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NUMERICAL SIMULATION OF CEILING COLLAPSE IN FULL-SCALE GYMNASIUM SPECIMEN USING ASI–GAUSS TECHNIQUE

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Abstract. Many ceiling collapse accidents were observed during the 2011 Great East Japan earthquake and have been observed during other earthquakes in Japan. A numerical seismic simulation of the collapse of the ceiling in a full-scale gymnasium specimen, which was tested at the E-Defense shaking table facility in 2014 [1], was conducted. The numerical model represented steel structural frames and a suspended ceiling. All of the members were modeled using linear Timoshenko beam elements. The adaptively shifted integration–Gauss technique, which shifts the numerical integration point adaptively to an appropriate position, was applied to a nonlinear finite element analysis of this structurally discontinuous problem. The preliminary simulation results showed that ceiling collapse progressed owing to detachment of the clips that connected the ceiling joists to the ceiling joist receivers and eventually resulted in the ceiling falling down.

1 INTRODUCTION

A large-space building, such as a school gymnasium, which is typically used as a shelter during major earthquakes, must maintain its ability to function after an earthquake disaster and withstand aftershocks. After the main shock of the 2011 Great East Japan earthquake, a series of aftershocks occurred, and it was reported that, in addition to the human casualties suffered, many school gymnasiums failed to function as shelters because of the structural damage that they suffered, including column–base damage, brace buckling, and damage caused by falling nonstructural elements such as ceiling components and lighting equipment. To address these problems, design guidelines for suspended ceilings have been issued by several institutions. These guidelines are based on investigations of ceiling damage observed during previous earthquakes and experimental data obtained from scale models of ceilings, which are not necessarily derived from the actual behavior of collapsed ceilings.

To examine the collapse mechanism of a suspended ceiling, a three-dimensional (3D) shaking table test was conducted on a full-scale school gymnasium specimen with a suspended ceiling at the E-Defense shaking table facility in 2014 [1]. A numerical simulation of the collapse of the ceiling in the gymnasium specimen, observed in the shaking table test, was conducted. The simulation was based on nonlinear finite element analysis utilizing linear Timoshenko beam elements and the adaptively shifted integration (ASI)–Gauss technique [2], [3]. The modeling method and preliminary simulation results are presented in this paper.

2 MODELING OF A GYMNASIUM SPECIMEN WITH A SUSPENDED CEILING

2.1 Gymnasium Specimen

A picture of the specimen is shown in Figure 1. The plan of the first floor is 30.0 m × 18.6 m and the top of the sloped roof is 9.09 m above the ground. The specimen has 6 spans in both the X and Y directions. The pitch of the roof is 3/10 (= 3.6/12). The specimen is typical of the construction of an elementary or middle-school gymnasium in Japan. The columns, girders, beams, and roof purlins are steel members with wide-flange or channel sections. The girders are framed into the columns by welding. The braces are round steel bars with turnbuckles. The beams, except those in the braced frames, are connected to the columns with bolts, and the roof purlins are connected to the girders with bolts.

The numerical model of the gymnasium specimen, including its suspended ceiling, is illustrated in Figure 2. All of the members, including the plaster board on the ceiling, were modeled using linear Timoshenko beam elements. In this preliminary simulation, all of the connections were modeled using rigid connections, whereas bolted connections will be modeled using pin connections in future simulations. The ASI–Gauss technique requires that one member be modeled with only two elements to accurately represent plastic behavior. For this reason, nodes were placed at the end and center points of all of the members. The total number of elements was 17,900, and the total number of nodes was 13,736. All of the nodes on the first floor were fixed, and the ground motion acceleration was input at these nodes.

Figure 1: Gymnasium specimen

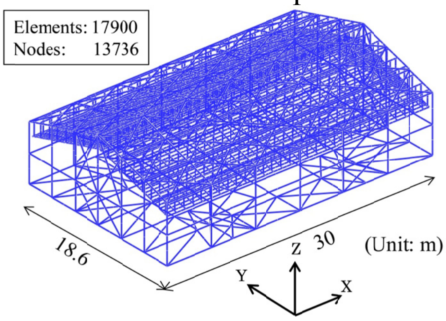
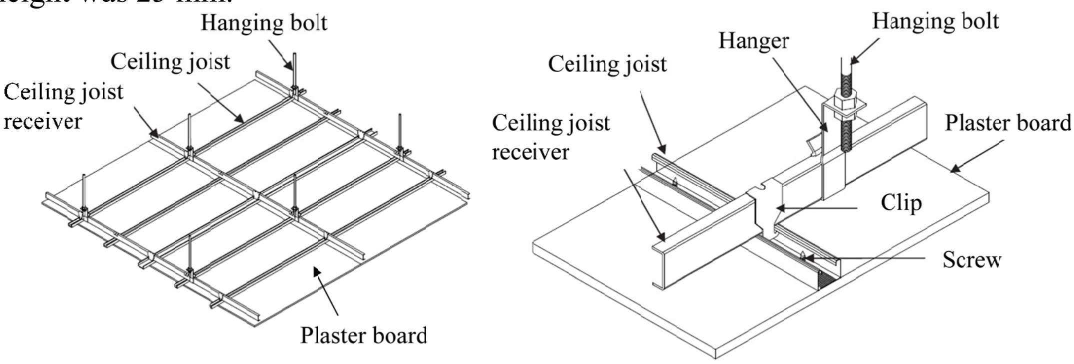


Figure 2: Model of gymnasium specimen

2.2 Suspended Ceiling

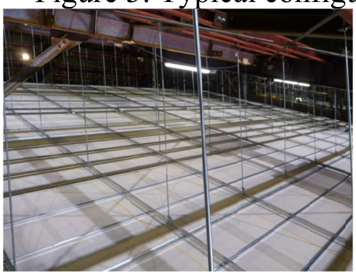
A typical configuration of a suspended ceiling is illustrated in Figure 3. Plaster board is attached to the ceiling joist with screws, the ceiling joists are attached to the ceiling joist receivers with clips, and the ceiling joist receivers are attached to the hanging bolt with hangers. In previous earthquakes, many ceiling collapse accidents have been caused by the detachment of the ceiling joist clips and hangers, resulting in the plaster board, ceiling joists, and ceiling joist receivers falling down. Therefore, in the model, the clips and hangers were modeled using beam element that can simulate fracture.

The suspended ceiling was modeled accurately, according to drawings of the design of the specimen. A picture of the suspended ceiling in the gymnasium specimen is shown in Figure 4(a), and the numerical model of the entire suspended ceiling is shown in Figure 4(b). The numerical model of a part of the ceiling is shown in Figure 4(c), along with the details of the element assemblage. The hanging bolt were spaced 1,000 mm apart in the X-direction and 1,147 mm along the slope in the Y-direction. The hanging bolts were 1,500 mm long, and the clip height was 25 mm.

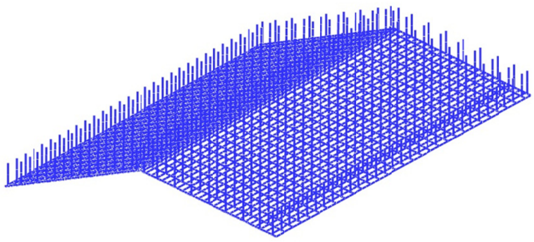


(a) Global (b) Detail

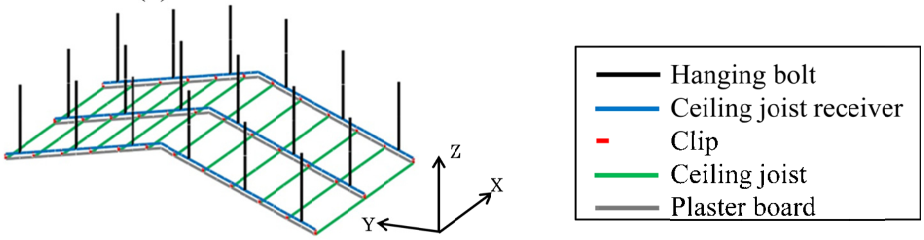
Figure 3: Typical configuration of suspended ceiling (perspective)



(a) Picture



(b) Overview



(c) Detail

Figure 4: Model of suspended ceiling

4 ANALYSIS METHOD

The ASI–Gauss technique [2], [3], which was used to shift the numerical integration point adaptively to an appropriate position, was employed in a nonlinear finite element analysis of the structure. The locations of the numerical integration and stress evaluation points used in the ASI–Gauss technique are illustrated in Figure 5. Two consecutive elements forming a member are considered to be a subset, and the numerical integration points of an elastically deformed member are placed such that the stress evaluation points are coincident with the Gaussian integration points of the member. Therefore, stresses and strains are evaluated at the Gaussian integration points of elastically deformed members, and the accuracy of the bending deformation is guaranteed even using one-point integration.

The updated Lagrangian method was used to consider geometric nonlinearity in the incremental analysis. The conjugate gradient (CG) method was used to solve the linear equations. The Newmark–β method was used for implicit time integration. The time step of the analysis was 1.0×10^{-3} s. The numerical simulation of the ceiling collapse was considered a structurally discontinuous problem. The detachments of the ceiling joists and ceiling joist receivers were considered by setting the sectional forces of the clips and hangers to be zero once the axial forces acting on these members exceeded the maximum strength. The contact of members with the ground was also considered.

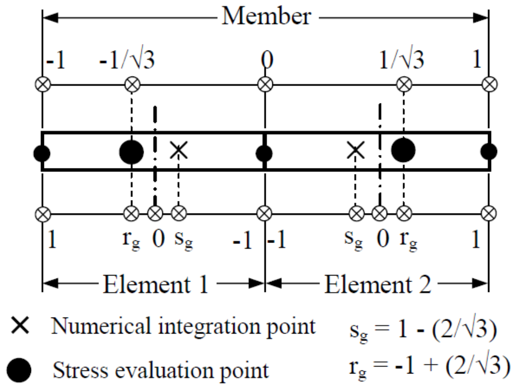


Figure 5 Location of numerical integration and stress evaluation points considered with the ASI–Gauss technique

5 PRELIMINARY SIMULATION RESULTS

A nonlinear time history simulation was conducted for the model of the full-scale gymnasium specimen with its suspended ceiling. The ground motion acceleration K-NET Sendai, which was observed during the 2011 Great East Japan earthquake and is shown in Figure 6, was scaled by 0.5 and input at all nodes on the first floor. The maximum strength of all of the clips was set to be 0.4 kN [4], and that of all the hangers was set to be 2.8 kN [5], to model the detachment of these elements.

The simulation results are shown in Figure 7. The ceiling joists and plaster boards on the right side of the suspended ceiling started to fall down approximately 72.5 s after the commencement of the simulation, as shown in Figure 7(a). The ceiling collapse commenced at 72.95 s, as shown in Figure 7(b). The clips became detached from the ceiling joist receivers, and the ceiling joists and plaster boards fell down at 74.2 s, as shown in Figure 7(c). Finally, the suspended ceiling had fallen completely at 75.2 s, as shown in Figure 7(d). The ceiling joists and plaster boards were all piled on the first floor. These results show that the numerical simulation of the ceiling collapse could be successfully conducted using the ASI–Gauss technique.

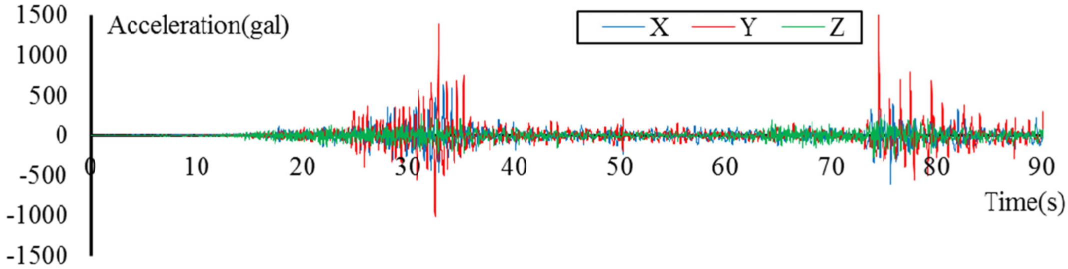
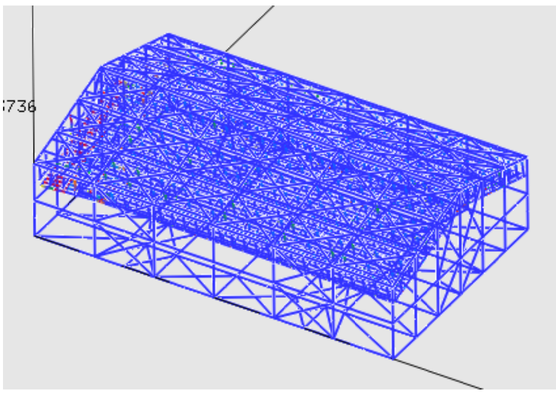
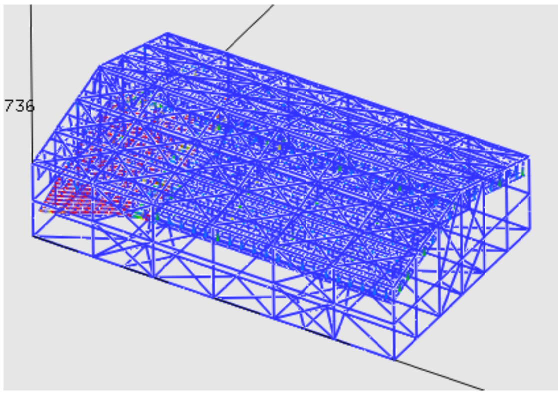


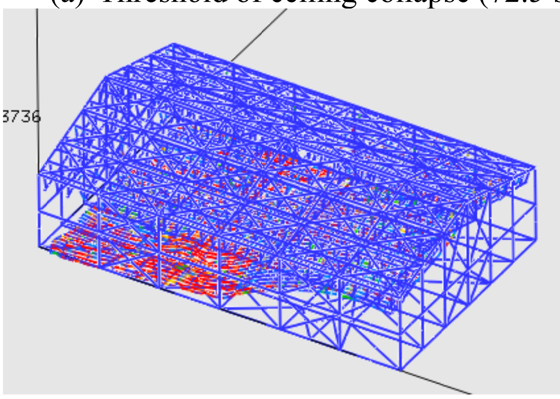
Figure 6: Ground motion acceleration (K-NET Sendai)



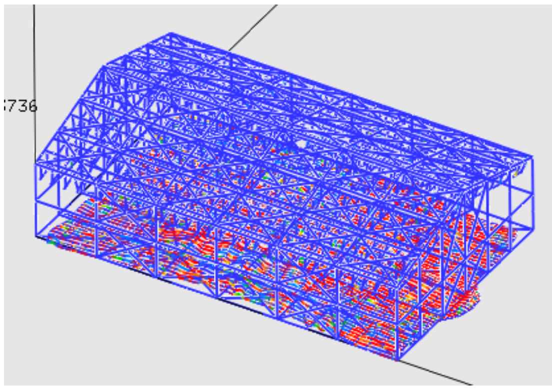
(a) Threshold of ceiling collapse (72.5 s)



(b) Progression of ceiling collapse(72.95 s)



(c) Progression of ceiling collapse (74.2 s)



(d) Complete falling-down (75.2 s)

Figure 7: Simulation results

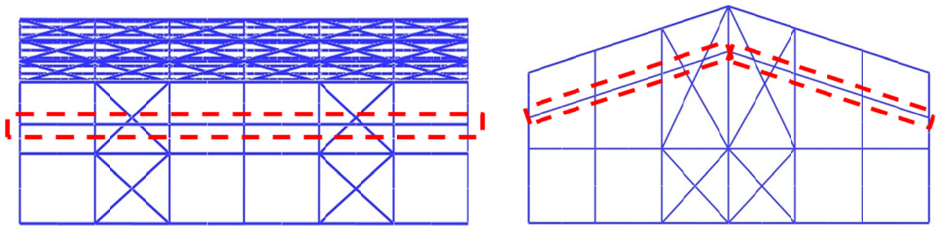
6 IMPROVEMENTS IN FUTURE SIMULATIONS

The numerical model shown in Figure 2 is being improved and calibrated so that the model corresponds better to the gymnasium specimen and better simulates the behavior observed in the 3D shaking table test. The issues to be addressed in future simulations are as follows.

- The beams are to be connected to the columns with bolts, and the roof purlins are to be connected to the girders with bolts. Currently, these connections are modeled as rigid connections. In addition, braces with turnbuckles are currently modeled using beam elements. These issues will be addressed by using truss elements to model the beams, braces, and roof purlins.
- A suspended ceiling is usually surrounded by outer walls. In the gymnasium specimen,

lateral joists are set on the perimeters so that the ceiling can be in contact with the outer walls, as shown in Figure 8. The contact of the suspended ceiling with the outer walls should be considered in future simulations.

- In the current model, the ceiling joists and ceiling joist receivers are continuous. In the gymnasium specimen, these members have splices that may become separated and cause partial collapse of the ceiling joists and ceiling joist receivers, as observed in the 3D shaking table test. Modeling of these members with splices may be required in future simulations.



(a) Elevation (X-Z) (b) Elevation (Y-Z)

Figure 8: Lateral joists to be in contact with ceiling

7 CONCLUSIONS

A numerical simulation of the collapse of the ceiling in a full-scale gymnasium specimen, which was tested at the E-Defense shaking table facility in 2014, was successfully conducted utilizing linear Timoshenko beam elements and the ASI–Gauss technique. A preliminary simulation showed that the ceiling collapse progressed owing to the detachment of clips that connected the ceiling joists to the ceiling joist hangers and ultimately resulted in the ceiling falling down. The issues to be addressed in future simulations, including the contact of the suspended ceiling with the outer walls, are addressed.

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