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COLLAPSE ANALYSIS OF CEILINGS SUSPENDED IN CONCERT HALLS

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Abstract. *In this study, a collapse analysis of a concert hall's box-type suspended ceiling containing level gaps was performed. A numerical model of the concert hall and ceiling, constructed with linear Timoshenko beam elements, was simulated by applying seismic waves. The adaptively shifted integration (ASI)-Gauss code, which can stably simulate such phenomena with strong nonlinearities such as fractures and contacts, was used in this analysis. The numerical results revealed that the collapse of the ceiling was caused by the detachment of clips connecting the ceiling joists to the ceiling joist receivers. The detachment of clips, in turn, was caused by the propagation of the impact force that was generated when the suspended ceiling collided with the wall. Furthermore, it was confirmed that the detachment progressed because the load distribution supported by the clips changed from its initial state. The results also showed that the locations of the clips detached by the collisions were strongly affected by the geometrical shape of the ceiling.*

1 INTRODUCTION

In Japan, there have been many reports of damages caused to the suspended ceilings of gymnasiums and concert halls during high-intensity earthquakes, such as the 2011 off the Pacific coast of Tohoku Earthquake and the 2016 Kumamoto Earthquake[1,2]. An example of such damage is shown in Figure 1. In response to these events, the Ministry of Land, Infrastructure, Transport, and Tourism of Japan enacted technical standards for anti-earthquake measures in ceilings and guidelines for preventing ceilings from falling.

These laws, however, only cover conventional, flat-shaped suspended ceilings, with an area mass of approximately 10 to 15 kg/m^2. Concurrently, high-density finishing materials are frequently used for suspended ceilings in buildings, such as concert halls, that require detailed acoustic design. In these cases, the ceilings have an area mass of approximately 20 to 40 kg/m^2. In addition to this, the acoustic design of the building requires the shape of the ceiling surface to be complex, and cases have shown that the geometric structure of the ceiling also affects its falling behavior[3]. Therefore, it is important to investigate the falling mechanism of suspended ceilings, which are heavy in weight and complex in structure, in order to determine efficient and effective anti-earthquake measures.

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In this paper, the falling behavior of suspended ceilings with box-shaped level gaps on the surface ("box-type suspended ceilings") was investigated. Firstly, a numerical model of a concert hall with a box-type suspended ceiling was constructed. This was followed by a motion analysis of the model using the finite element method by applying a seismic wave. The adaptively shifted integration (ASI)-Gauss technique[4,5], a large-scale finite element analysis code that can solve stably even for analyses with strong material and geometric nonlinearities, including contact and fracture, was used for this analysis.

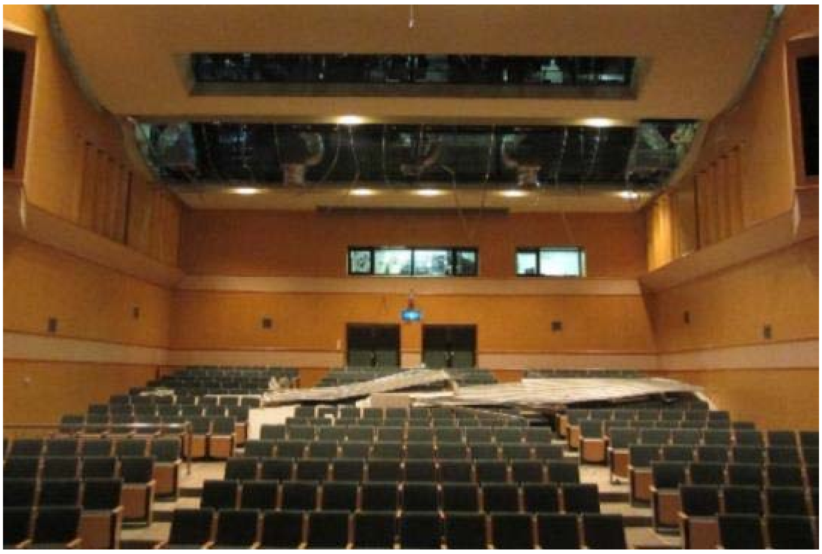


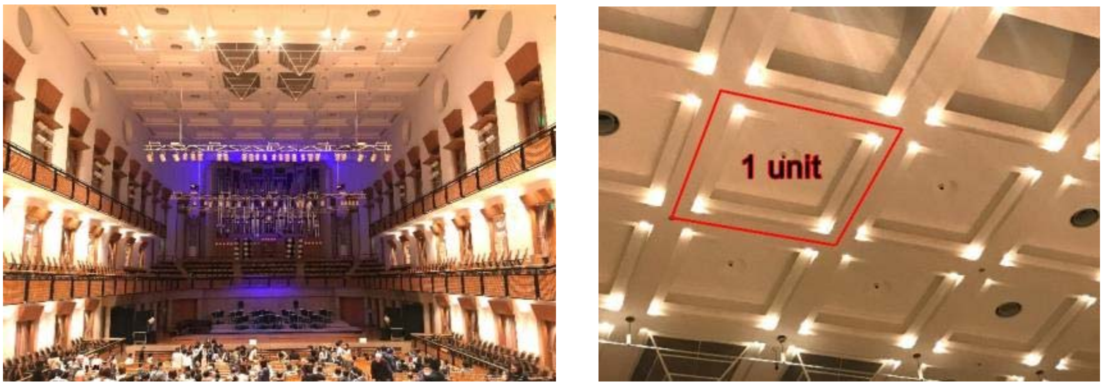
Figure 1: Ceiling collapse that occurred during the 2016 Kumamoto Earthquake1

2 BOX-TYPE SUSPENDED CEILING

As described above, suspended ceilings attached to acoustic facilities such as concert halls are characterized by an increase in the weight and complexity of the structure. In order to obtain reliable results, the specifications of the numerical model were determined in reference to the ceiling of an actual concert hall, as shown in Figure 2. The ceiling of the concert hall was constructed by connecting units, as indicated by a red solid line in Figure 2(b). Level gaps were provided to delimit the units. The entire ceiling was connected by a total of 96 units: 16 units (X-direction) x 6 units (Y-direction).

Table 1 and Figure 3 present the specifications and outline of the box-type suspended ceiling, respectively. The size of each unit was 3.6 m (X-direction) x 4.0 m (Y-direction). The area mass of the ceiling was 22.2 kg/m^2, and the weight of each unit was 319 kg. The suspended ceiling consists of finishing materials, hanging bolts, ceiling joists, and ceiling joist receivers; these members were connected with joint components such as screws, clips, hangers, and ceiling joist joints. The ceiling joists were fastened to the finishing material using screws. Clips were used to connect the ceiling joists and ceiling joist receivers, and hangers were employed to join the ceiling joist receivers and hanging bolts. The specifications of members and joint components were the same as those used in conventional type ceilings.

The height and width of the level gap were 300 mm. The finishing materials constituting the steps were not individually separated and were connected by L-shaped members provided at corners. Two ceiling joists were located at the bottom and the side of the level gap, respectively, and connected by ceiling joist receivers. Additionally, all the ceiling joist receivers were welded.

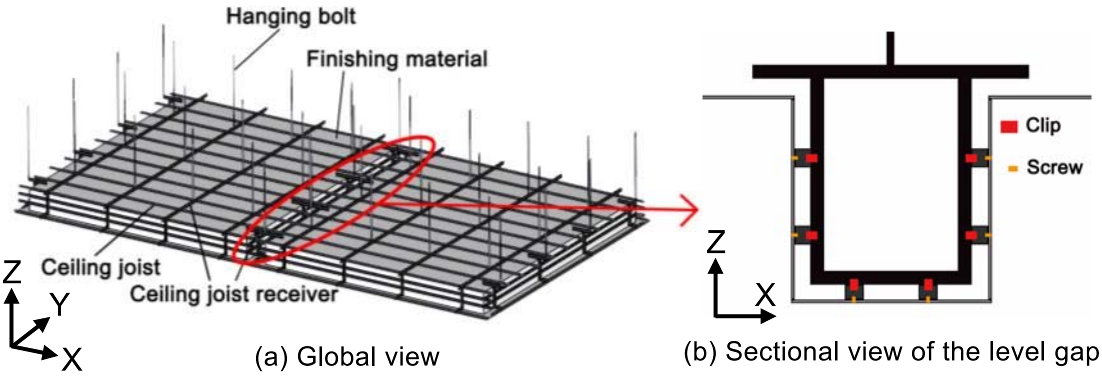


(a) Overall view (b) Box-type suspended ceiling

Figure 2: Interior view of the T concert hall

Table 1: Specifications of the box-type suspended ceiling

Item	Spec
Horizontally projected area	57.6×24.0 [m] (1,382.4 [m^2])
Total area	1,785.6 [m^2]
Area mass	22.2 [kg/m^2]
Clearance	None
Hanger length	1,000 [mm]
Interval of hangers	900×1,333 [mm]
Hanging bolt	W3/8 hanging bolt
Hanger	Free hanger (permissible substitute of JIS standard)
Single ceiling joist	JIS19 type @300 [mm]
Double ceiling joist	JIS19 type @100 [mm]
Ceiling joist receiver	JIS19 type @900 or 1100 [mm]
Clip	One-touch clip for JIS19 type
Finishing material	FG board 6 [mm] + Plaster board 12.5 [mm] + FG board 6 [mm]



(a) Global view (b) Sectional view of the level gap

Figure 3: Outline of the box-type suspended ceiling

3 NUMERICAL MODELS AND CONDITIONS

This section describes the numerical model of the box-type suspended ceiling, the structural frame model of the concert hall, and the full model of the concert hall and the suspended ceiling. All the models were constructed using linear Timoshenko beam elements, with each member modeled using a minimum of two elements. Furthermore, the elasto-plastic flow theory was used as the constitutive law for the elements.

3.1 Box-type suspended ceiling model

An overview of a single-unit ceiling model is displayed in Figure 4. The ceiling model was constructed in reference to the concert hall shown in Figure 2. Based on a previous study[6], the finishing materials were modeled independently and sequentially to reproduce the individual falling of the ceiling, and accordingly, a clip was modeled using two members. The clearance between the finishing materials and the length of a ceiling joist joint were taken as 2 mm. The structural strength of the finishing material was considered by integrating a fiber gypsum (FG) board and a plaster board, and the density was obtained by superimposition. The hanging bolt was modeled with ten elements to reflect the buckling phenomena, and two small elements with greatly reduced bending rigidity were used at both ends to mimic a pin connection. The ceiling joist receivers were modeled with four elements, and all the other members were modeled with two elements.

Figure 5 shows the complete model of the ceiling linked with 96 units. The total number of elements and nodes were 322,712 and 272,062, respectively. The size of the model was 57.6 m (X-direction) × 24.0 m (Y-direction), and the total weight was 30.7 ton (i.e. an area mass of 22.2 kg/m^2).

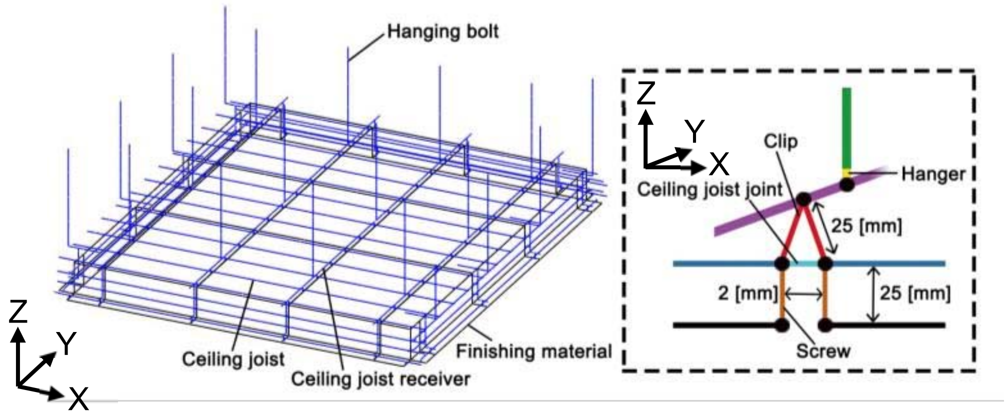


Figure 4: Single-unit model of the box-type suspended ceiling

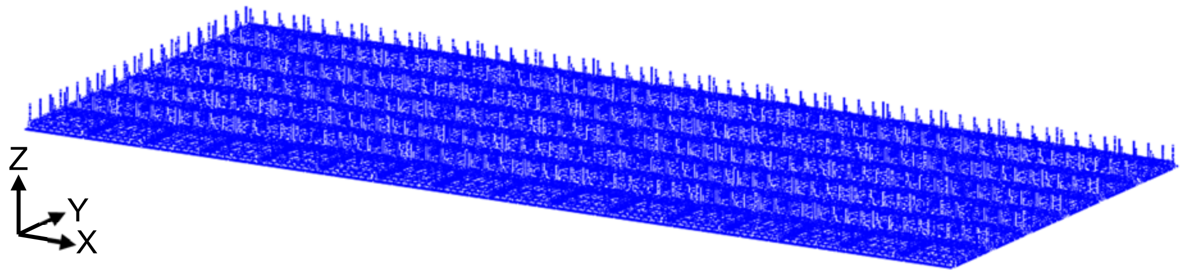


Figure 5: Full model of the box-type suspended ceiling

3.2 Structural frame model of the concert hall

Figure 6 demonstrates the structural frame model of the concert hall. A five-story reinforced concrete (RC) building, with a size of 75.3 m (X-direction) x 35.4 m (Y-direction) x 23.15 m (Z-direction), was modeled as the concert hall. The plan configuration consisted of a semi-circular section as the stage and a rectangular section as the audience seating. The audience seats were modeled on the rectangular section of the first floor and the cantilevered sections of the upper floors.

The pillars, girders, and beams were modeled using two elements per member. The shear walls were modeled by positioning the elements in the shape of a cross. Assuming that the shear wall element was rigid to the in-plane direction, the moment of inertia of the area in that direction was multiplied by 10,000. The entire building, except the roof, was set to be of reinforced concrete. The roof was to be constructed of H-shaped steel girders and beams.

The reduction in the rigidity due to the cracking of concrete was considered by introducing the degrading tri-linear model in the constitutive law of the RC members.

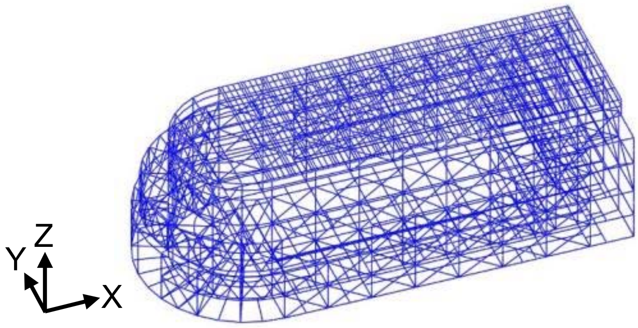


Figure 6: Structural frame model of the concert hall

3.3 Concert hall model with suspended ceiling

Figure 7 shows the concert hall model with the box-type suspended ceiling. This model was constructed by connecting the hanging bolts of the ceiling model to the beam joints at the roof level of the structural frame model. The maximum height of the ceiling from the ground level was 22.15 m.

To reflect the collision phenomena occurring between the ceiling and the wall, the horizontal member mimicking the wall was set on the same level as the ceiling (Z = 21.85 m). The material constants and sectional properties of the horizontal members were set as those of RC shear walls with a thickness of 150 mm. Although the finishing materials in the actual ceiling were arranged without any gaps, the distance for the contact determination between the horizontal members and the adjacent finishing materials was set as 1 mm to stabilize the contact calculation.

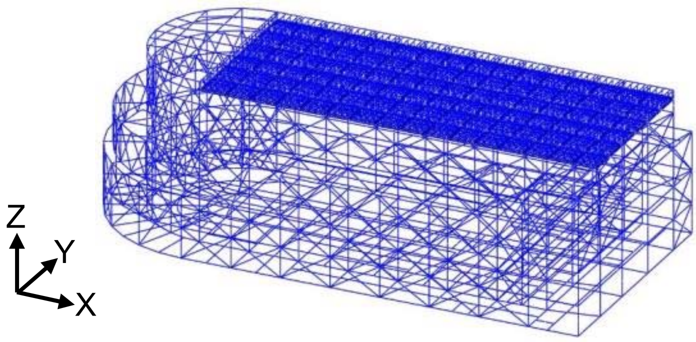


Figure 7: Concert hall model with the box-type suspended ceiling

3.4 Detachment conditions of joint components

An experiment on a full-scale gymnasium with a suspended ceiling[7] conducted using a large-scale shake-table reported the detachment of joint components as the main cause of ceiling collapse. In this numerical analysis, detachment conditions were introduced based on preliminary tests[7-9] conducted on hangers, screws, clips, and ceiling joist joints. The detachment of these joints was simulated by fracturing the elements if the conditions were satisfied. Two detachment conditions were used: load conditions determined by the sectional forces acting on the elements and displacement conditions determined by the deformation occurring in the elements. Table 2 lists the detachment conditions of the joint components.

The load conditions for the clips, depending on their type, were set as their detachment conditions. Because a clip was modeled using two members as described in Section 3.1, the clip was set to detach in the analysis when the sum of the sectional forces acting on the two members exceeded the value presented in Table 2.

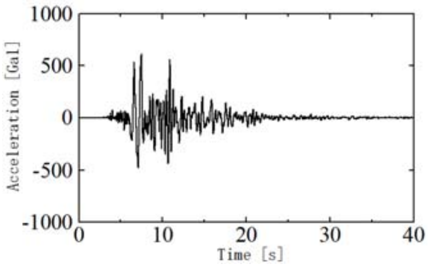
To prevent the detachment of the ceiling joist joints caused by instantaneous impact, the axial strain, generated under a static tensile axial force of 0.29 kN, was set in addition to the load condition.

Table 2: Detachment conditions for the joint components

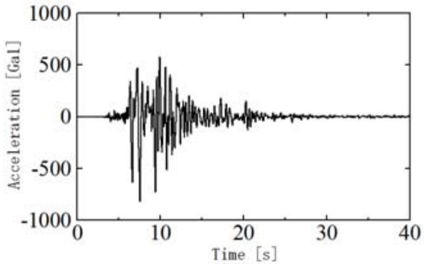
<table>
<tr><th colspan="2">Item</th><th colspan="3">Condition</th></tr>
<tr><td colspan="2">Hanger</td><td colspan="3">Tensile axial force 2.80 [kN]</td></tr>
<tr><td colspan="2">Ceiling joist joint</td><td colspan="3">Tensile axial force 0.29 [kN] and Axial strain 4.93×10^{-5}</td></tr>
<tr><td rowspan="3">Clip</td><td>Single (front cover)</td><td colspan="3">Tensile axial force 0.35 [kN]</td></tr>
<tr><td>Single (back cover)</td><td colspan="3">Tensile axial force 0.70 [kN]</td></tr>
<tr><td>Double</td><td colspan="3">Tensile axial force 0.80 [kN]</td></tr>
<tr><td colspan="2">Screw</td><td>Tensile axial force 0.40 [kN]
and Axial displacement 3 [mm]</td><td>or</td><td>Shear force 0.30 [kN] and
Shear displacement 18 [mm]</td></tr>
</table>

3.5 Input wave

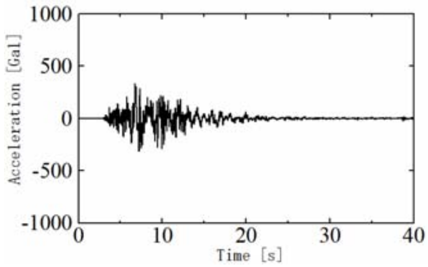
In the analysis, the 1995 Japan Meteorological Agency (JMA) Kobe wave was used as the input seismic wave. The acceleration waveform is depicted in Figure 8 and the response acceleration spectrum is presented in Figure 9. The time duration of the analysis was 30 s and time increment was 0.001 s.



(a): X-axis direction



(b): Y-axis direction



(c): Z-axis direction

Figure 8: Acceleration waveform of the 1995 JMA Kobe wave

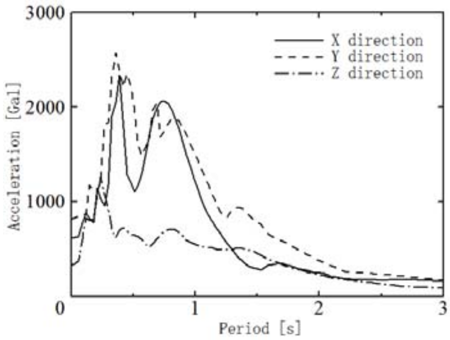


Figure 9: Response acceleration spectrum of the 1995 JMA Kobe wave

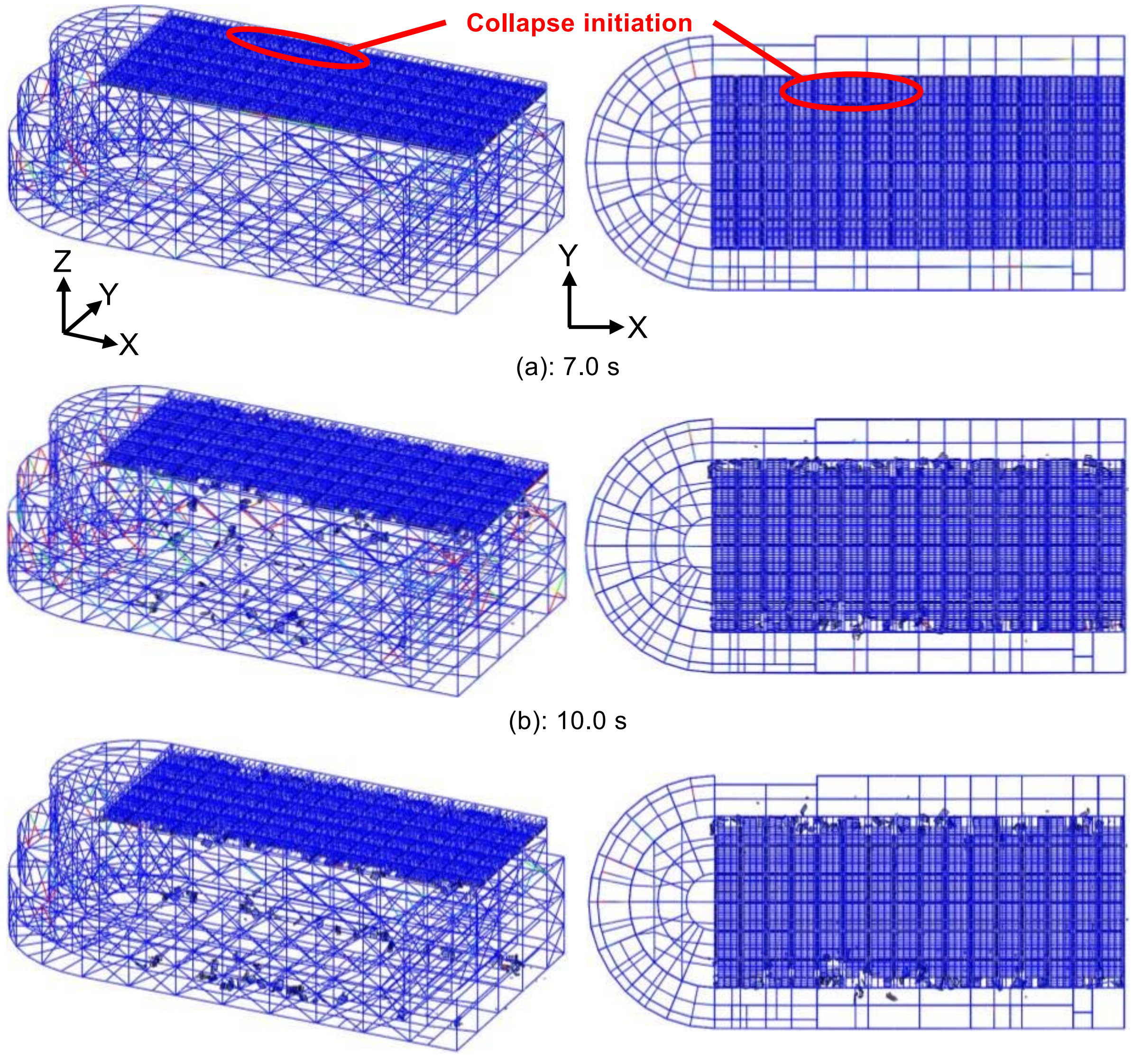
4 NUMERICAL RESULT

This section focuses on the collapse sequence of the ceiling obtained by the numerical analysis. The cause of the ceiling collapse was investigated by comparing the collapse sequence with the distribution of the detached clips.

4.1 Collapse sequence of ceiling

Figure 10 shows the ceiling collapse sequence obtained by the analysis. It confirmed that the ceiling along the horizontal members initiated collapse at 7.0 s when the first peak appeared in the input seismic wave. This collapse then continued for a few seconds. Therefore, it was inferred that the collision between the ceiling and the horizontal members significantly affected the collapse. However, the ceiling at the X-direction edge of the building had not collapsed. This was because the vibration in the Y-direction dominated the vibration in the X-direction, and as the total wall area was larger in the X-direction than in the Y-direction.

The ceiling collapsed jointly with the finishing materials and ceiling joists, whereas the ceiling joist receivers remained attached to the rest. This confirmed that the ceiling collapse was mainly caused by the detachment of the clips. These results were in good agreement with the results of the gymnasium ceiling damage reproduction experiment[7].



(a): 7.0 s

(b): 10.0 s

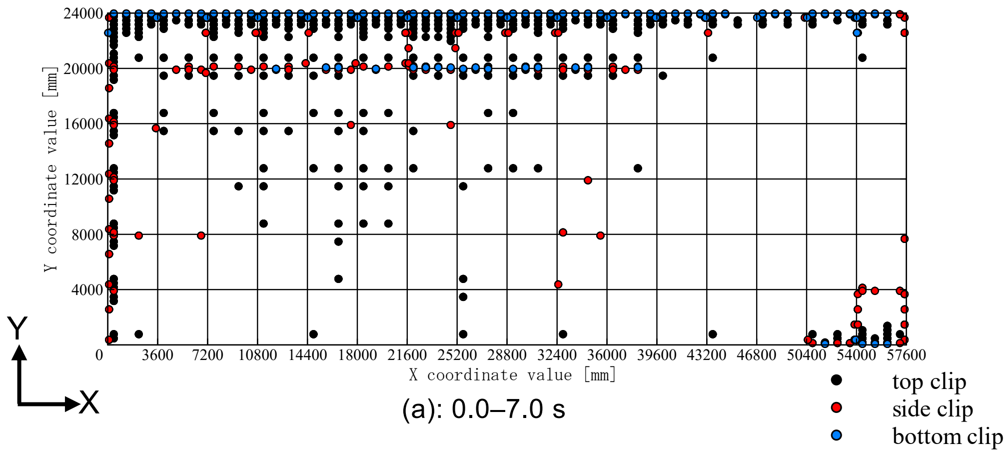
(c): 13.0 s

Figure 10: Collapse sequence of the ceiling

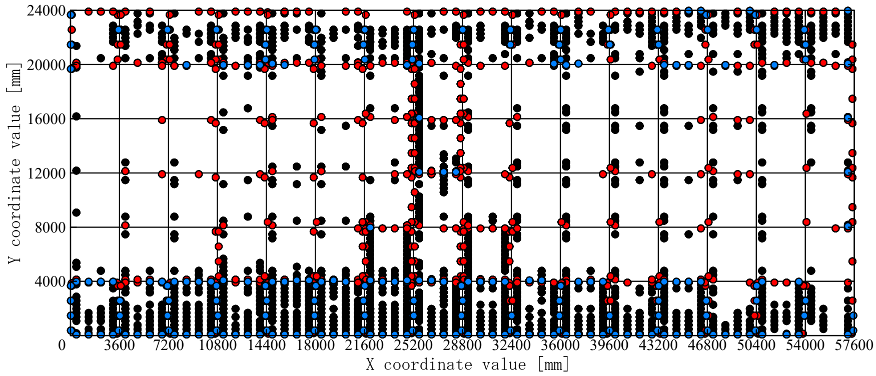
4.2 Detachment sequence of clips

Figure 11 depicts the locations of the clips that were detached in the analysis. The locations of the clips in the level gap are shown in Figure 12. The lattice lines in the figure represent the boundary of the units, along which the level gaps are located.

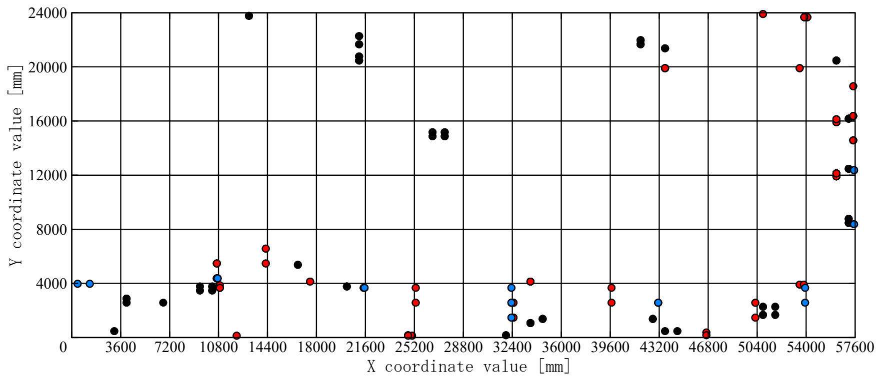
According to Figure 11 (a), the clips beside the walls were detached at 7.0 s, which was the same time the ceiling collided with the walls. The collisions between the ceiling and the walls applied an impact force on the joint components, which caused the detachment of the clips, and consequently, the ceiling collapse. Once the clip detached, the load supported by the clip was redistributed to the adjacent clip, and the detachment progressed.



(a): 0.0–7.0 s



(b): 7.0–10.0 s



(c): 10.0–30.0 s

Figure 11: Distribution of the detached clips

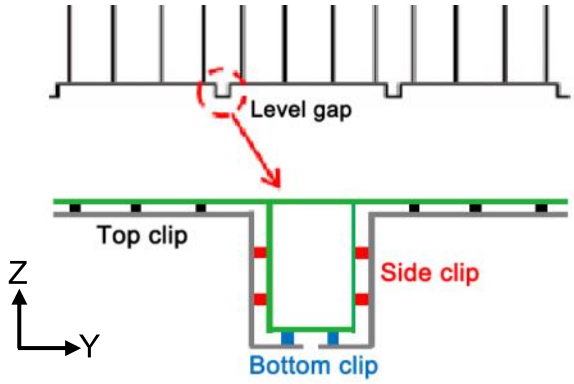


Figure 12: Location of each clip in the level gaps

4.3 Detachment mechanism of clips in level gaps

According to Figure 11, it is confirmed that the clips were detached in multiple locations along the level gaps perpendicular to the wall. On the other hand, the detachment of clips did not progress to the inner part of the ceiling. In former case, the level gaps perpendicular to the wall were highly rigid to the direction of collision, and the impact force was barely absorbed, whereas in the latter, in the level gaps parallel to the wall, the impact force generated by the collision was transformed into a local moment and thus, the impact force was easily absorbed (Figure 13).

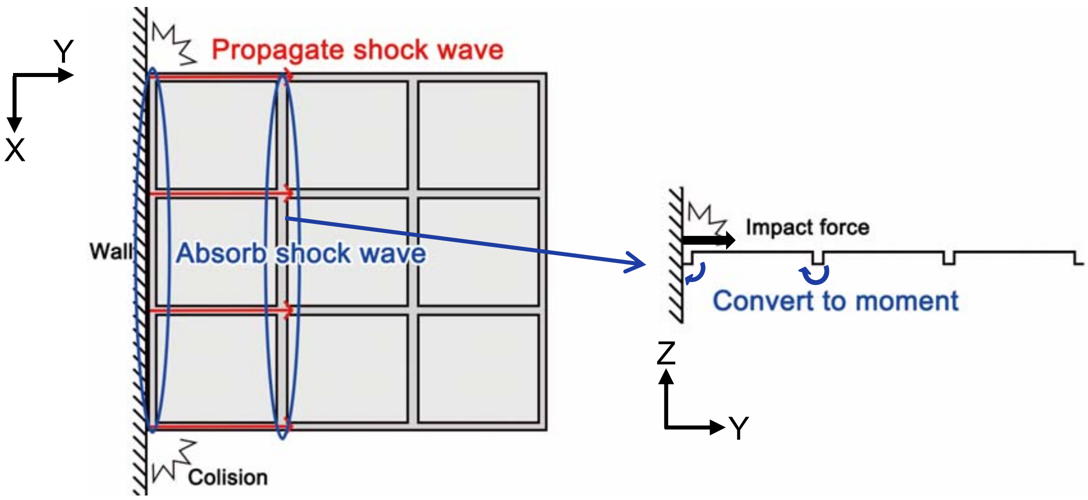


Figure 13: Mechanism of clip detachment in the level gaps

5 CONCLUSIONS

In this study, a concert hall model with a box-type suspended ceiling was constructed as an example of an acoustic facility with a heavy, complex suspended ceiling. A seismic motion analysis was conducted using the ASI-Gauss code.

Based on the numerical results, the following conclusions regarding the collapse mechanism of box-type suspended ceilings were drawn:

a) Once the ceiling collided with the wall, the shock waves propagated to the clip connecting the ceiling. If the clip detached, the load supported by the clip was redistributed to the adjacent clip, and the detachment progressed.
b) There was a tendency for the clips to detach easily in the level gaps perpendicular to the wall. However, the detachment of clips did not progress to the inner part of the ceiling. In the former case, the level gaps were rigid to the direction of collision and easily propagated the shock waves, whereas in the latter, the shock waves tended to attenuate by converting the impact force into a local moment in the level gaps parallel to the wall.

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