16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 2935 (Abstract ID)

Registration Code: S-Y1464678686

COLLAPSE MECHANISM OF WIDE-AREA SUSPENDED CEILING BASED ON FULL-SCALE SHAKE TABLE EXPERIMENT OF SCHOOL GYMNASIUM

T. Sasaki(1), A. Aoi(2), H. Tagawa(3), K. Kajiwara(4), D. Sato(5)

(1) Researcher, National Research Institute for Earth Science and Disaster Resilience, tomo_s@bosai.go.jp
(2) Researcher, Takenaka Corp. (former National Research Institute for Earth Science and Disaster Resilience), aoi.atsushi@takenaka.co.jp
(3) Assoc. Prof., Mukogawa Women's University (former National Research Institute for Earth Science and Disaster Resilience), tagawa@mukogawa-u.ac.jp
(4) Manager, National Research Institute for Earth Science and Disaster Resilience, kaji@bosai.go.jp
(5) Assoc. Prof., Tokyo Institute of Technology. (former National Research Institute for Earth Science and Disaster Resilience, sato.d.aa@m.titech.ac.jp

Abstract

In the 2011 off the Pacific coast of Tohoku Earthquake, a lot of suspended ceilings suffered damage and collapsed due to lack of their seismic performance. New seismic standards for wide-area suspended ceiling have been in effect from April 2014 in Japan. In the new standards, screw fastening to the connection of metal parts, a lot of bracings and clearance between ceilings and walls are required. However, collapse mechanism of ceiling is not yet clarified enough and effective seismic countermeasures are needed.

To identify the collapse mechanism of non-seismic ceiling and evaluate seismic performance of seismically designed ceiling, two series of full-scale shake table experiment is conducted. The specimen is designed as the steel school gymnasium with suspended ceiling. Structural members are designed based on the current Japanese code. In the gymnasium specimen, two different types of ceiling are installed; one is the non-seismic ceiling designed as the typical ceiling without any seismic countermeasures, the other is the seismically designed ceiling based on new seismic standards for ceiling.

Based on the experiment, collapse mechanism is clarified. In the case of non-seismic ceiling under sloped roof, collapse initiated by up-lifting moment around side wall. In the case of seismically designed ceilings, the failure mechanism depends on the balance of the strength of braces and metal connections between braces and frame.

Keywords: Suspended Ceiling, Steel Gymnasium, Collapse Mechanism, Full-scale Shake Table Experiment, E-Defense

1. Introduction

In the 2011 off the Pacific coast of Tohoku Earthquake, a lot of suspended ceilings in large-space structures such as gymnasium suffered damage and collapsed due to lack of their seismic performance[1]. In 2016 Kumamoto Earthquake, several gymnasium also suffered damage as shown in Photo 1. Because the school gymnasiums are generally expected to be used as evacuation shelters after strong earthquake, their seismic performance including nonstructural components and serviceability after earthquake is important. Thus, new seismic standards for wide-area suspended ceiling have been in effect from April 2014 in Japan. In the new standards, screw fastening to the connection of metal parts, a lot of bracings and clearance between ceilings and walls are required. However, collapse mechanism of ceiling is not yet clarified enough and effective seismic countermeasures are needed.

Photo 1 Collapse of Suspended Ceiling in Gymnasium during Kumamoto Earthquake

To identify the collapse mechanism of non-seismic ceiling and evaluate seismic performance of seismically designed ceiling, two series of full-scale shake table experiment is conducted. The specimen is designed as the steel school gymnasium with suspended ceiling. Structural members are designed based on the current Japanese code. In the gymnasium specimen, two different types of ceiling are installed; one is the non-seismic ceiling designed as the typical ceiling without any seismic countermeasures, the other is the seismically designed ceiling based on new seismic standards for ceiling. This paper represents experimental results and collapse mechanism of suspended ceilings.

2. Experimental Setup

Photo 2, Figure 1 and Table 1 show gymnasium specimen used for full-scale shake table experiment. The gymnasium specimen is designed as a steel gymnasium in elementary or junior high schools based on current Japanese code. Its size is 18.6 m x 30 m, which is larger than E-Defense shaking table, its height is 9.09 m and it has 10:3 sloped roof.

It is designed based on allowable stress design with base shear coefficient C_0 of 0.2. Its main column and roof girder is H400x200x8x13, its beam is H248x124x5x8, its column in end panel is H250x125x6x9 and H300x150x6.5x9, and its base girder is tapered H900x300x16x28. Diameter of vertical braces are 20 mm in end panel and 27 mm in the others, and that of lateral braces are 16 mm. Yield strength and tensile strength of column, girder, braces is the range of 291 to 330 N/mm^2 and 443 to 482 N/mm^2, respectively.

Photo 3 and Table 2 show suspended ceiling installed inside gymnasium specimen. Two series of shake table experiment were conducted; 1) the gymnasium specimen with nonseismic ceiling and 2) that with seismically designed ceilings with seismic coefficient of 1.1G and 2.2G. Nonseismic ceiling is designed as typical ceiling without any seismic countermeasures. Nonseismic ceiling is hanged by bolts with a diameter of 10 mm, length of 1500 mm and distance of 1147 x 1000 mm. Light-weight steel members for nonseismic ceiling is 19 type channel members defined in JIS (Japan Industrial Standard) with a section of 25×19×0.5 for narrow ceiling joists, 50×19×0.5 for wide ceiling joists and 38×12×1.2 for ceiling joists receivers. JIS confirmed easy-construction ceiling clips and hangers are used as connections. Ceiling panels are consists of gypsum boards with thickness of 9.5 mm and rock wool acoustic boards with thickness of 9 mm. Unit weight of ceiling is 13.1 kg/m^2. There is no clearance between ceiling and wall/column.

Photo 2 Full-scale Gymnasium Specimen

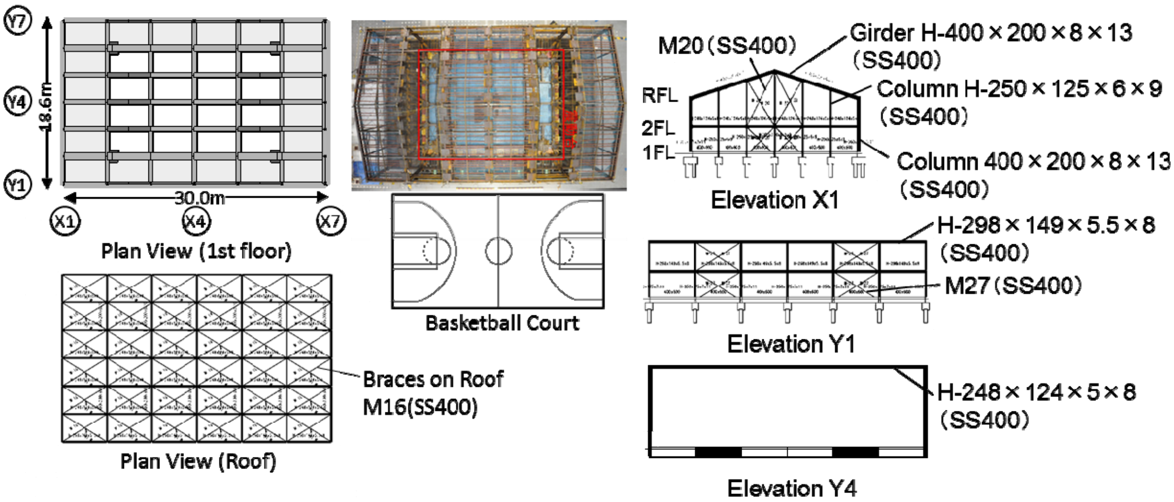


Fig. 1 Experimental Specimen

Table 1 Specification of Gymnasium Specimen

Item		Specification
Structure		One Story Steel Gymnasium
Weight	Superstructure	71t (without weight on roof)
	Weight on Roof	30t
	Total Weight	230t
Height		9.090m
Plan Size		30.0m×18.6m (6 x 6)
Design		Allowable stress design (Base-shear $C_0 = 0.2$)
Members	Column	H400×200×8×13 (SS400) H250×125×6×9 (SS400) H300×150×6.5×9 (SS400)
	Girder	H400×200×8×13 (SS400)
	Beam	H248×124×5×8 (SS400)
	Vertical Braces	M20, M27 (SNR400B) Pipe-type Turnbuckle
	Lateral Braces	M16 (SNR400B) Pipe-type Turnbuckle

(a) Nonseismic ceiling (b) Seismically designed ceiling with seismic coefficient of 1.1G (c) Seismically designed ceiling with seismic coefficient of 2.2G

Photo 3 Suspended Ceiling

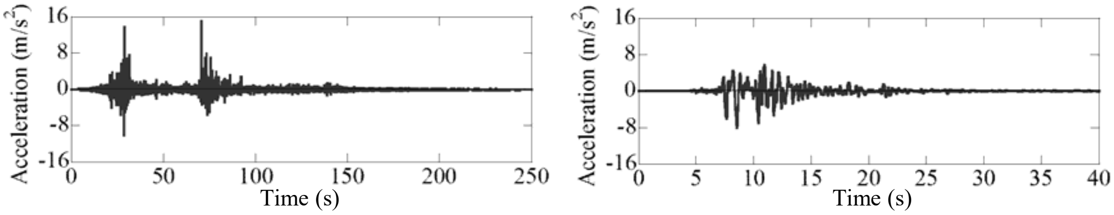
Table 2 Specification of Suspended Ceiling

	Specification		
	Nonseismic Ceiling	Seismically Designed Ceiling with Seismic Coefficient of 1.1G	Seismically Designed Ceiling with Seismic Coefficient of 2.2G
Experimental Date	Jan. 27-28, 2014	H26.2.27～28	
Seismic Coefficient	N/A	1.1	2.2
Hanging Bolts	Φ10 mm Bolts		
Length of Bolts	1500mm		
Distance of Bolts	1147×1000mm	860×1000mm	860×1000mm
Ceiling Joist Receiver	JIS 19 type (38x12x1.2)@1000mm	JIS 19 type (38x12x1.2)@1000mm	[-40×20×1.6 @1000mm
Hanger	JIS Confirmed Hanger (for slope ceiling)	Aseismic Clip with screw	Aseismic Clip with screw
Narrow Ceiling Joist	JIS 19 type (25x19x0.5)@364mm	JIS 19 type (25x19x0.5)@303mm	JIS 25 type shape section with thicker steel (t=0.8mm) (50x25x0.8)@303mm
Wide Ceiling Joist	JIS 19 type (50x19x0.5)@1820mm	JIS 19 type (50x19x0.5)@910mm	
Clip	JIS 19 type Easy Construction Clip	Aseismic Clip with Screw	Aseismic Clip with Screw
Brace	N/A	27 pairs of braces with section of [-40x20x1.6	30 pairs of braces with section of C-50x25x10x1.6
Clearance	0 mm	More than 60 mm	
Ceiling Panel	Gypsum boards (t=9.5mm) + Rock wool acoustic boards (t=9mm)		
Ceiling Unit Weight	13.1kg/m^2	13.8kg/m^2	16.0kg/m^2

Seismically designed ceilings with seismic coefficient of 1.1G (designated as 1.1G seismic ceiling) is designed as ceiling assembled using JIS confirmed, widely used lightweight steel members based on new Japanese seismic design code for ceiling. On the other hand, seismically designed ceilings with seismic coefficient of 2.2G (designated as 2.2G seismic ceiling) is designed as ceiling assembled using lightweight steel members with large enough sections based on new Japanese seismic design code for ceiling. Seismically designed ceilings with seismic coefficient of 1.1G and 2.2G are hanged by bolts with a diameter of 10 mm, length of 1500 mm and distance of 840 x 1000 mm. Light-weight steel members for 1.1G seismic ceiling is 19 type channel members defined in JIS (Japan Industrial Standard) with a section of 25×19×0.5 for narrow ceiling joists, 50×19×0.5 for wide ceiling joists and 38×12×1.2 for ceiling joists receivers. There are 27 pairs of ceiling braces with section of [-40x20x1.6 for 1.1G seismic ceiling. On the other hand, light-weight steel members for

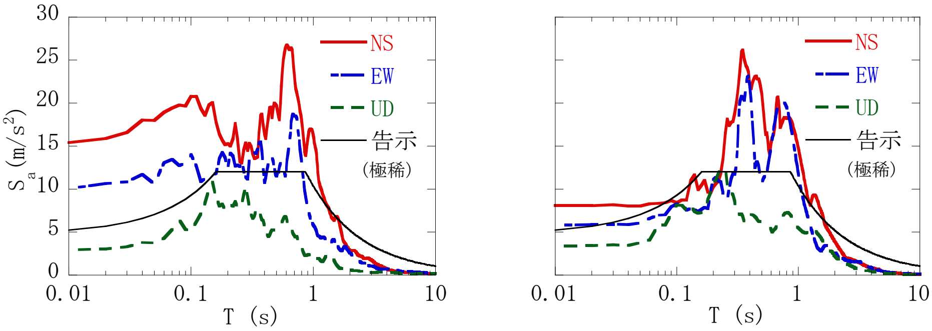
2.2G seismic ceiling is channel members with a section of 50x25x0.8 for ceiling joists and [-40×20×1.6 for ceiling joists receivers. There are 30 pairs of ceiling braces with section of C-50x25x10x1.6 for 2.2G seismic ceiling. Unit weights of 1.1G and 2.2G seismic ceilings are 13.8kg/m^2 and 16.0kg/m^2, respectively.

Figs. 2 and 3 show imposed motions for full-scale shake table experiment. K-NET Sendai record is the record observed at K-NET Sendai station during the 2011 off the Pacific coast of Tohoku Earthquake, while JMA Kobe record is the record observed at JMA Kobe observatory during 1995 Kobe earthquake. For nonseismic ceiling, 5%, 25% and twice of 50% of K-NET Sendai record are imposed. On the other hand, for 1.1G and 2.2G seismic ceiling, 5%, 25%, 50%, 80% and 100% of K-NET Sendai record are imposed first, then 100% and 150% of JMA Kobe record are imposed.



(a) K-NET Sendai Record (b) JMA Kobe Record

Fig. 2 Imposed Motion (Span Direction)



(a) K-NET Sendai Record (b) JMA Kobe Record

Fig. 3 Response Spectrum

3. Experimental Results

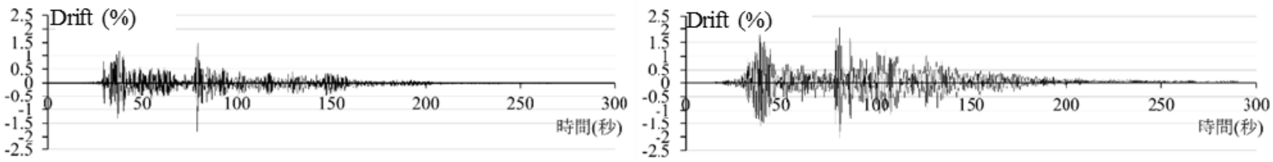
3.1 Structural response

Photo 4 shows damage of braces after all excitations. All vertical and lateral braces are buckled due to expansion resulting from yielding braces. There is no specific damage to structural members except for braces, such as columns, girders and beams.

(1) Vertical Braces (2) Lateral Braces

Photo 4 Damage of Braces after All Excitations

Fig. 4 shows story drift at roof top during K-NET Sendai 100% excitation and Table 3 shows peak story drift at roof top. Story drift at roof top is calculated as displacement measured at center of roof top divided by roof height of 9.09 m. During K-NET Sendai 50% excitation, peak story drift is 0.65% in span direction, which is larger than that of 0.41% in ridge direction. On the other hand, peak story drift is increased to 1.81% in span direction, which is smaller than that of 2.09% in ridge direction. The reason why roof drift in ridge direction is larger than that in span direction in larger excitation levels is yielding of vertical braces and decrement of story stiffness in ridge direction.



(a) Span Direction (b) Ridge Direction

Fig. 4 Story Drift at Roof Top (K-NET Sendai 100% Excitation)

Table 3 Peak Story Drift at Roof Top

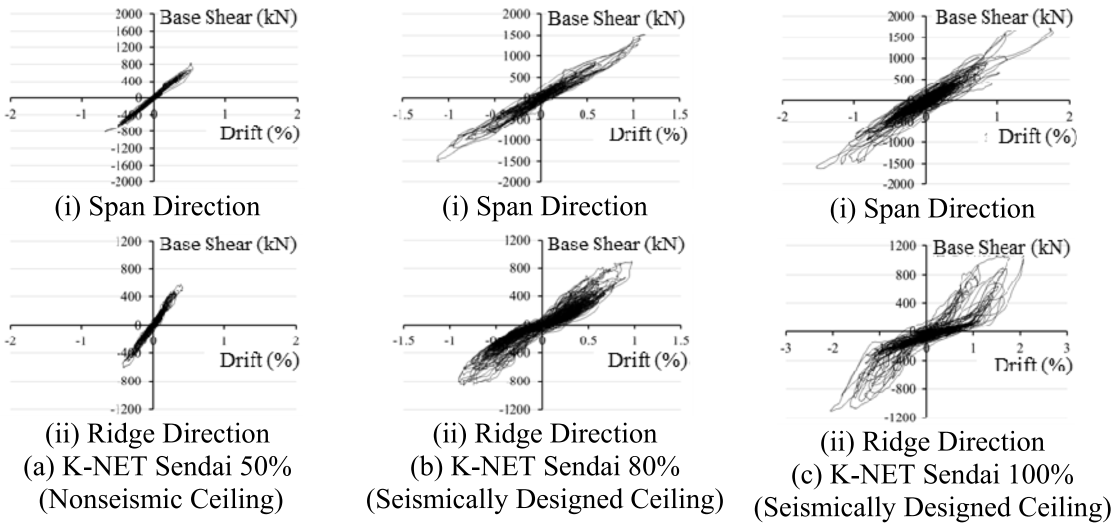
Ceiling	Excitation	Drift angle (%)	
		Span	Ridge
Nonseismic Ceiling	K-NET Sendai 25%	0.27	0.17
	K-NET Sendai 50%(1)	0.68	0.42
	K-NET Sendai 50%(2)	0.65	0.52
Seismically Designed Ceiling	K-NET Sendai 25%	0.28	0.18
	K-NET Sendai 50%	0.65	0.41
	K-NET Sendai 80%	1.14	1.03
	K-NET Sendai 100%	1.81	2.09
	JMA Kobe 100%	1.45	3.20
	JMA Kobe 150%	2.05	4.47

Figs. 5 and 6 show base shear vs. story drift hysteresis. Base shear is calculated from summation of shear force of column and horizontal component of axial force of braces evaluated from measured strain. As shown in Fig 5(a), the gymnasium specimen remained elastic until K-NET Sendai 50% excitation. From K-NET Sendai 80%, Columns and vertical braces started to yield. As shown in Fig. 5, especially large measured displacement during JMA Kobe 100% and 150% excitations, bilinear hysteresis with slip response can be identified in shape of hysteresis loop.

Fig. 7 shows roof acceleration at X4Y5 during 1st K-NET Sendai 50% excitation in gymnasium specimen with nonseismic ceiling and Tables 5 and 6 show average of peak values of accelerations measured by 35 accelerometers. In Tables 4 and 5, table acceleration and ceiling acceleration described later are also show for comparison. As shown in Tables 4 and 5, roof acceleration in ridge direction kept constant values of 4.2-4.4G during K-NET Sendai 80% and later excitations because base shear reached its yield value due to yielding of braces.

3.2 Collapse mechanism of nonseismic ceiling

Photo 5 shows damage of nonseismic ceiling. During 1st K-NET Sendai 50% excitation, hanging bolts near the top of roof first detached from ceiling joist receivers, then ceiling clips were broken and ceiling panels with ceiling joists warped. During 2nd K-NET Sendai 50% excitation, warped ceiling panels vibrated severely and ceiling panels with ceiling joists fell down. Based on the damage survey after shake table experiments, it was clarified that there is trace of gypsum boards due to uplifting of ceiling panels at the rooftop and less damage of ceiling panels at the edge.



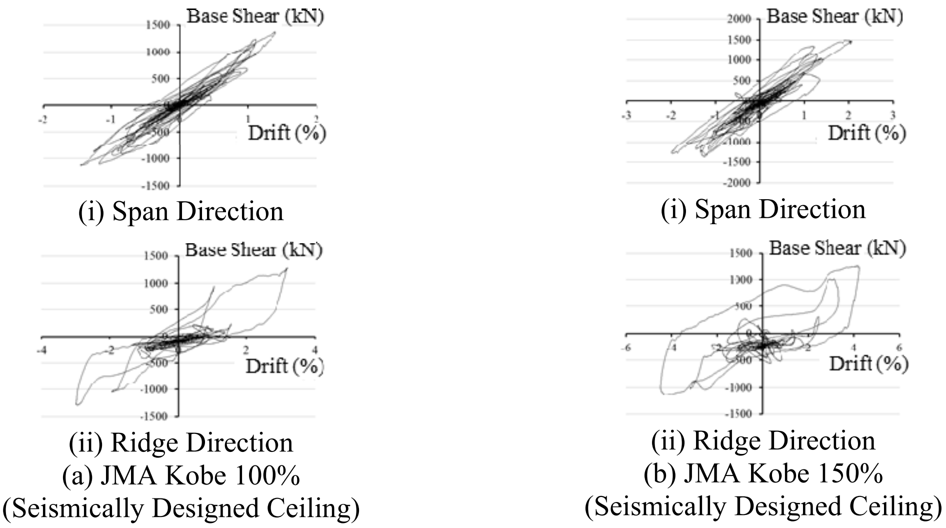
(i) Span Direction (i) Span Direction (i) Span Direction

(ii) Ridge Direction
(a) K-NET Sendai 50%
(Nonseismic Ceiling)

(ii) Ridge Direction
(b) K-NET Sendai 80%
(Seismically Designed Ceiling)

(ii) Ridge Direction
(c) K-NET Sendai 100%
(Seismically Designed Ceiling)

Fig. 5 Base Shear vs. Story Drift Hysteresis during K-NET Sendai Excitations

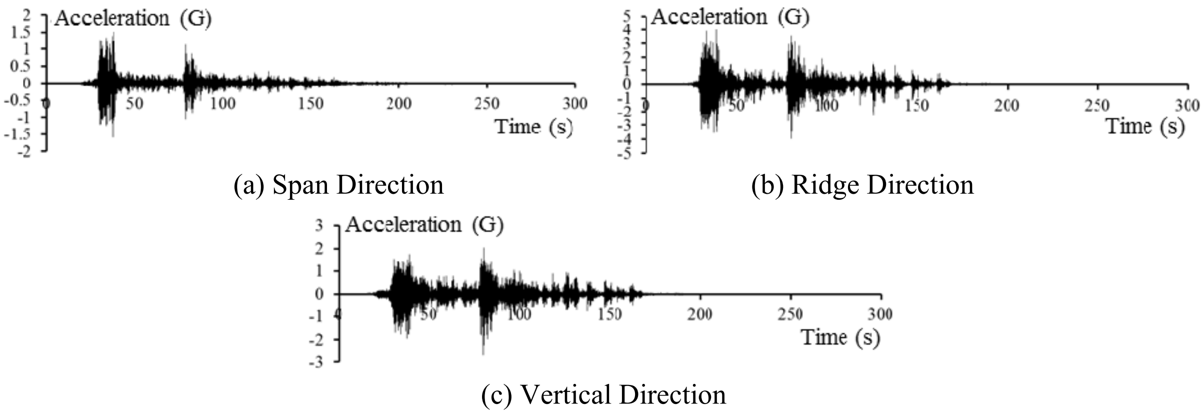


(i) Span Direction (i) Span Direction

(ii) Ridge Direction
(a) JMA Kobe 100%
(Seismically Designed Ceiling)

(ii) Ridge Direction
(b) JMA Kobe 150%
(Seismically Designed Ceiling)

Fig. 6 Base Shear vs. Story Drift Hysteresis during JMA Kobe Excitations



(a) Span Direction

(b) Ridge Direction

(c) Vertical Direction

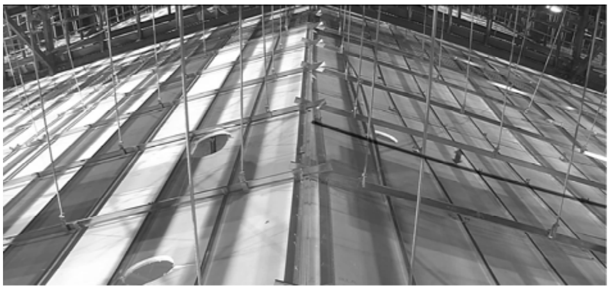
Fig. 7 Roof Acceleration (X4Y5) (Nonseismic Ceiling, 1st K-NET Sendai 50% Excitation)

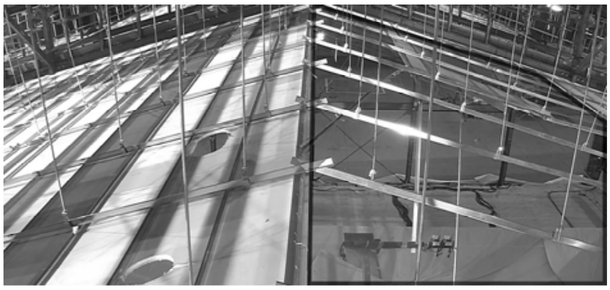
Table 4 Average of Peak Acceleration in Gymnasium Specimen with Nonseismic Ceiling

	Table Accel. (G)			Roof Accel. (G)			Ceiling Accel. (G)		
	Span	Ridge	Vertical	Span	Ridge	Vertical	Span	Ridge	Vertical
K-NET Sendai 25%	0.35	0.20	0.09	1.38	1.97	1.42	1.36	0.88	1.12
K-NET Sendai 50% (1)	0.77	0.44	0.21	2.72	3.35	2.49	6.21	2.76	4.04
K-NET Sendai 50% (2)	0.77	0.46	0.21	2.79	3.48	2.73	7.99	4.15	5.51

Table 5 Average of Peak Acceleration in Gymnasium Specimen with 1.1G and 2.2G Seismic Ceilings

	Table Accel. (G)			Roof Accel. (G)			1.1G seismic ceiling Ceiling Accel. (G)			2.2G seismic ceiling Ceiling Accel. (G)		
	Span	Ridge	Vertical	Span	Ridge	Vertical	Span	Ridge	Vertical	Span	Ridge	Vertical
K-NET Sendai 25%	0.40	0.18	0.08	1.25	1.39	1.03	0.86	0.65	1.10	0.88	0.76	1.32
K-NET Sendai 50%	0.77	0.40	0.20	2.37	2.99	2.27	2.03	1.50	2.56	2.07	1.61	2.59
K-NET Sendai 80%	1.18	0.71	0.30	3.98	4.19	3.42	3.34	2.04	4.39	3.32	2.06	4.43
K-NET Sendai 100%	1.36	0.73	0.36	4.23	4.23	3.23	3.71	2.62	4.78	4.14	2.33	5.26
JMA Kobe 100%	0.93	0.78	0.44	3.70	4.23	3.04	8.09	4.48	9.21	5.34	3.40	7.81
JMA Kobe 150%	1.62	1.23	0.73	3.98	4.44	3.18	7.57	4.81	9.18	7.60	4.62	10.59


(a) 1st K-NET Sendai 50% Excitation


(b) 2nd K-NET Sendai 50% Excitation

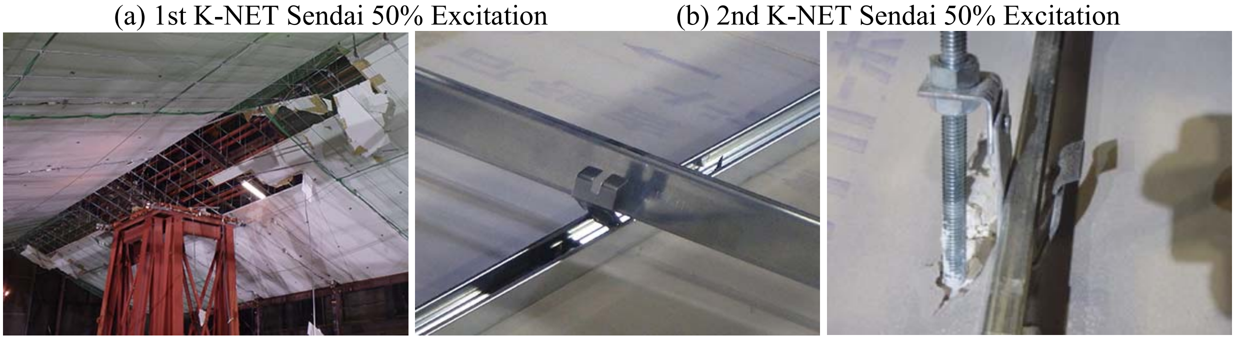

(c) After All Excitations

Photo 5 Damage of Nonseismic Ceiling

Fig. 8 shows peak values of ceiling accelerations measured from 20 to 35 sec (a-c) and 70 to 80 sec (d-f). As shown in Figs. 8(a) and (d), acceleration in positive span direction was larger in south part of ceiling (upper part in figures) was larger than that in north part of ceiling (lower part in figure). On the other hand, as shown in Figs. 8(b) and (e), acceleration in negative span direction was larger in north part of ceiling was larger than that in south part of ceiling. Maximum acceleration in positive and negative span direction was 90.6m/s^2 at X3Y3 shown in Fig8(b). This large accelerations observed in a half part of ceiling resulted from collisions between walls and ceilings. Based on the maximum acceleration of 90.6m./s2, impact force in unit width, which is evaluated from multiplying of unit weight of 13.1kg/m2 and length of ceiling of 9.71m, was 11.5kN/m. Based on the past research on strength of ceiling panels evaluated from in-plain pushover experiment of ceiling panels,

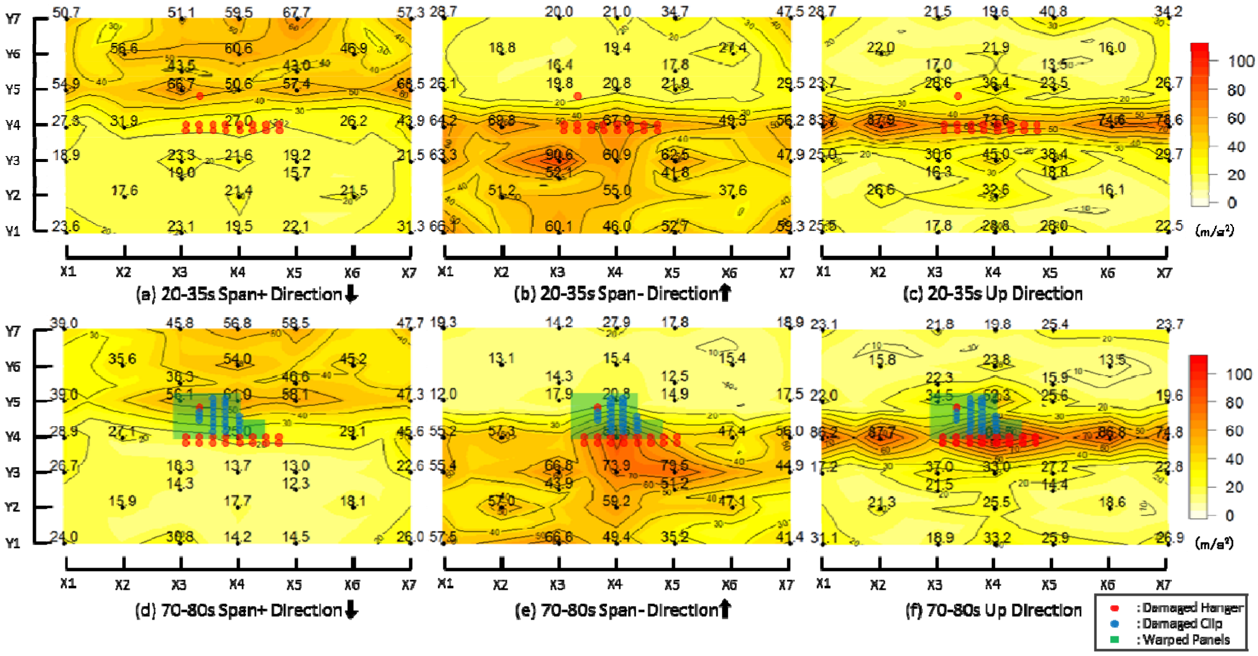


Fig. 8 Damage of Nonseicmic Ceiling and Acceleration Distribution

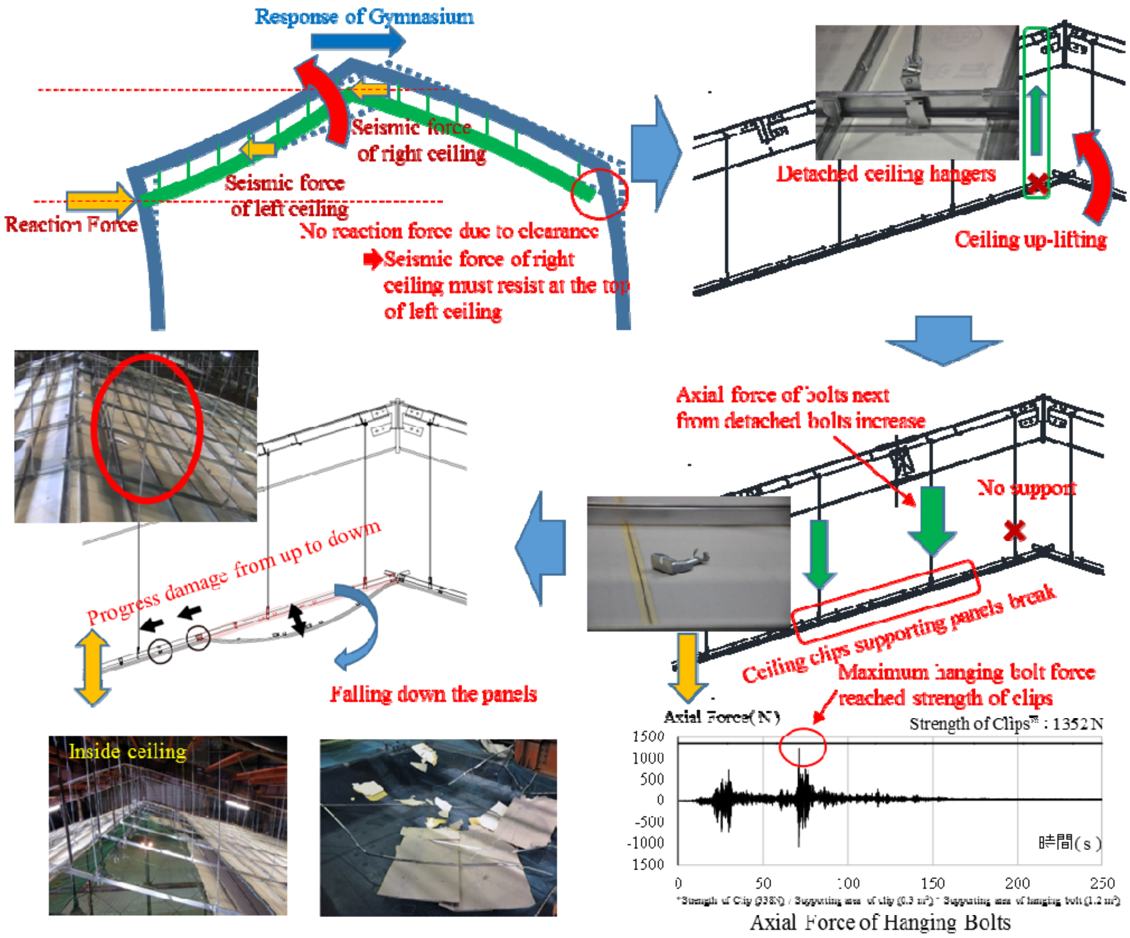


Fig. 9 Collapse Mechanism of Nonseismic Ceiling

it was 16.1kN/m [2], which is 1.4 times larger than impact force observed in shake table experiment. Thus, the edge of ceiling did not suffer severe damage.

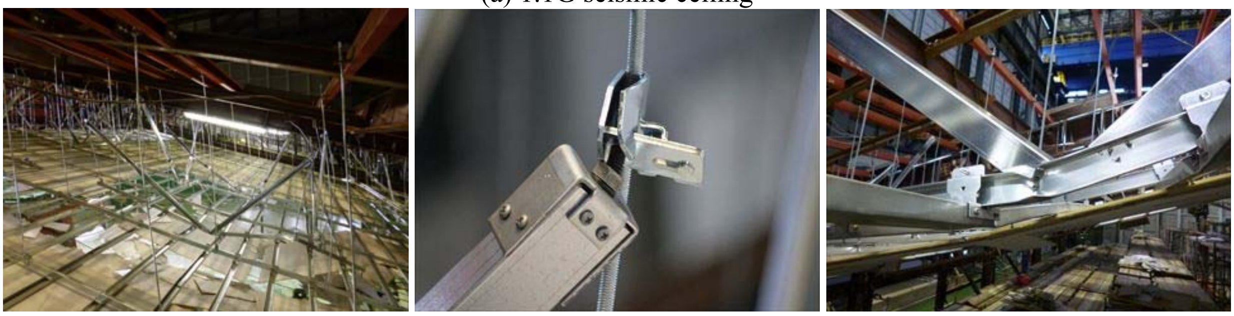
As shown in Figs. 8(c) and (f), large acceleration in up direction occurred at the rooftop, where the hangers detached. Acceleration at X4Y5 in south part of ceiling, close to the location where clips broke, is more than 15m/s2 larger than that at the other location. This difference resulted in the severe damage to the south part of ceiling.

Fig. 9 shows collapse mechanism of nonseismic ceiling. When the ground acceleration acts to building, inertia force acts to ceiling as shown in top left figure in Fig. 9. Because axes of inertia force of left and right ceiling and reaction force is different, moment acts to ceiling and up-lifting of ceiling at rooftop occurs due to its moment. Then ceiling hangers close to rooftop detached due to compression resulting from up-lifting of ceiling. Vertical force acted to hanging bolts next from detached bolts increases. Thus, ceiling clips underneath those hanging bolts break and ceiling panels with ceiling joists warp. Warped ceiling panels vibrate easily and larger vertical vibration result in damage progress from up to down and falling down the panels.

3.3 Failure mechanism of 1.1G and 2.2G seismic ceiling

Photo 6 shows damage of 1.1G and 2.2G seismic ceilings after JMA Kobe 150% excitation. In 1.1G seismic ceiling, ceiling braces buckled first during K-NET Sendai 80% excitation, horizontal ceiling displacement increased and edge of ceiling panels suffered severe damage due to collision of ceiling and columns during JMA Kobe 100% excitation. On the other hand, in 2.2G seismic ceiling, bottom and top connections of ceiling braces raptured, ceiling joist receivers and ceiling joists deformed and ceiling panels fell down due to rapture of screws fasten the boards resulting from deformation of ceiling joists.

(a) 1.1G seismic ceiling

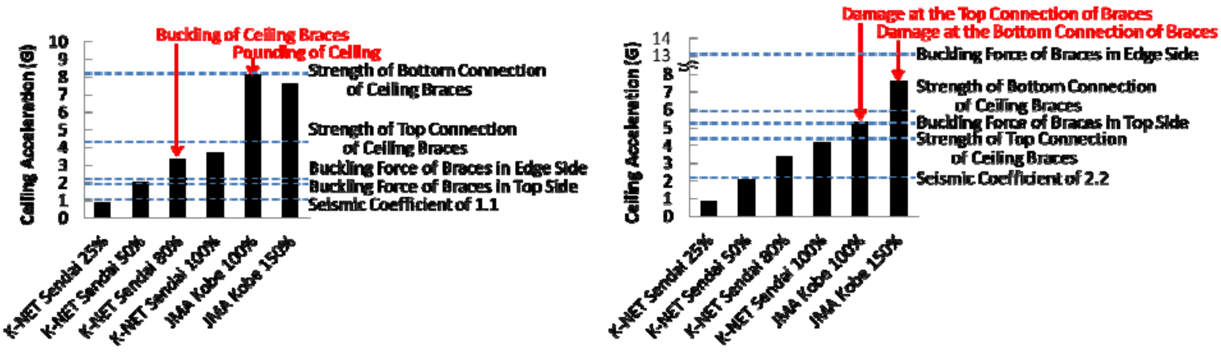


(b) 2.2G seismic ceiling

Photo 6 Damage of 1.1G and 2.2G seismic ceilings after JMA Kobe 150% excitation

Fig. 10 shows peak ceiling acceleration. Acceleration related to the strength of ceiling members/parts evaluated from element tests are also shown in Fig. 10. In 1.1G seismic ceiling, During K-NET Sendai 80% excitation, ceiling acceleration exceeds acceleration related to buckling of ceiling braces as shown in Fig. 10 (a). This result correlates with the observed damage as buckling of braces.

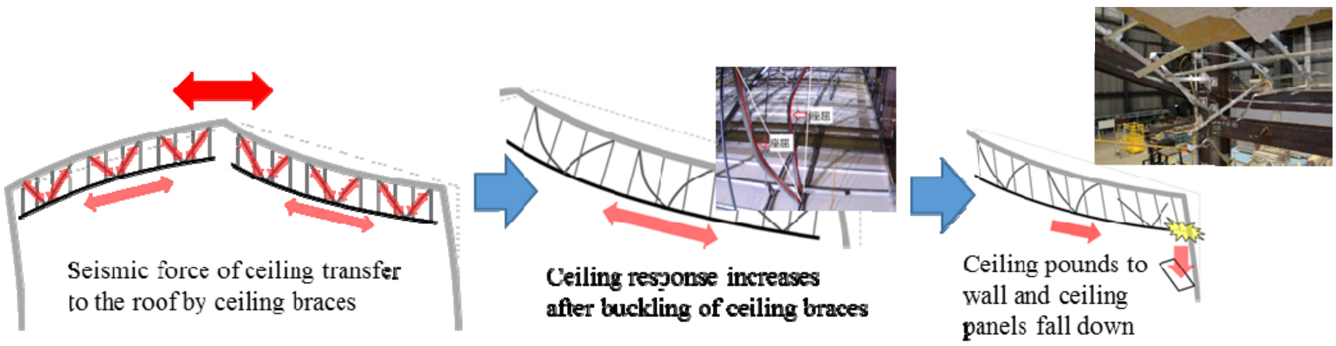
On the other hand, in 2.2G seismic ceiling, ceiling acceleration exceeded acceleration related to strength of top connections of braces during JMA Kobe 100% excitation. This result correlates with the observed damage as rupture of top and bottom connections of braces. It should be important noted that stronger buckling strength of braces than strength of bottom and top connections of ceiling braces in 2.2G seismic ceiling resulted in different damage mechanism with 1.1G seismic ceiling.



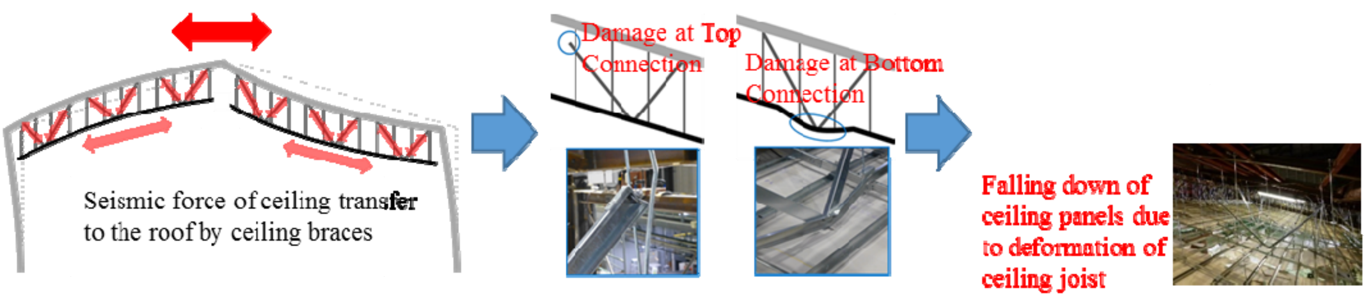
(a) 1.1G seismic ceiling (b) 2.2G seismic ceiling

Fig. 10 Peak Ceiling Acceleration

Fig. 11 shows failure mechanism of seismically designed ceiling. If ceiling has stronger strength of brace connections than buckling strength of braces, ceiling pounds to walls and falls down due to increment of displacement resulting from buckling of ceiling braces as shown in Fig. 11(a). On the other hand, if ceiling has stronger buckling strength of braces than strength of brace connections, ceiling panels fall down due to deformation of ceiling joists resulting from damage of brace connections as shown in Fig. 11(b). As described here, it is clear that failure mechanism of ceiling depends on relations between strength of brace connections and buckling strength of braces.



(a) Strength of connections of braces > buckling strength of braces (1.1G seismic ceiling)



(b) Strength of connections of braces < buckling strength of braces (2.2G seismic ceiling)

Fig. 11 Failure mechanism of seismically designed ceiling

4. Conclusions

To clarify the collapse mechanism of ceilings, full-scale shake table experiment on school gymnasium with suspended ceiling was conducted. Based on the experimental results, the following conclusions are deduced;

1. Collapse mechanism of sloped nonseismic ceiling without any seismic countermeasures is clarified. When the ground acceleration acts to building, inertia force acts to ceiling. Because axes of inertia force of left and right ceiling and reaction force is different, moment acts to ceiling and up-lifting of ceiling at rooftop occurs due to its moment. Then ceiling hangers close to rooftop detached due to compression resulting from up-lifting of ceiling. Vertical force acted to hanging bolts next from detached bolts increases. Thus, ceiling clips underneath those hanging bolts break and ceiling panels with ceiling joists warp. Warped ceiling panels vibrate easily and larger vertical vibration result in damage progress from up to down and falling down the panels.

2. Failure mechanism of seismically designed ceiling with braces and clearance at edge of ceiling depends on relation between strength of brace connections and buckling strength of braces. If ceiling has stronger strength of brace connections than buckling strength of braces, ceiling pounds to walls and falls down due to increment of displacement resulting from buckling of ceiling braces. On the other hand, if ceiling has stronger buckling strength of braces than strength of brace connections, ceiling panels fall down due to deformation of ceiling joists resulting from damage of brace connections.

5. Acknowledgements

The shake table experiment on full-scale school gymnasium specimen with wide-area suspended ceiling was conducted based on the extensive support of Large-space School Structure's Experimental Research Committee (Chief Professor Toshimi Kabeyasawa (The Tokyo University), Associate Professor Tsuyoshi Seike(The Tokyo University), Professor Satoshi Yamada (Tokyo Institute of Technology), Dr. Hiroshi Fukuyama (National Research Institute for Land and Infrastructure Management)) and Experimental Planning Working Group (Chief Dr. Tomohiro Sasaki (National Research Institute for Earth Science and Disaster Resilience), Mr. Tsutomu Ota (Horie Engineering and Architectural Research Institute Co., Ltd), Associate Professor Toru Eguchi (Yokohama National University), Associate Professor Jun Iyama (The University of Tokyo), Dr. Tadashi Ishihara (Building Research Institute))for experimental plan and design of steel gymnasium specimen and suspended ceilings. The authors greatly appreciated to give important information about damage of school and cultural facilities in recent earthquake by Mr. Mitsugu Hirota (MEXT, Ministry of Education, Culture, Sports, Science and Technology). The autors also greatly appreciated to be advised about experimental plan by Committee for Advance of Seismic Countermeasures for Nonstructural Components in School Facilities held by MEXT.

6. References

[1] T. Seike, R. Eguchi, R. Kumagai, K. Sato, A. Natori, Y. Wakiyama, T. Inoue, S. Yamada and Y. Shimada (2014): Damage to Nonstructural Elements of School Buildings and Gymnasiums due to the 2011 Tohoku Earthquake and Aftershocks, *AIJ J. Technol. Des.*, Vol. 20, No. 44, pp. 405-410.

[2] Y. Morita, T. Ishihara, S. Inai, M. Watakabe, Y. Wakiyama and H. Kikitsu (2014): Experimental study on seismic performance of ceilings without clearance Part.3 Results of static compression tests, AIJ Annual Conference, pp. 981-982.