A Study on the Behaviour of Seismically Egineered Ceiling Systems of Large Open Structures Subjected to Earthquake Excitations

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SUMMARY:
The present paper discusses shaking table tests and experiments to evaluate clip connection strength that were carried out in an attempt to clarify the failure mechanisms involved in the collapse of large suspended ceilings in past earthquakes. The specimens correspond to part of a collapsed ceiling, and test input waves are calculated with the oscillatory property tests and the time history analysis based on the observed ground motion in the 2001 Geiyo Earthquake. The results of shaking tests at different input levels clarified the dynamic characteristics of suspended ceilings, and a number of the ceiling specimens were damaged in a manner that would have led to the collapse of a large suspended ceiling. Damage to the metal furring suspended ceiling systems used in Japan is due primarily to the failure of clip connections. To overcome this, we developed a seismically engineered suspended ceiling system in order to improve the seismic performance of conventional ceilings that use steel members.

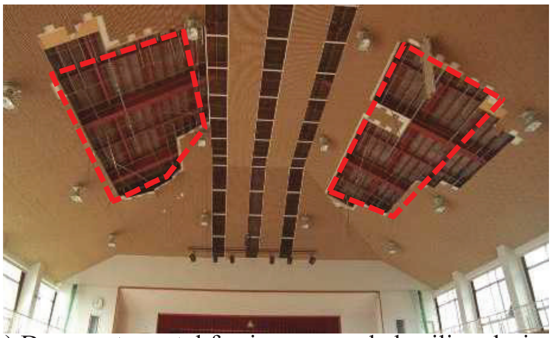
Keywords: Large open structures, Metal furring suspended ceiling, Seismically engineered ceiling clip, Earthquake damage, Shaking table tests

1. INTRODUCTION

On March 11, 2011 at 14:46, a magnitude 9.0 earthquake occurred off the coast of Honshu, Japan. The 2011 Great East Japan Earthquake was followed by a powerful tsunami that hit the east coast and caused extensive damage to the Tohoku and Kanto regions. In particular, damage concentrated on nonstructural component materials, such as ceilings, whereas in large open structures, such as gymnasiums, shopping centers, and production plants, structural components were largely undamaged. In production plants, several hundred square meters of plaster board ceiling was broken during the earthquake, which represented large significant property and functional losses. Nonstructural damage has often dominated the overall cost of repairs. Failure of large suspended ceiling systems is one of the most widely reported types of nonstructural damage to buildings associated with previous earthquakes, such as the 2001 Geiyo Earthquake, the 2003 Tokachi-oki Earthquake, and the 2005 Miyagi-ken Oki Earthquake [AIJ,2001, Nishiyama, et al., 2002, NILIM&BRI,2003,2005]. Nonstructural components, such as suspended ceilings, are not a part of the main load-resisting system. Therefore, these components are often neglected from a structural design point of view. Moreover, provisions related to nonstructural components in Japan’s seismic codes are inadequate.

Nonstructural components inside buildings, such as metal furring suspended ceiling systems, can be particularly vulnerable because they are subject to the motion of the building itself, which is an amplified version of the ground motion. Reducing damage to nonstructural components can be critical to the operability of key emergency response facilities, such as hospitals, data centers, and communications centers.

The present paper discusses shaking table tests and experiments to evaluate clip connection strength. It is hoped that the results can provide some insights into the failure mechanism involved in the collapse of large suspended ceiling structures in many past earthquakes. The models used in this study emulate an area of collapsed ceiling, and the test input waves are calculated through oscillatory property tests and a time history analysis using the observed ground motion in the 2001 Geiyo earthquake. The results of shaking tests at various input levels clarified the dynamic characteristics of the suspended ceilings, and a number of ceiling specimens were damaged in a manner that would have led to the collapse of a large suspended ceiling. Damage to metal furring suspended ceiling systems used in Japan is primarily due to the failure of clip connections. We therefore developed a seismically engineered ceiling clip (SECC) for use in suspended ceiling systems in order to improve the seismic performance of conventional ceilings that use steel members [Watakabe, et al., 2011]. The seismic performance of the developed ceiling systems was verified by the Great East Japan Tohoku Earthquake. The present paper introduces an effective clip connection method that was developed in order to reduce the likelihood of ceiling failure.



(a) Damage to metal furring suspended ceiling during the 2001 Geiyo Earthquake

(b) Damage to metal suspended ceiling during the 2011 Great East Japan Earthquake

Photograph 1. Damage to metal furring suspended ceiling systems used in gymnasiums

2. DAMAGE TO SUSPENDED CEILING SYSTEMS AND DYNAMIC CHARACTERISTICS OF A GYMNASIUM

2.1. Damage to metal furring suspended ceiling

Examples of metal furring suspended ceilings in gymnasiums that were damaged by the 2001 Geiyo Earthquake [Koshihara, 2001] and the 2011 Great East Japan Earthquake [NILIM, 2011] are shown in **Photograph 1**. The photographs show that breakage occurred at the center of the pitched ceiling. These gymnasiums are composed of lower SRC, an RC frame, and an upper steel frame. No damage to the steel roof structures, SRC structures, or RC columns was observed.

It is possible that in certain parts of the hanging ceiling, the fastening bolts came out of the furring-strip receptacles, so that the strips and chalk wall fell separately. This type of damage may originate in the destruction of ceiling junction clips, as was seen during the 2001 Geiyo Earthquake. Such damage indicates that the joint between the M-bar and the channel is a weak point. In addition to such breakage of ceiling clips, there are many other types of damage that cause the furring strips and chalk wall to fall.

2.2. Collapse mechanism of metal furring suspended ceiling system

2.2.1. Dynamic characteristics of gymnasium

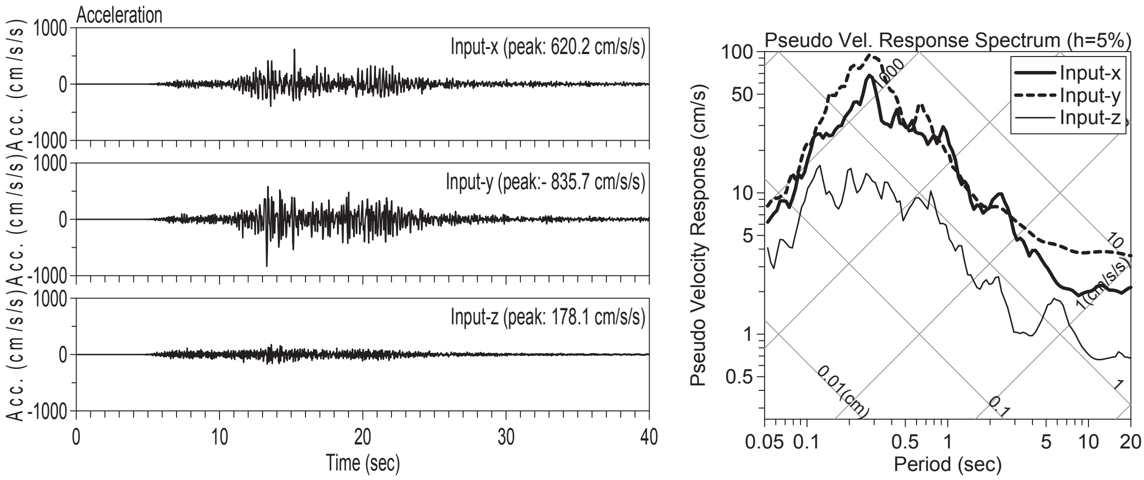
The seismic design of nonstructural components is currently based on the equivalent lateral force method, in which metal furring suspended ceiling systems are designed to withstand a lateral seismic force that is a fraction of the weight of the ceiling. However, the response of the suspended ceiling system depends on, for example, the response of the supporting large open structure, the size and weight of the ceiling, and the location of the ceiling in the building.

First, in order to investigate the failure mechanism that led to the collapse of large metal furring suspended ceilings during past earthquakes, the oscillatory properties of the 2001 Geiyo Earthquake, which damaged a school gymnasium, were estimated based on microtremor observations and forced vibration tests. Natural frequencies and damping ratios are very important parameters for characterizing the dynamic response of the damaged gymnasium. These dynamic characteristics have previously been investigated based on microtremor observations and forced vibration tests [Wakiyama, et al., 2010].

Second, a modeling and response time history analysis was conducted. In order to verify the accuracy of the modeling method, a comparison was made between the dynamic characteristics of the damaged gymnasium estimated using the analytical model and the observed values, and the results are shown in **Table 1**. The simulated results are based on the three-dimensional (3D) model shown in **Figure 2**. It can be seen that there is good agreement between the measured and simulated results.

Table 1. Fundamental frequencies of the gymnasium

	Transverse direction(x)	Longitudinal direction(y)	Vertical direction(z)
Observed(Hz)	4.6	6.6	5.6
Simulated(Hz)	4.8	6.6	5.5
Simulated /Observed	1.04	1.00	0.98



(a) Input acceleration time histories for the three directions

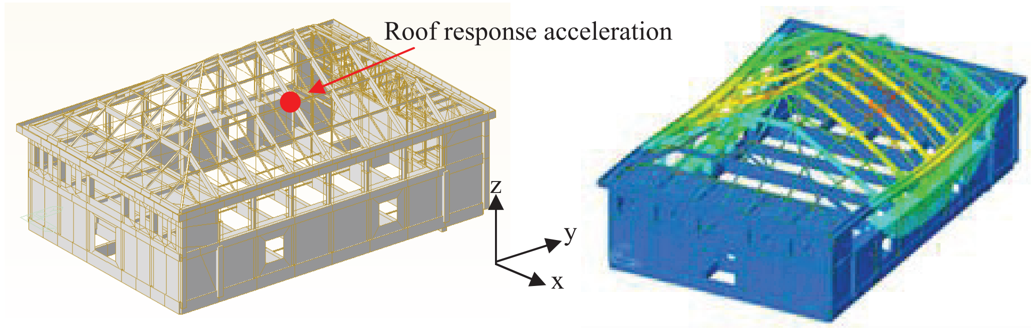
(b) Pseudo-velocity response spectrum with damping ratio of 5%

Figure 1. Acceleration time histories and pseudo-velocity response spectrum of ground motion records during the 2001 Geiyo Earthquake

Figure 1 shows the acceleration time histories and pseudo-velocity response spectrum with a damping ratio of 5% for the strong motion record at Kumano station, which recorded an intensity of 6- during the main shock of the 2001 Geiyo Earthquake. It can be seen that the maximum acceleration in the longitudinal direction (y) exceeds 800 cm/s^2, and the pseudo-velocity response spectrum has peaks at a period of approximately 0.3 s. The coincidence of the fundamental natural period (0.20 s to 0.23 s) of the gymnasium with the predominant period of the earthquake ground motion is considered to have caused a resonance phenomenon that led to strong motion of the building.

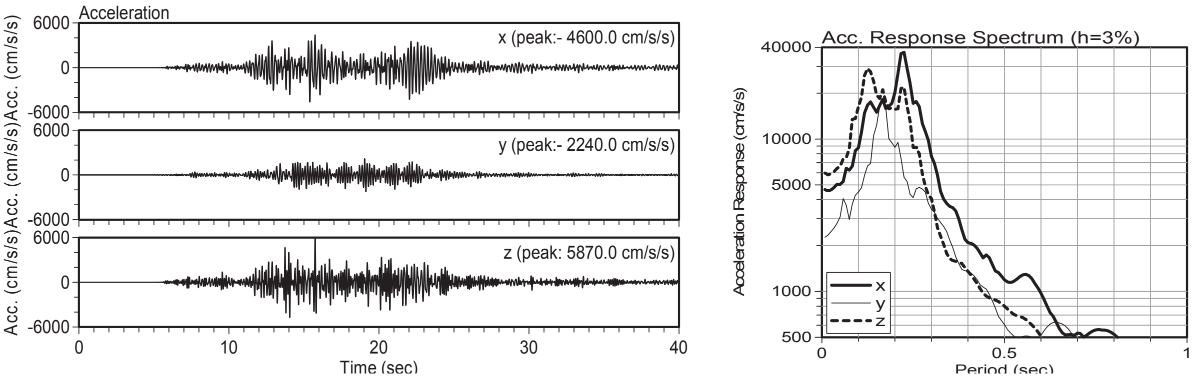
2.2.2. Numerical simulation results

In order to confirm the response of the gymnasium, a time history analysis were carried out using the 3D analytical model shown in **Figure 2**. For the input ground motion waveform to the analytical model, the acceleration time history records observed near the gymnasium was adopted. **Figure 1** shows the details of the input acceleration in the analytical model. The peak acceleration exceeded 600 cm/s^2 in the transverse (x) and longitudinal (y) directions, whereas the vertical (z) acceleration had a peak value of approximately 170 cm/s^2. The analysis was run using the linear modal time history analysis method with a constant damping of 3%, the value of which was decided based on the measurement results.The simulated acceleration response time histories and pseudo-acceleration response spectrum of the roof component indicated by the red ● symbol in **Figure 2(a)**, are shown in **Figures 3(a)** and **3(b)**, respectively.



(a) Schematic of the 3D dynamic model (b) Fundamental vibration mode(4.84Hz)

Figure 2. Outline of analytical model and vibration mode



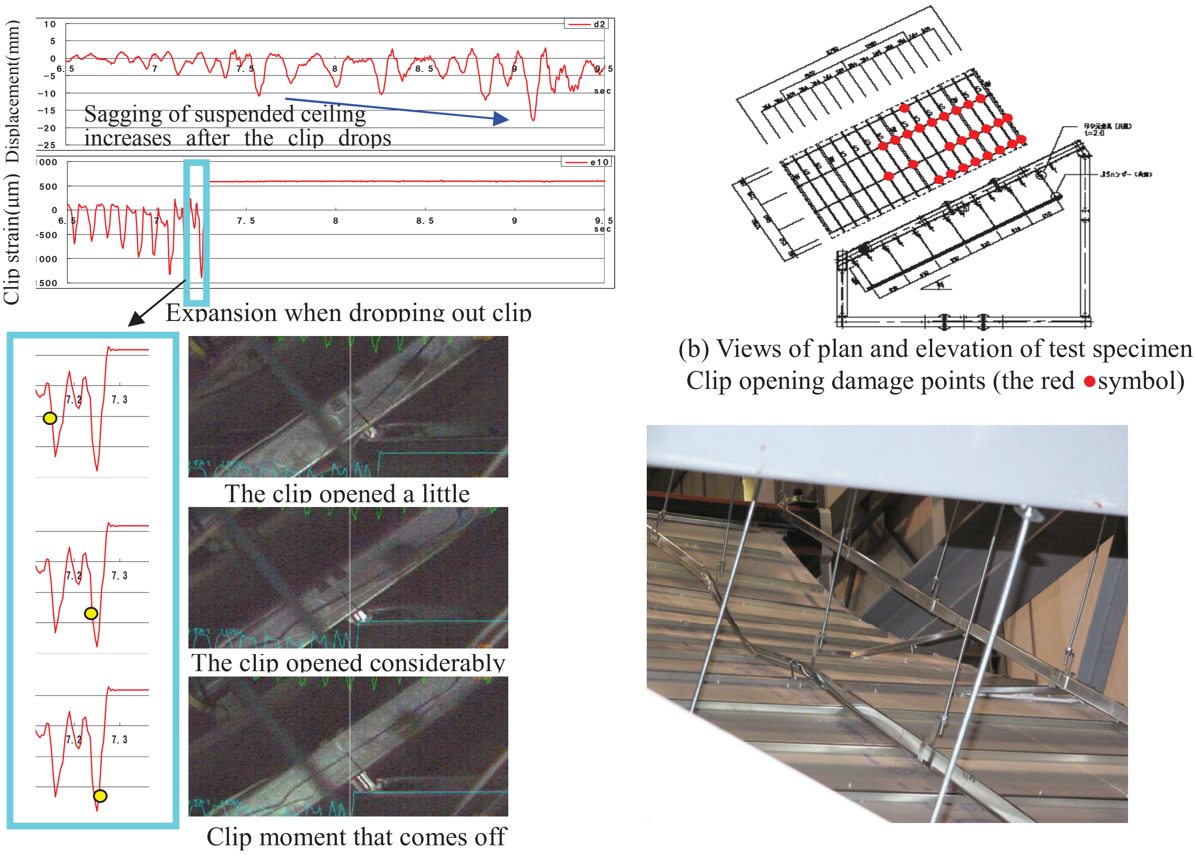
(a)Roof acceleration response time histories (b) Pseudo-acceleration response spectrum with damping ratio of 3%

Figure 3. Simulated roof acceleration response time histories and pseudo-acceleration response spectrum of damaged gymnasium at the position indicated by the red ● symbol in **Figure 2(a)**

A significant difference in dynamic response exists between the upper steel roof and the lower RC frames due to the irregular distribution of stiffness. Although the maximum acceleration of the input ground motion is 830 cm/s in the horizontal direction and 180 cm/s^2 in the vertical direction, the acceleration response of the roof component is amplified significantly, having values of 4,600 cm/s^2 in the x-direction and 5,870 cm/s^2 in the z-direction. Thus, particularly strong amplification occurs in the vertical direction. In the present study, the relationship between the vertical and lateral acceleration response at the roof level is investigated. The vertical acceleration response of large open structures, such as gymnasiums, strongly depends on the lateral excitation. In a previous study, the relationship between the lateral and vertical responses of a gable roof was confirmed by shaking table tests and analyses [Ishioka, et al., 2010].

In the present study, In order to investigate the collapse mechanism of a metal furring suspended ceiling, as indicated by the red dotted lines in Photograph 1(a), a series of shaking table tests was carried out. The seismic response of gable roofs is known to be amplified in the vertical direction under horizontal input. However, the influence of pitch on the amplification of vertical vibration has not yet been clarified. Thus, in the present study, the damaged gymnasium structure was simulated using these dynamic properties and the relationship between the horizontal and vertical excitation response of nonstructural components was investigated.

An experimental investigation of the damaged ceiling shown in Photograph 1(a) was conducted. The ceiling structure selected for the present study was set on a roof slab in a gymnasium damaged during the 2001 Geiyo Earthquake. **Figure 4** shows the shaking table test results for the metal furring suspended ceiling of the damaged gymnasium. **Figure 4(a)** shows the clip dropout process before the M-bar falls. The metal-sheet clips hanging from the metal furring channels were found to have been damaged by the roof motion.



(a) Clip dropout process before falling of the M-bar (c) Failed situations of the ceiling elements

Figure 4. Experimental results for the metal furring suspended ceiling obtained using a shaking table

3. OUTLINE OF THE SECC

The metal furring suspended ceiling system considered herein is composed of steel members and plasterboards, as shown in **Figure 5**. The M-bar, which is attached directly to the plasterboard, is connected to the channel by means of a clip, which is a discrete metal part. The clip can be connected using either a front or back configuration. This type of system is easily constructed and is widely used in Japan. Damage caused by previous earthquakes and the results of previous studies (Wakiyama et al., 2010, Sato et al., 2011) have revealed that the clip is the critical component that can cause a ceiling to fail and collapse. Based on the above damage examples, an SECC construction method is developed for the purpose of effectively reinforcing a ceiling junction. An outline of the method is shown in **Figure 5**. According to the size of a common clip, the SECC comes in two sizes: single and double. The mounting method is shown in **Photograph 2**.

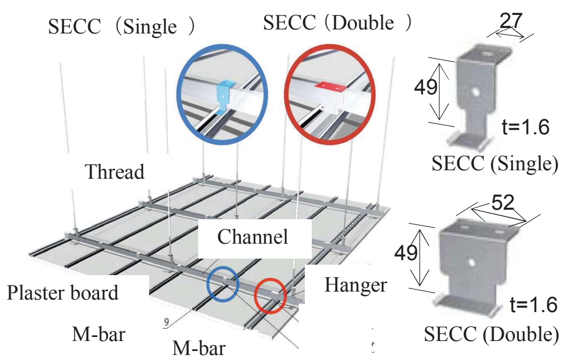
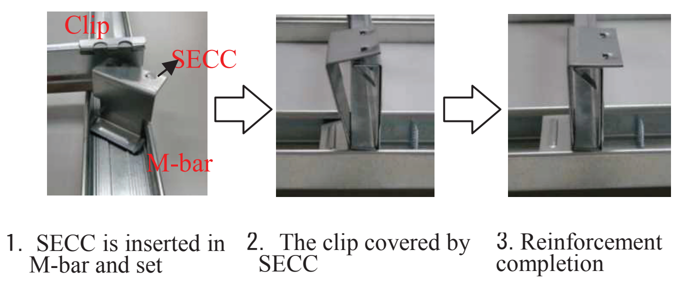


Figure 5. Schematic of SECC (unit: mm)



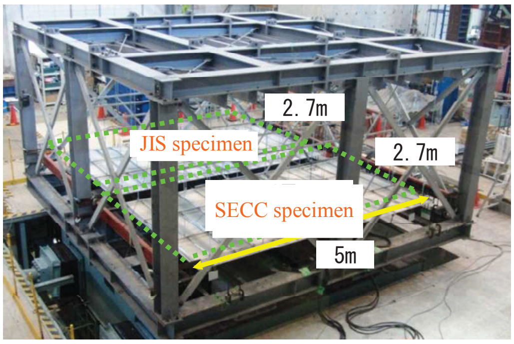
Photograph 2. Connection of the SECC

It is only inserting in from the existing common clip; welding or bolting are unnecessary, making the construction process easy.

4. SHAKING TABLE TESTS

4.1. Outline of Experimental Tests

In this section, the series of tests devised to verify the strength of the developed SECC is described. The test frame is designed to be used for seismic testing of the metal suspended ceiling systems using simulated roof motion. The overall size of the frame is 5.5 m × 5.5 m and its height is 4.0 m. A shaking table test was carried out in order to verify the performance of the SECC. **Photograph 3** shows an outline of the shaking table test. The ceiling has an area of 2.7 m × 5.0 m and a mass of 189 kg. The M-bars are placed 0.303 m apart, and the metal furring suspended ceiling specimens without SECC and with SECC were excited simultaneously in order to compare the performance of the SECC construction method and the metal furring suspended ceiling system. The input waveforms used were scaled versions (4%, 8%, 12%, 16%, 20%, 32%) of the roof acceleration response simulated by the ground motions recorded at Kumano station during the M6.7 Geiyo Earthquake in Japan on 24th March, 2001.



Photograph 3. Test frame and the suspended ceiling specimen mounted on a shaking table

In order to compare the performance of the reinforced ceiling with and without the SECC construction method, the size of the ceiling specimen produced respectively four ceiling specimens with and without the SECC. Four different areas of the ceiling were investigated for each case, giving a total of eight specimens covering an area of 2.7 m × 5.0 m. The ceiling material was, and did not install all the clearances at the edge of the ceiling with 19 shape of JIS material (Rubber is set up at the edge). The ceiling board was assumed putting 9.5 mm by two plasterboards.

Table 3. Characteristics of specimens for shaking table test

Specimen No.	Suspending length(mm)	Suspended ceiling Type	With or without the brace	With or without the SECC
I	800	Flat	Without the brace	With
			Without the brace	Without
II	1500	Flat	Without the brace	With
			Two pairs	Without
III	800～2400	Curved surface	Without the brace	With
			One pair of curve and horizontal	Without
IV	2400	Flat	Without the brace	With
			Two pairs brace , two steps and horizontal	Without

The experimental tests and specimens are shown in **Table 3** and **Figure 6**, respectively. The experimental parameters were the hanging length and the ceiling shape (flat or curved surface), as well as the presence or absence of the SECC. A swinging stop brace was set up respectively about the examination specimens for hanging length to exceed 1,500 mm**.** A general construction method was followed, and both multiplications of the curved surface part of the ceiling specimen No. III were the clips**.** Ceiling specimen No. I has the same specifications as the gymnasium described later herein. The input waveform to the shaking table was based on the results of the seismic response analysis for this gymnasium. A series of shaking table tests was conducted with an input acceleration of approximately 1,800 cm/s^2 in the x-direction and a maximum vertical input of approximately 1,400 cm/s^2. The former value was chosen so as not to exceed the practical upper limit of 2,000 cm/s^2 of the shaking table. The input waveform used in the shaking table test and its spectrum are shown in **Figures 3(a)** and **3(b)**, respectively.

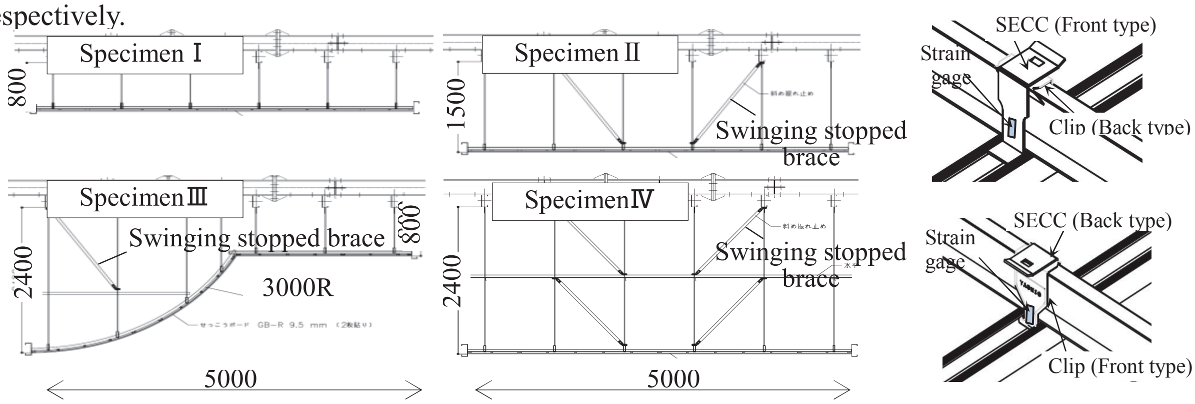


Figure 6. Elevation of the metal furring suspended ceiling specimens (unit: mm)

4.2. Measurement Plan

The specimens were instrumented with a variety of sensors, such as accelerometers and displacement transducers. A schematic of the sensor layout is shown in **Figure 7**. Accelerometers were installed at nine locations, and displacement meters at four locations. The vertical acceleration was measured at all nine locations, and the horizontal acceleration was measured at the three central points on the specimens.

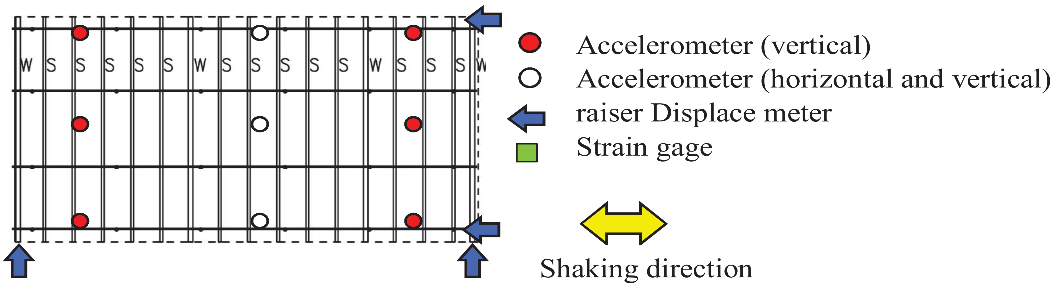


Figure 7. Locations of accelerometers on the suspended ceiling and transducers at the base of the frame

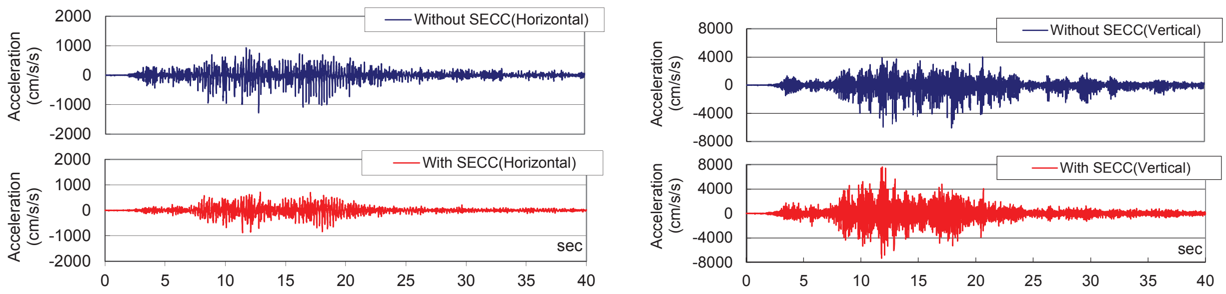
4.3. Experimental Results

4.3.1. Fundamental frequencies of the ceiling specimens

White noise testing was used to determine the frequencies of the suspended ceiling systems. The fundamental frequencies for the horizontal and vertical directions of each test specimen were obtained

Table 4. Fundamental frequencies of suspended ceiling specimens

No.	Fundamental frequency (Hz)			
	Specimen of suspended ceiling without the SECC		Specimen of suspended ceiling with the SECC	
	Horizontal	Vertical	Horizontal	Vertical
I	7.4	10.8	12.1	19.4
II	15.8	18.2	12.1	19.2
III	12.9	19.7	12.1	19.1
IV	12.5	18.2	12.8	17.1



(a) Acceleration time histories of horizontal direction (b) Acceleration time histories of vertical direction

Figure 8. Acceleration response time histories of ceiling specimen No. IV

by finding the frequency associated with the peak in the acceleration transfer function. **Table 4** shows the fundamental frequencies measured for each ceiling specimen. Since each case did not take the clearance at the edge, the difference of the characteristic frequency by the difference between the length of the hanging bolt and the ceiling shape was not so seen. However, compared with experimental tests, the fundamental frequency of the metal furring suspended ceiling without the SECC was low.

4.3.2. Acceleration response of ceiling test specimens during bi-directional input motion tests

Comparing the experimental results with and without the SECC reveals the reinforcement effect of the SECC. Figure 8 shows the time histories of the horizontal and vertical acceleration responses on the plasterboard of the ceiling specimens, with and without the SECC, for an input acceleration of about 1,300 cm/s^2 in the horizontal direction and 1,800 cm/s^2 in the vertical direction. The maximum vertical acceleration response without the SECC is approximately 6,000 cm/s^2 and with the SECC is approximately 8,000 cm/s^2. Although there is no difference in the horizontal response with or without the SECC, a larger vertical response is found with the SECC. This confirms the increase in the rigidity of the ceiling reinforced with the SECC.

The relationship between the vertical input acceleration and the maximum acceleration response on the plasterboard of the ceiling is shown in **Figure 9**. The tendency to serve as large response acceleration was seen as input acceleration became large, although there was no difference against the acceleration of a ceiling by the traditional method of construction and a seismically engineered ceiling clip construction method when input acceleration was small.

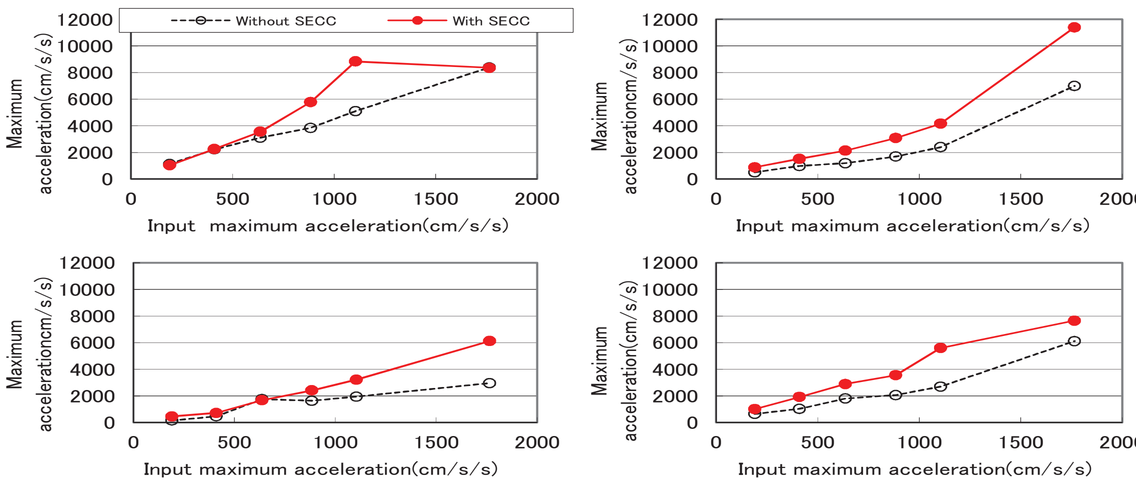


Figure 9. Relationships between input vertical motion and maximum vertical acceleration response on the plasterboard of the metal furring suspended ceiling with and without the SECC

However, it is referring to the destructive situation of the ceiling which was non-damage mostly as for the ceiling reinforced with the SECC construction method while, as for ceiling response acceleration. A damage situation, any case's suffered directly the damage at the time of the maximum input the ceiling without the SECC having been serious, not related. The most critical ceiling element in the metal furring suspended ceiling systems was the clip connection between the M-bar and the channel. The roof floor vertical acceleration that caused ceiling failure was greater than approximately 1.0 G for ceiling test specimens with dimensions of 5.0 m × 5.0 m.

Table 4. Damage levels of metal furring suspended ceiling systems with and without SECC

Specimen No.	Damage situation	
	Without SECC	With SECC
Ⅰ	Damage to clip opening : 23points(38%)	No damgage
	Damage to clip hanger : 5points(21%)	
Ⅱ	Damage to clip opening : 22points(37%)	No damgage
	Damage to clip hanger : 4points(17%)	
Ⅲ	Damage to clip opening : 11points(15%)	No damgage
	Damage to clip hanger : 0points(0%)	
Ⅳ	Damage to clip opening : 20points(33%)	No damgage
	Damage to clip hanger : 5points(21%)	

4.3.3. Damage to experimental testing ceiling

The damage that occurred to the metal furring suspended ceiling specimens for each experimental testing case is shown in **Photograph 4** and listed in **Table 4**. For example, as shown in **Photograph 4**, for all of the tests, most of the clip connections between the M-bar and the channel of the metal furring suspended ceiling specimens without the SECC failed.

A gap appears between the M-bar and the channel as the clip opens. The compressive force in this component does not occur until the gap disappears.

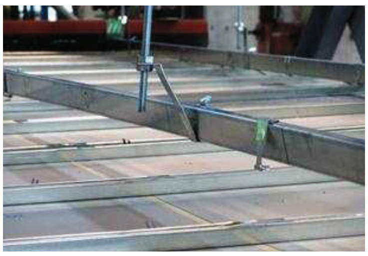
Based on the experimental results, for the traditional method of construction, a number of clips in the central section separated and the ceiling deformed severely. The clip of this shows the thing which it pulled and was destroyed in response to load by up-and-down motion.

Ceiling specimen No. Ⅰ

Damage to clip and hanger

No damage

Ceiling specimen No. Ⅱ



Damage to clip and hanger

(a) Without SECC

No damage

(b) With SECC

Photograph 4. Examples of damage to metal furring suspended ceiling with and without SECC

5. CONCLUSIONS

In the present study, the dynamic behavior of metal furring suspended ceiling systems subjected to simulated input motions of various durations was investigated experimentally and analytically. Based on the analytical results and the results of dynamic tests using a shaking table, the following conclusions can be drawn:

(1) The vertical acceleration response of large open structures such as gymnasiums, depends strongly on the lateral excitation. This investigation revealed that knowledge of the vertical response of such structures is necessary in order to better understand their overall responses. It was found that the ceiling response was highly correlated to the responses in the horizontal and vertical directions.
(2) The dynamic test results for the metal furring suspended ceiling of a damaged gymnasium obtained in shaking table tests confirmed that the metal-sheet clips holding the metal furring channels were damaged by the roof response to the input motion.
(3) The present study was conducted in order to develop a seismically engineered ceiling clip (SECC) for metal furring suspended ceilings in large open structures, and the seismic performance of the SECC was verified. The present paper described an effective method of clip connection that was developed in order to reduce the likelihood of ceiling failure.

AKCNOWLEDGEMENTS
The present study was conducted as part of a research project under the auspices of the Building Standard Maintenance Promotion Program by the Ministry of Land, Infrastructure, Transport, and Tourism. The present paper also presents results obtain through joint research with Toda Corporation, Nishimatsu Construction, and the Yashio Kenzai Corporation. It describes here and appreciates to whom it may concern.

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