comparing the location of the detached clip elements and the collapsed area of the non-resistant ceiling, as shown in Figure 10, we can confirm that the ceilings have fallen at the location where numerous clips have detached. Figure 11 shows the response acceleration at the evaluation points shown in the figure. The response accelerations of the earthquake-resistant ceiling are suppressed in all three directions owing to the earthquake resistance measures. We can assume that the non-resistant ceiling shakes greatly and collides with the wall such that the impact forces are frequently delivered to the clips, and eventually cause the collapse of the ceilings. Meanwhile, the detachment of clips did not occur in the earthquake-resistant ceiling, as shown in Figure 9. Hence, the earthquake-resistant ceiling did not fall. Further, the earthquake-resistant ceiling never collided with the wall because of the clearance and braces.



(a) Non-resistant ceiling (25s) (b) Non-resistant ceiling (70s)



(c) Earthquake-resistant ceiling (70s)

Figure 9: Location of detached clip elements

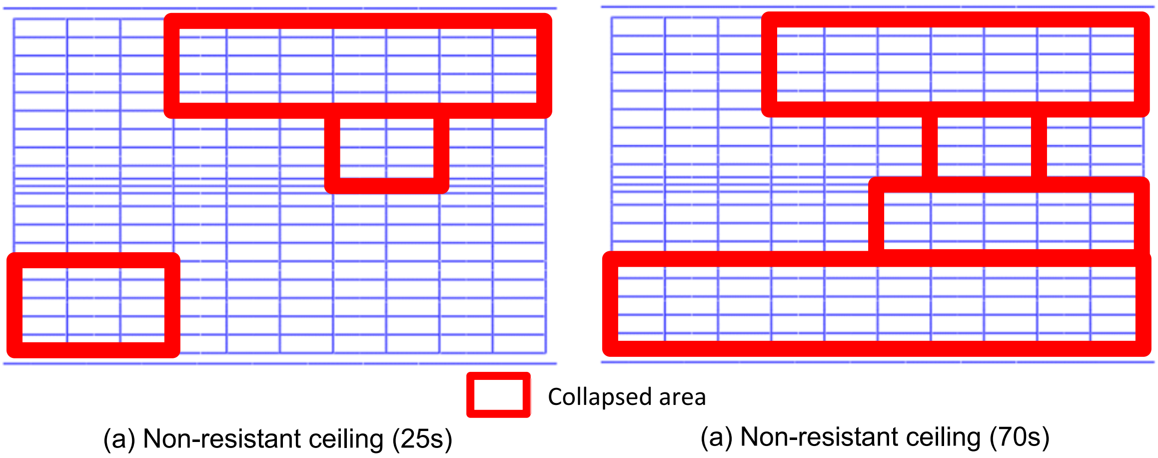


Figure 10: Collapsed area of non-resistant ceilings

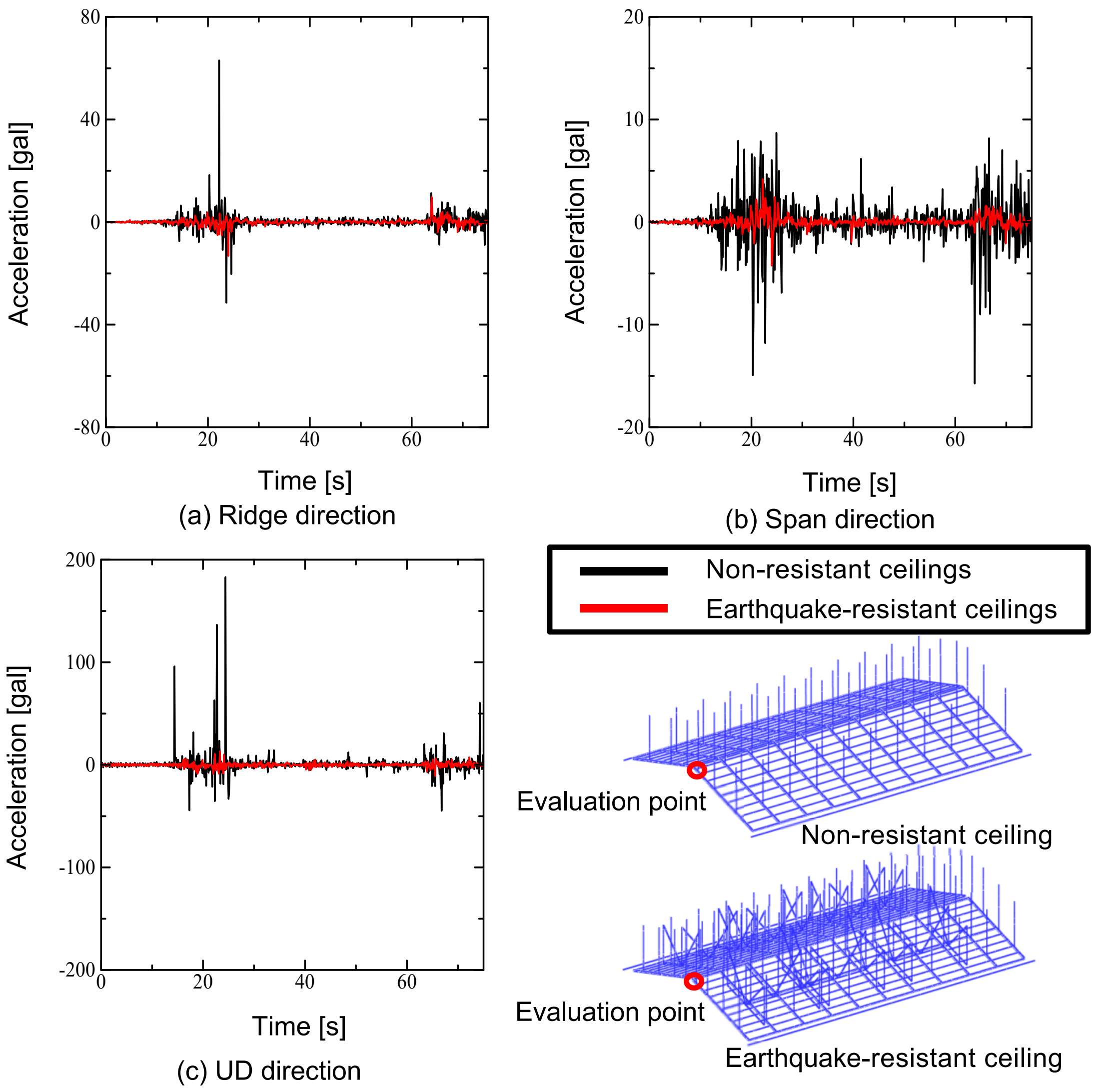


Figure 11: Response acceleration

5 CONCLUSIONS

In this study, two types of partial ceiling models (non-resistant ceiling and earthquake-resistant ceiling) were prepared. Some analyses were performed using the ASI-Gauss code and by applying a seismic wave, observed during the 2011 Great East Japan Earthquake, to the ceiling models.

It was observed from the numerical results that the non-resistant ceilings swayed greatly and collided with the walls. The metal fittings detached occasionally during the impact. The ceilings collapsed at the parts where numerous metal fittings detached. Meanwhile, none of the metal fittings detached and the ceilings were safely installed in the case of the earthquake-resistant ceilings. The earthquake-resistant ceilings never collided with the walls, owing to two primary reasons: suppression of motion by the additional braces and the large clearance between the ceiling and wall.

By comparing the numerical results of the non-resistant ceiling and earthquake-resistant ceiling under a seismic excitation, the effects of the earthquake-resistant measures were noticeably observed. However, we will continue to obtain safe but more efficient earthquake resistance measures, as the current earthquake countermeasures exhibit problems such as high costs and long construction periods.

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