Seismic Loss of Functionality in High-Rise and Low-Rise Office Buildings: The 2011 E-Defense shaking table test

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SUMMARY:
Large scale shaking table tests were conducted to evaluate the seismic loss of functionality of buildings due to interior space damage. The test specimen was designed to simulate both dynamic response characteristics of high-rise and low-rise building to evaluate comprehensive basic data of interior space damage. The predominant period of input motion was considered both characteristics of subduction earthquakes and near fault earthquakes. The specimen has a large interior space, 20m×10m plane size, 3.8m floor height, 2.4m ceiling height to simulate interior space damages due to interaction among ceilings, partition walls, suspended air conditioners, and office furniture. In the large intensity of floor response, the unprepared rooms suffer significant damage to the contents, while rooms prepared with special tools remain very slight damage. These damages were compared with some proposed damage indexes to contribute to improvement of these damage indexes.

Keywords: High-rise building, Low-rise building, Seismic Loss of Functionality, E-Defence Shaking Table test

1. INTRODUCTION

The Japanese archipelago is a high risk of being attacked by large earthquakes at the Nankai trough subduction zone until the middle of this century, including a high risk of inland earthquakes occur around the large subduction earthquakes. After the 2011 off the Pacific coast of Tohoku Earthquake, it is also said that the increased risk of M7-class earthquake in the Southern Kanto Region.
In the 2011 Great East Japan earthquake, Japan Meteorological Agency Seismic Intensity 6 lower or more was observed in a large area throughout Tohoku and Kanto region and a number of buildings in large area suffered damage of interior space. In high-rise buildings around Shinjuku area, even though structural members of buildings were very little damage, damage of sprinkler-heads, fall of ceiling boards on upper floors, movement of furniture on casters such as a photocopy machine, and fall of books occurred (Hisada et al. 2012). These damages led to the function loss of the building and had an influence on recovery after the earthquake greatly.
Considering those aspects, this paper investigates the seismic loss of functionalities in high-rise buildings through large scale shaking table tests on a high-rise building. A substructure test method (Nagae et al. 2010) was employed, and a test specimen representing a 30-story steel high-rise building was shaken on the E-Defense shaking table (Hyogo Earthquake Engineering Research Center 2005). In the test specimen, a large interior space was modelled as a full-scale mockup using system ceiling, partition wall, air-conditioning equipment, sprinkler pipes filled with water, and office furniture. Some equipment and furniture was prepared for prevention of swinging and falling in order to evaluate the effect of prevention. And the test specimen was designed to be able to reproduce low-rise buildings response to evaluate comprehensive basic data of interior space damage.

2. TEST SPECIMEN

2.1. Structural design

The test specimen was designed to simulate both seismic response characteristics of high-rise and low-rise building to evaluate comprehensive basic data of interior space damage. As for the high-rise building test, the method (Nagae et al.2010) is employed that reproduces the possible seismic responses of a prototype building, which has thirty stories with a total height of 120 m. The test specimen has three substitute layers and three steel moment frames for the interior spaces. The substitute layers, which consist of concrete slabs and rubber bearings, are arranged to represent the lower and intermediate stories of the prototype. In this case, the test specimen represents the natural period of 3.0-4.0 seconds. Figure 1. is the concept of modelling, Figure 2. is the elevation of the specimen, and Figure 3. is the framing elevation and beam plan. Table 1. is the list of member section. The high-rise model is possible to generate large displacement on the top of the specimen, such as about 1m (half amplitude).However, for the safe operation of the tests, the steel frames of laboratories were made stronger than design level, so the prototype drift is not occurred in the steel frames.

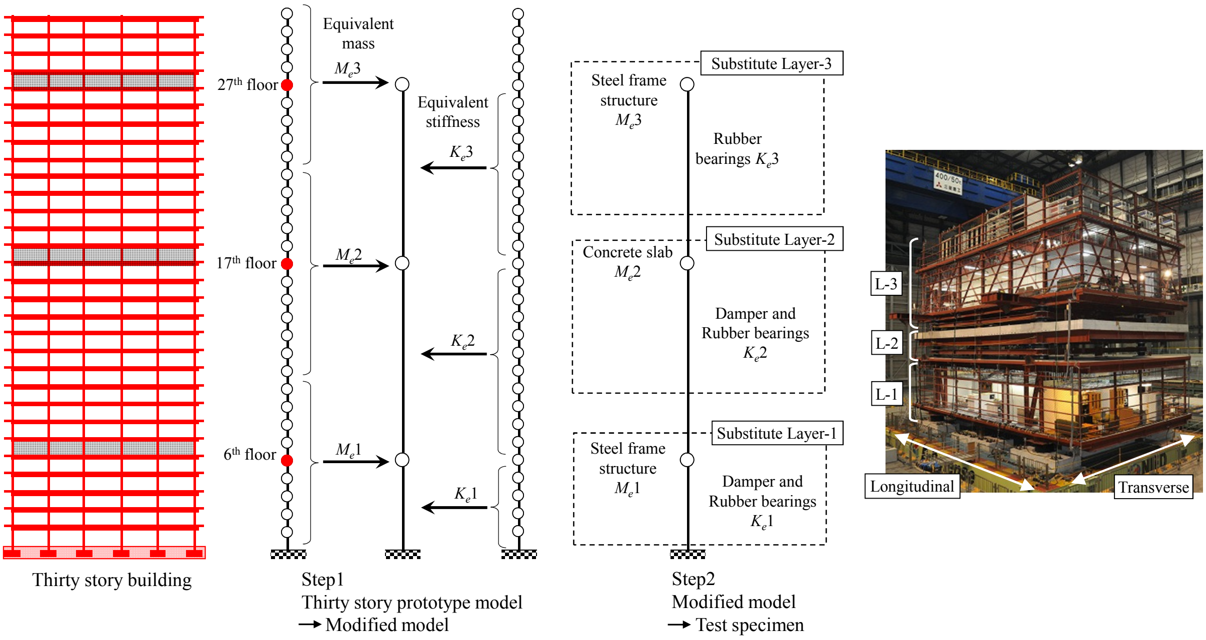
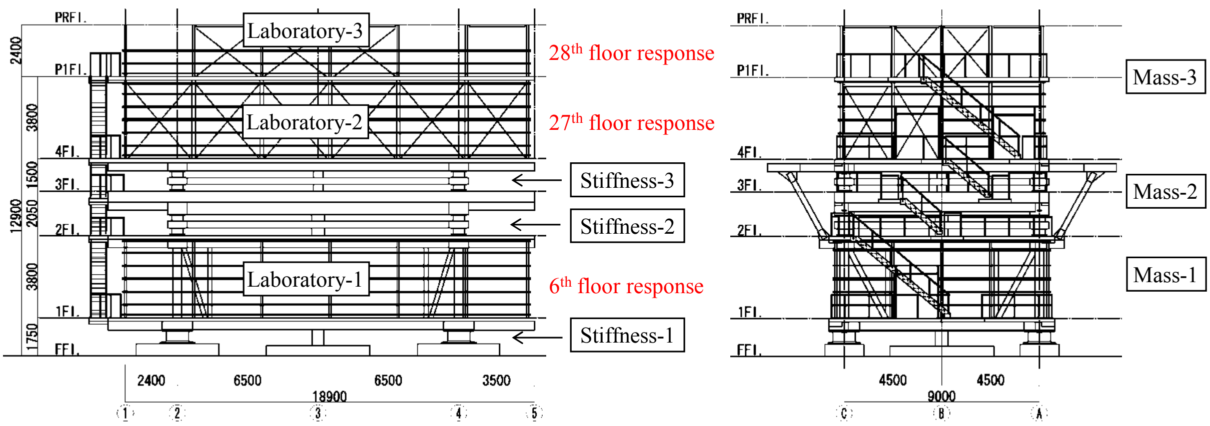
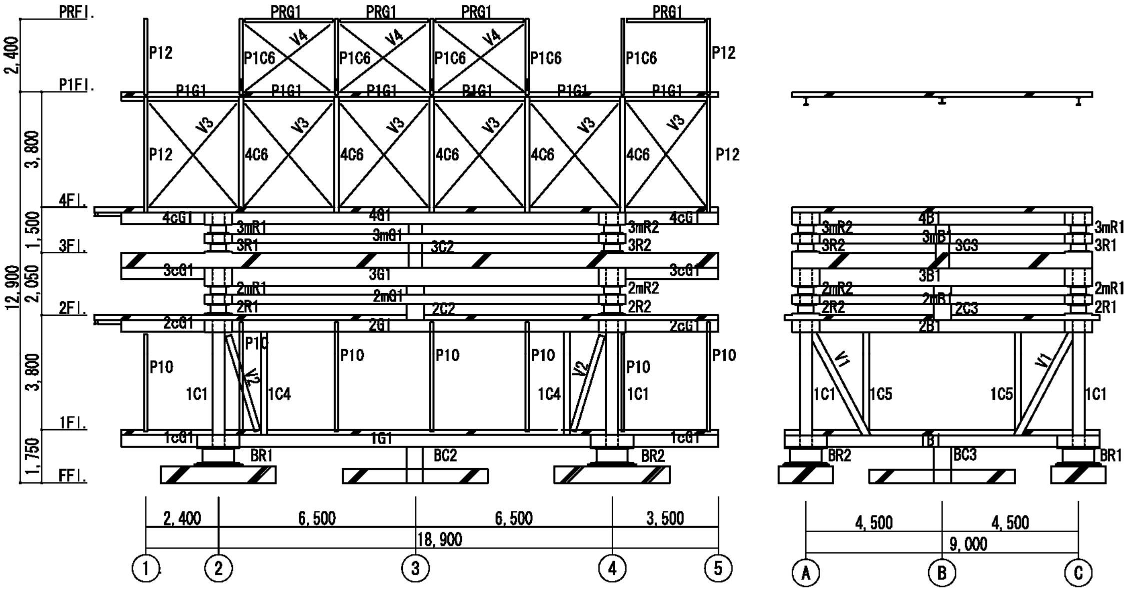


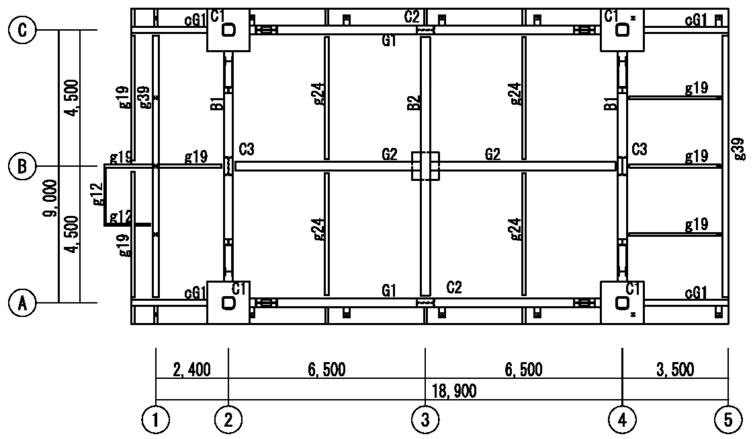
Figure 1. Development from prototype to test specimen



(a)Longitudinal direction (b)Transverse direction

Figure 2. Elevation of specimen





	Floor height(m)	Weight(kN)
PRFL	–	24
P1FL	2.4	880
4FL	3.8	1044
3mFL	0.88	101
3FL	0.62	2395
2mFL	1.36	119
2FL	0.66	909
1FL	3.8	1068
FFL	1.75	7

Figure 3. Framing elevation, beam plan and design load

Table 1. List of Member Section

(a) Beam

Floor	cG1・cG2	G1	G2	cB1	B1	B2	B3
PR		H-100×100×6×8					H-100×100×6×8
P1		H-125×125×6.5×9			H-396×199×7×11		H-125×125×6.5×9
4	BH-396×200×9×19	H-390×300×10×16	H-600×200×11×17	BH-396×400×12×19	H-390×300×10×16		H-396×199×7×11
3m		H-300×300×10×15			H-300×300×10×15		
3	BH-590×200×12×19	H-588×300×12×20	H-440×300×11×18		H-582×300×12×17	H-440×300×11×18	
2m		H-300×300×10×15			H-300×300×10×15		
2	H-396×199×7×11	H-390×300×10×16	H-400×200×8×13	BH-396×400×32×25	H-390×300×10×16	H-400×200×8×13	
1	H-396×199×7×11	H-390×300×10×16	H-390×300×10×16		H-390×300×10×16	H-390×300×10×16	

(b) Column

Floor	C1	C2	C3
4		H-400×200×8×13	H-400×200×8×13
3m		H-400×200×8×13	H-400×200×8×13
3		H-500×200×10×16	H-500×200×10×16
2m		H-500×200×10×16	H-500×200×10×16
2	□-400×25		
1		H-582×300×12×17	H-582×300×12×17

mark	C4,C5,C6
PRC6	H-125×125×6.5×9
P1C6	H-194×150×6×9
2C4	H-200×200×8×12
2C5	H-200×200×8×12

(c) Binding beam, intermediate post, brace

mark		mark	
g12	H-125×60×6×8	V1	H-250×255×14×14
g19	H-198×99×4.5×7	V2	2[-200×90×8×13.5
g24	H-248×124×5×8	V3	2L -60×60×5
g39	H-390×199×7×11	V4	M-16
P10	H-100×100×6×8		
P12	H-125×125×6.5×9		

(d) Rubber bearing

mark	Horizontal stiffness(kN/m)
3mR1	630
3mR2	1260
3R1,3R2	1090
2mR1,2mR2	630
2R1,2R1	1260
BR1	1210
BR2	800

As for the low-rise building test, the substitute layers are fixed with the steel members and the natural period and the lateral strength capacity are adjusted to fit generic low-rise buildings. In this case, the test specimen represents the natural period of 0.5 seconds. Figure 4. is details of substitute layer-2.

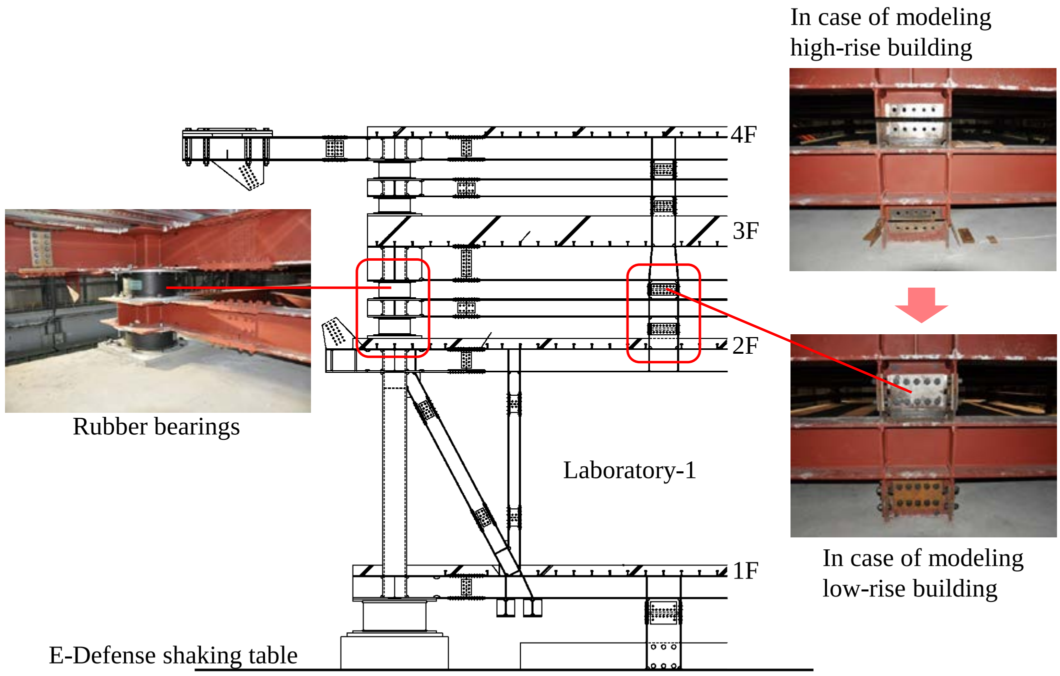
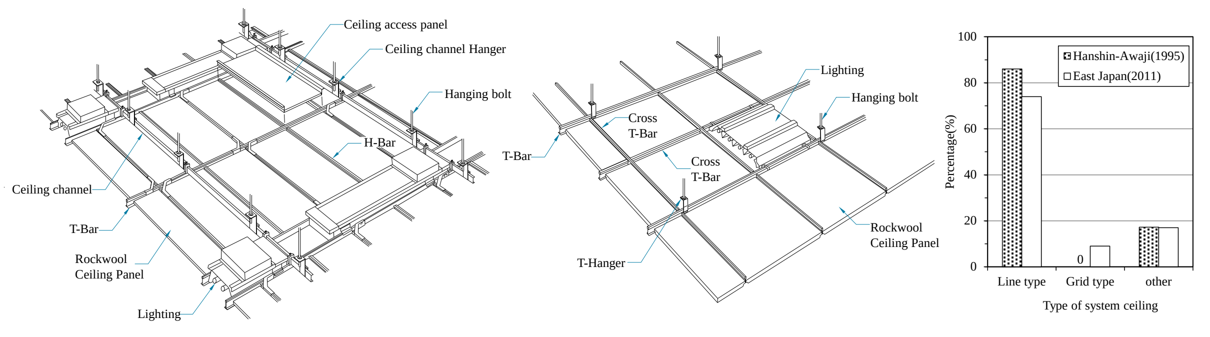


Figure 4. Details of substitute layer-2

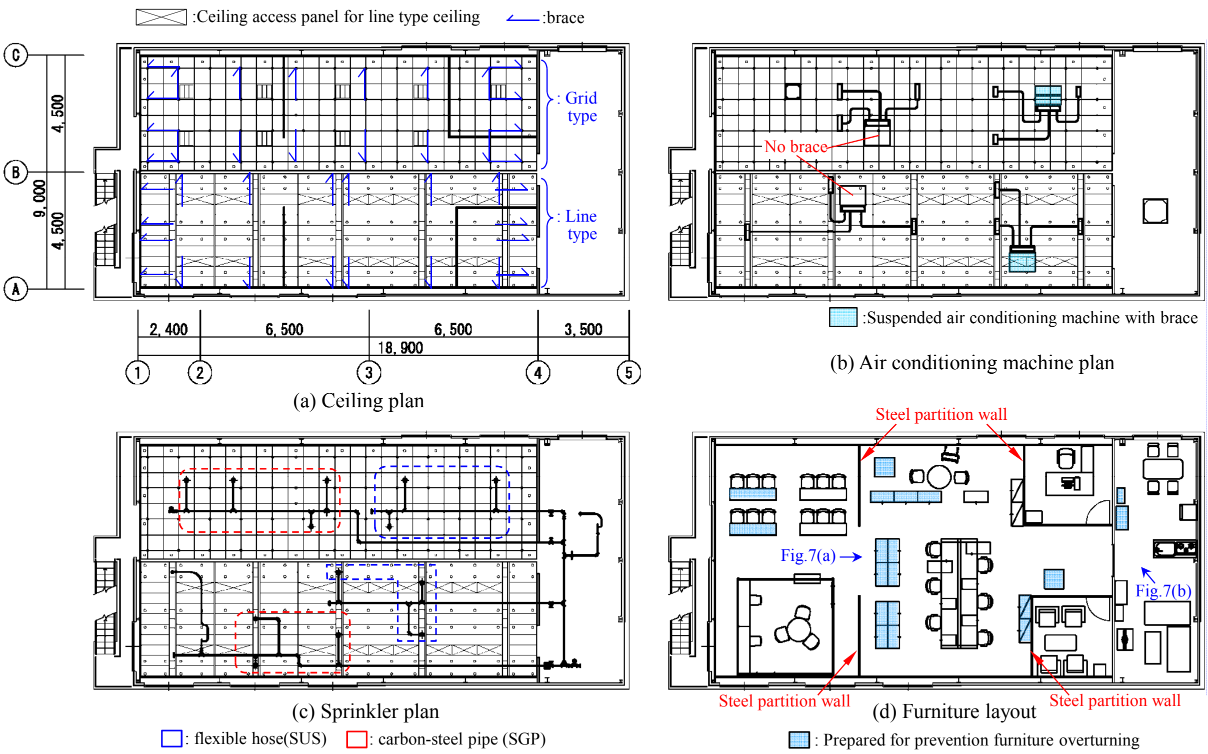
2.2. Interior space design

The test specimen has a large interior space, 20m×10m plane size, 3.8m floor height, 2.4m ceiling height. In the interior space, various types of realistic office rooms are set up on the specimen's floors and ceilings. Office building, especially high-rise building in Japan, system ceiling is commonly used. Figure 5. is the type of system ceiling used in Japan(Rock Wool Association Japan, 2012). In the case of new construction, most of the ceiling is grid type. But line type is often a percentage of the total number of damage, so both ceiling types were modelled in the interior space. Figure 6.(a) is the ceiling plan. In case of high-rise building model, ceiling bases composed of LGS were strengthened by braces. In case of low-rise building model, the braces were taken away. Figure 6.(b) is the air conditioning machine plan suspended in the ceiling, (c) is the sprinkler plan, and (d) is the layout of furniture. Steel partition walls were installed to simulate interaction between ceiling and partition wall.



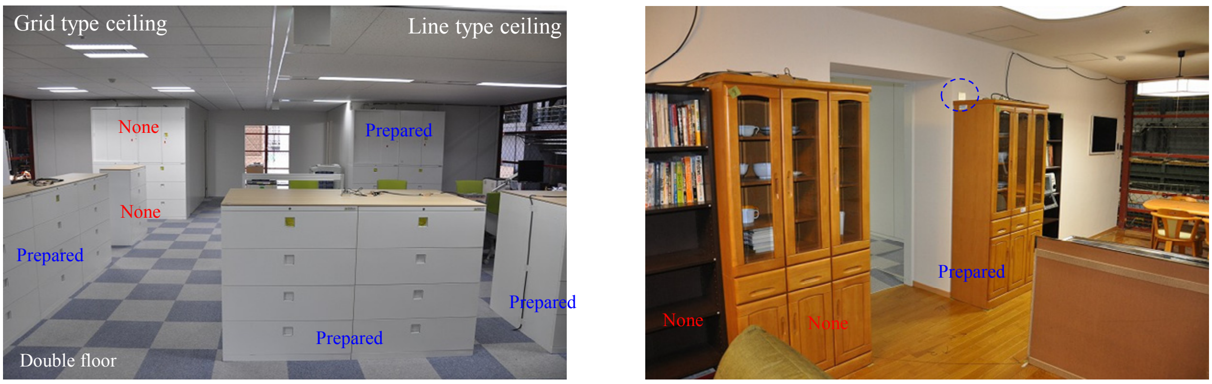
(a) Line type (b) Grid type (c) Statistical trend of seismic damage

Figure 5. Type of system ceiling



(a) Ceiling plan (b) Air conditioning machine plan (c) Sprinkler plan (d) Furniture layout

Figure 6. Plans of Laboratory-2

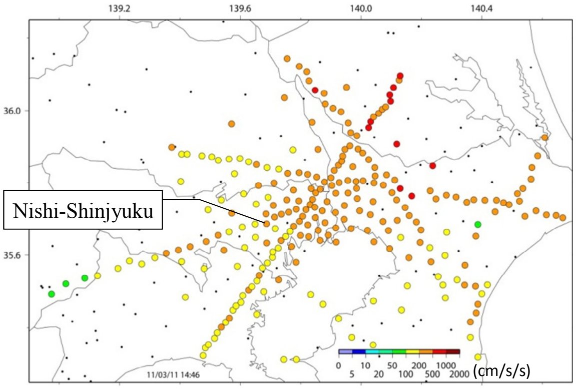


(a) Office room (b) Living and dining room

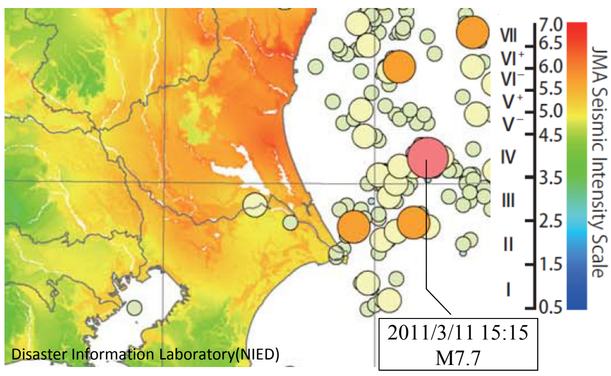
Figure 7. Pictures of the Laboratory-2 (Position the camera's shooting showed in Fig.6 (d))

3. INPUT MOTION

The Metropolitan Seismic Observation network(MeSO-net), which consists of 296 observation sites, has been constructed(Hirata et al. 2009, Sakai et al. 2009) and valuable observation records were also obtained by the 2011Great East Japan Earthquake. Figure 8. is color coding map of observed data. In the shaking tests of this paper, we used the observed record concerning the 2011Great East Japan Earthquake from Nishi-Shinjyuku observation site of MeSO-net. In addition to the main shock, the record of aftershock (Ibaraki-ken Oki earthquake, M7.7, 2011/3/11 15:15) observed in Nishi-Shinjuku was adopted. This aftershock record is considered to include the long period ground motion characteristics in the Tokyo Metropolitan Area strongly. The aftershock record is adjusted to 330% multiplication corresponding to engineering bedrock velocity level of scenario earthquake in the northern part of Tokyo Bay (Cabinet Office, Government of Japan 2004). Also the record of the 1995 Hyogo-ken Nanbu Earthquake (JMA-Kobe), which included short period components, was adopted.

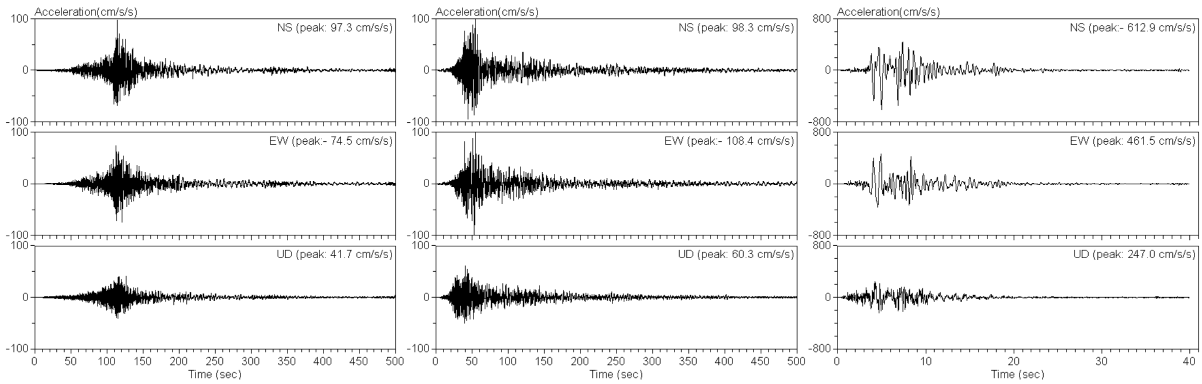


(a) MeSO-net observation points and observed maximum acceleration (2011/03/11 14:46)

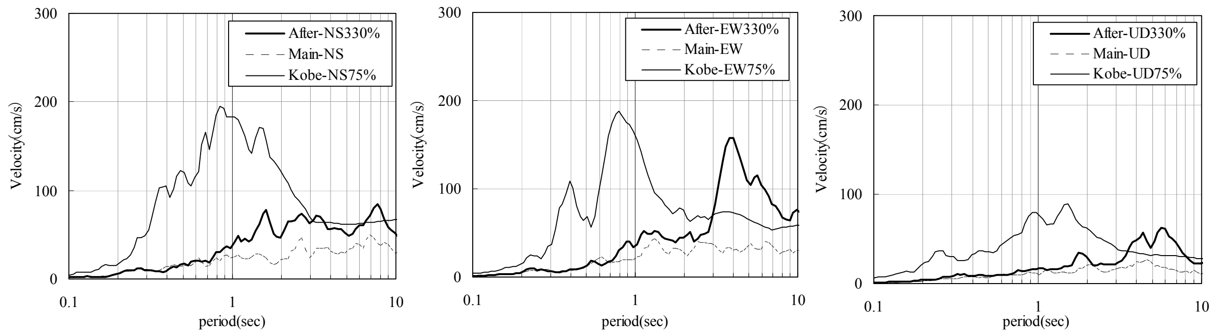


(b) Seismic intensity map of the main shock and epicenter distribution of after shocks

Figure 8. Color coding map of observed data on the 2011 Great East Japan Earthquake



(a) Main shock 100% (b) After shock 330% (c) JMA-Kobe 75%



(d) Velocity response spectra (h=0.05)

Figure 9. Input motion for shaking test

Table 2. Shaking test schedule

Type	Date	Input earthquake	Maximum acceleration(cm/s^2)	Maximum velocity(cm/s)
High-rise	2011/10/04	JMA-Kobe 25%	223	26
		Main shock 50%	49	8
		Main shock 100%	98	17
		After shock 150%	52	20
	2011/10/07	After shock 75%	26	10
		After shock 330%	114	44
Low-rise	2011/10/12	After shock 330%	114	44
		JMA-Kobe 25%	223	26
		JMA-Kobe 50%	445	53
		JMA-Kobe 75%	668	79

4. TEST RESULTS

The shaking test was carried out by entering the EW component of the input motion in the direction of the longitudinal, the NS component in the direction of the transverse, and the UD component in the vertical direction of the test specimen. Figure 10. shows the distribution of the maximum response acceleration. In the case of high-rise model, Laboratory-1(Lab-1) reproduces the response of 6th floor(lower floors), and Laboratory-2(Lab-2) reproduces the response of 27th floor(upper floors). In the case of low-rise model, Lab-1 reproduces the response of 1st floor, and Lab-2 reproduces the response of 3rd floor. Examine a case of Lab-2 acceleration was maximum in the test results of each model(High-rise: After shock 330%, Low-rise: JMA-Kobe 75%).
Figure 11. shows correlation of maximum response acceleration and maximum response velocity. Natural frequency of each model calculated from test results was almost satisfied with the design values. A curve to describe overturning ratio of rigid bodies was proposed using maximum acceleration and maximum velocity (Kaneko. et al. 2000). Figure 12. is the comparison of the proposed overturning curve and test results in Figure 11. In the case of high-rise model, bookshelf-A, long vertical type, is close to the acceleration of overturning criteria. In the case of low-rise model, bookshelf-A is in very high possibility of overturning, especially at Laboratoy-2. Figure 13. shows video image capture after the end of the each shaking test. The test results were consistent with the proposed curve as a whole. And furniture prepared for prevention of overturning was remained stable, except in the case of low-rise model Lab-2 with JMA-Kobe75% input.

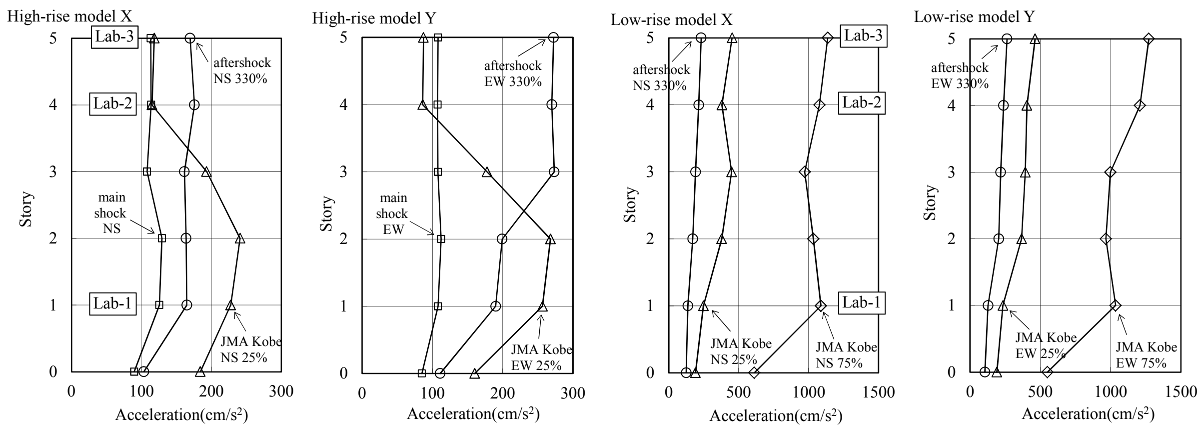
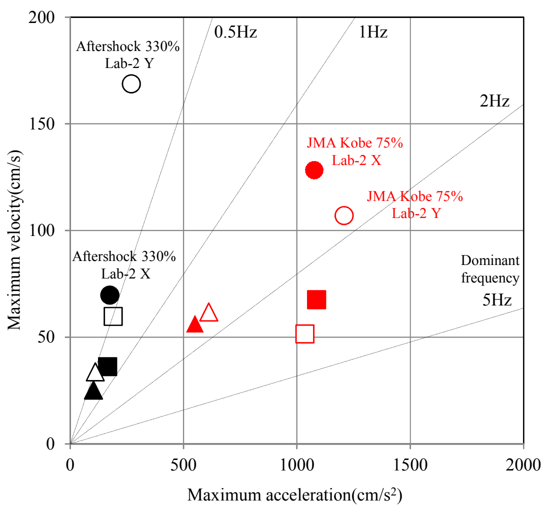


Figure 10. Maximum response acceleration



Natural frequency(Hz) calculated from floor acceleration

		Longitudinal(Y)		Transverse(X)	
		designed value	after shock 330%	designed value	after shock 330%
High-rise	1st	0.29	0.28	0.29	0.32
	2nd	0.71	0.78	0.71	0.81
	3rd	1.14	1.30	1.14	1.28

		Longitudinal(Y)		Transverse(X)	
		designed value	JMA-Kobe75%	designed value	JMA-Kobe75%
Low-rise	1st	1.54	1.20	1.92	1.35
	2nd	4.76		3.57	
	3rd	9.09		7.69	

○: Lab-2, Longitudinal
●: Lab-2, Transverse
□: Lab-1, Longitudinal
■: Lab-1, Transverse
△: Shaking table, Longitudinal
▲: Shaking table, Transverse

Black mark High-rise model
Red mark Low-rise model

Approximation of dominant frequency is $A_{max}/V_{max}/2\pi$.

Figure 11. Correlation of maximum response acceleration and maximum response velocity

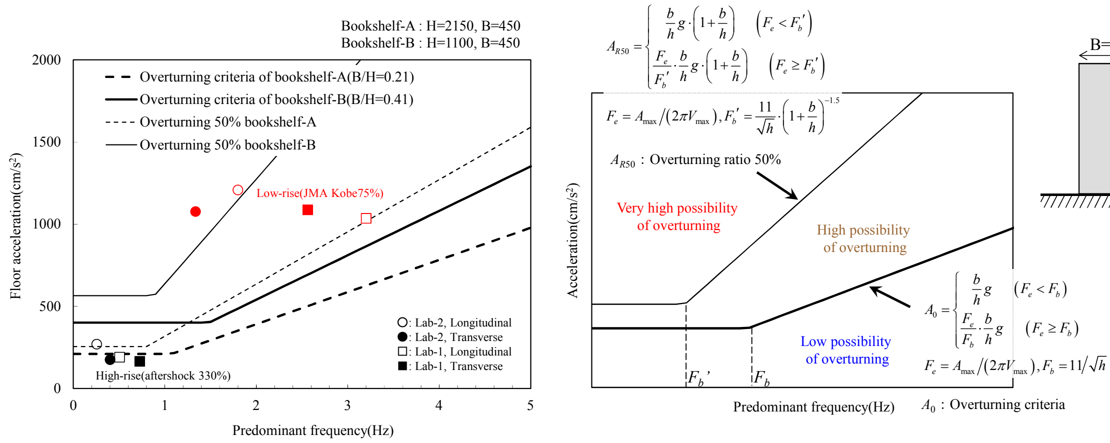
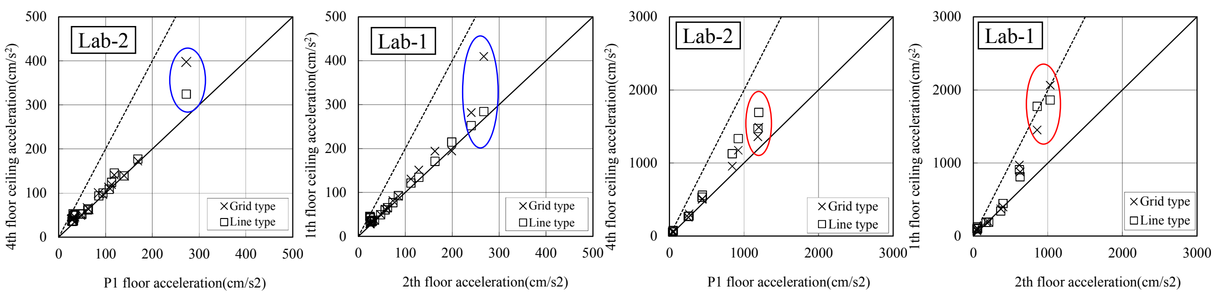


Figure 12. Correlation of maximum response acceleration and maximum response velocity

(a) High-rise building model (Input aftershock330%)

(b) Low-rise building model (Input JMA-Kobe 75%)

Figure 13. Video image capture after the end of the shaking test



(a) High-rise model (: Input after shock 330%)   (b) Low-rise model (: Input JMA-Kobe 75%)

Figure 14. Maximum acceleration of the ceiling surface to the structure maximum acceleration

Figure 14. shows maximum acceleration of the ceiling surface for all tests in each case of the high-rise and low-rise model. Since the raw data of ceiling surface acceleration had a large value with pulsed waveform due to the collision of ceiling board, low pass filter (cutoff frequency 25Hz) was applied. Although the low-rise model's ceiling bases were taken away braces, response magnification of ceiling surface was about 2.0. But in this case, falling of ceiling board occurred both Lab-1 and Lab-2. Figure 15. shows the video image capture during the shaking test at the time of ceiling board falling, and the position of falling ceiling board. Falling boards were concentrated in the line type, and mainly the ceiling access panel fell. Comparing the ceiling damages of Lab-1 and Lab-2, observed floor response and ceiling surface acceleration were same level, but falling board area in Lab-2 was more than six times area in Lab-1. One possible reason for this result is the effects of interaction between the ceiling and the partition wall.
Figure 16. shows maximum acceleration of the air conditioning machine suspended from the structure and its installation conditions. The raw data of machine was applied same low pass filter as Figure 14. Response magnification of the prepared machine was less than 2.0, but unprepared machine was more than 2.0. In Figure 16., picture of observation after the test(Low-rise model, JMA-Kobe75%) is also shown. Unprepared air conditioning machine moved widely and deformed ceiling hanging bolt.
In this test, as the first attempt to evaluate seismic loss of functionality of air conditioning equipment, the machines were running during shaking test. The all machine's functionality was maintained as a result, but preparing brace to machines is recommended to reduce the risk of ceiling damage.

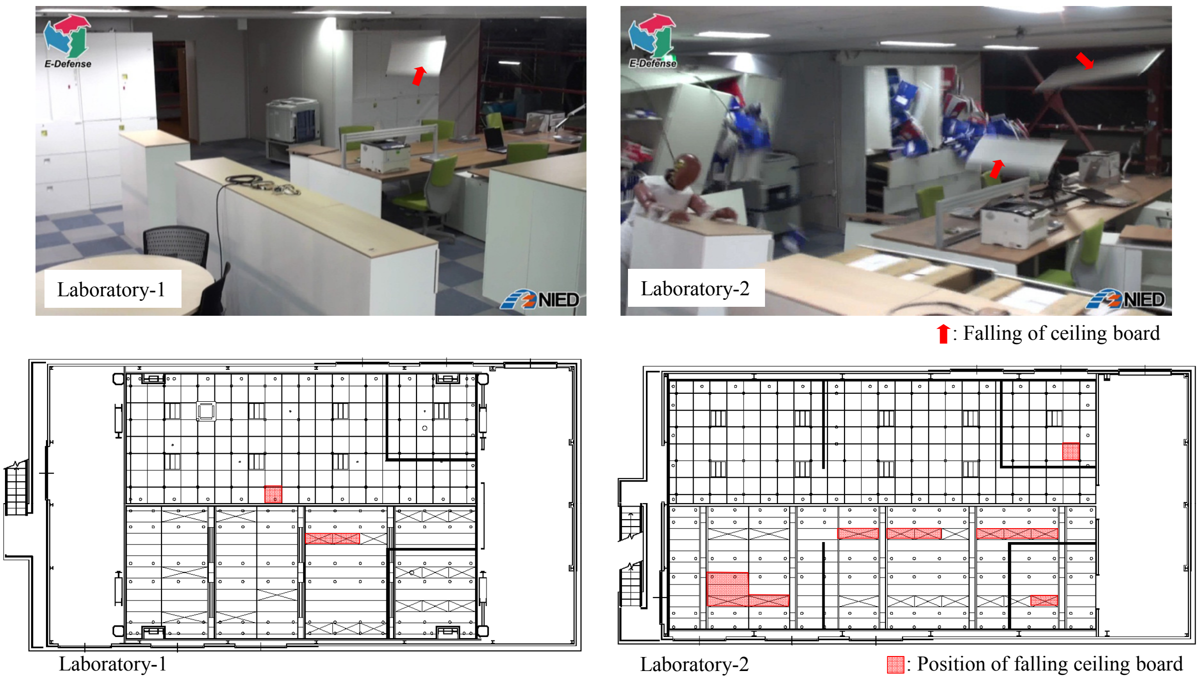


Figure 15. Video image capture during the shaking test (Low-rise building model, JMAKobe75%)

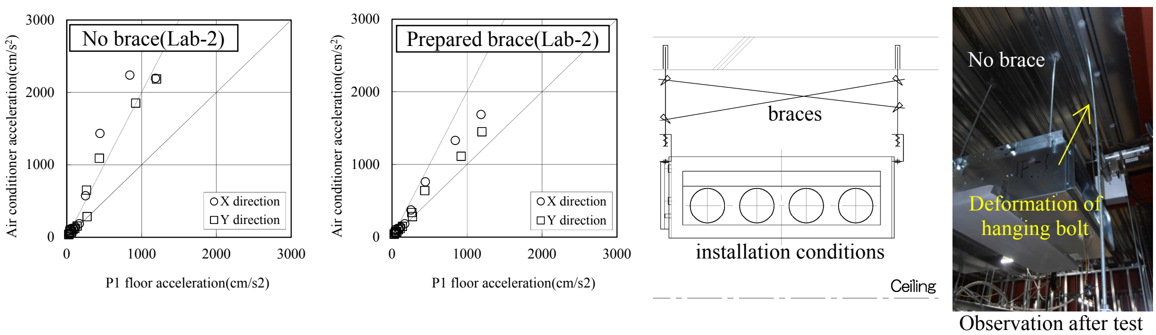


Figure 16. Maximum acceleration of the air conditioning machine and installation conditions of machine

5. CONCLUSION

To investigate the seismic loss of functionality of buildings due to interior space damage, large scale shaking table tests were conducted using the E-Defense shaking table. The test specimen was constructed to simulate both dynamic response characteristics of high-rise and low-rise building to evaluate comprehensive basic data of interior space damage. As the result of shaking table test, the test specimen was well simulated both dynamic response characteristics of high-rise and low-rise building. In the test specimen, in order to simulate realistic interior space damage, a large interior space was modelled as a full-scale mockup using system ceiling, steel partition wall, air-conditioning equipment suspended in the ceiling, sprinkler pipes filled with water, and office furniture. Through a series of tests, major observations obtained from this study are summarized as follows:

1. From the test results of high-rise building model, prevention of furniture overturning and moving is a very effective mitigation of the interior space damage, because of seismic response characteristics of high-rise buildings.
2. From the test results of low-rise building model, prevention of furniture overturning is also a very effective mitigation of the interior space damage. However, depending on the characteristics of the input ground motion, low-rise building response may become very large, evacuation activity in the room is also required in order to ensure personal safety.
3. Two types of system ceiling used in Japan were adopted in the tests, and measures to reduce the shaking, such as ceiling bases strengthened by braces, has improved the seismic performance of the both system ceiling. In case of unprepared braces, the risk of falling ceiling board becomes higher.
4. To reduce the seismic loss of functionality of buildings due to interior space damage, design and construction considering the interaction among the non-structural elements, equipment instruments, and furniture is important. For example, preparing brace to air conditioning equipment is effective to reduce the risk of ceiling damage.

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