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Both the 2011 Off the Pacific Coast of Tohoku Earthquake (that caused the Great East Japan Earthquake Disaster) and the 1995 Southern Hyogo Prefecture Earthquake (that caused the Great Hanshin-Awaji Earthquake Disaster) claimed many lives and caused enormous damage. However, their damage situations are entirely different. The 2011 Off the Pacific Coast of Tohoku Earthquake (hereafter "the 2011 Tohoku Earthquake") produced catastrophic tsunami damage, but the building damage caused by ground motion was not as serious as that in the 1995 Southern Hyogo Prefecture Earthquake. This was because the ground motion with a period of 1 second or less, which affects buildings little, was predominant in the 2011 Tohoku Earthquake. On the other hand, the ground motion with a period of 1 to 2 seconds, which causes heavy damage to buildings, was predominant in the 1995 Southern Hyogo Prefecture Earthquake (see Figure).

The 2011 Tohoku Earthquake produced "long period ground motion" with a period of 2 seconds or more in the Tokyo metropolitan area and swayed super-high rise buildings heavily. However, there were no serious damages in any super-high rise buildings because they already equipped earthquake-resistant systems such as seismic isolation and vibration damping. In truth, the aftermath of long-continued or repeated long period ground motions on the super-high rise buildings is still unknown and should be studied in the future.

The "slightly short period (1 to 2 sec.) ground motion" and "long period (2 sec. or more) ground motion" could cause damage situations that cannot be truly represented by a single indicator of the current seismic scale. The vibration period of ground motion is considerably affected by not only the hypocenter but also the ground structure and propagation path of seismic waves. Thus, it differs by location even in the same earthquake. Because the slightly short period ground motion damages wooden houses and low- and medium-rise buildings, new evaluation indicators for that may be necessary.

In order to reduce earthquake damage, it is also necessary to achieve mutual collaboration among academic or technological fields, such as seismology, geotechnical engineering, civil engineering, and building engineering, as well as to share and integrate the knowledge in each field, rather than to conduct a study separately in each field.

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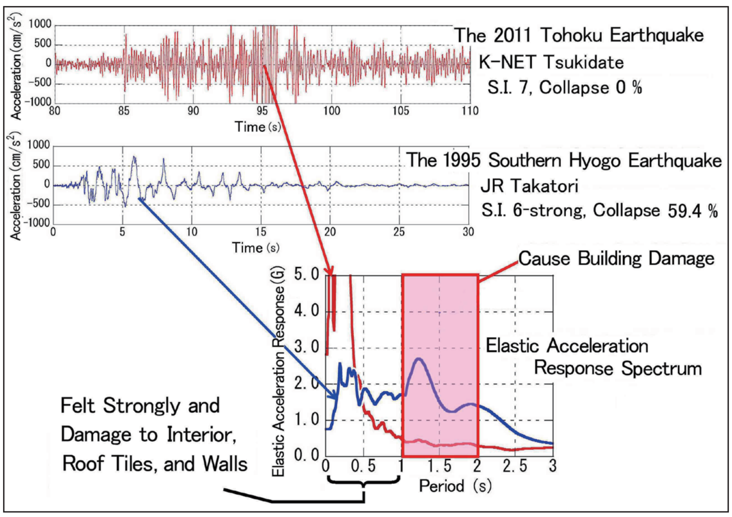

Figure : Comparison of Ground Motions in the 2011 Tohoku Earthquake and the 1995 Southern Hyogo Prefecture Earthquake. (Provided by Y. Sakai)

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Building Damage Depending on Earthquake Vibration Period and New Technology Issues

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1 Introduction

The 2011 Off the Pacific Coast of Tohoku Earthquake (hereafter the "2011 Tohoku Earthquake") that caused the Great East Japan Disaster left approximately 20,000 people dead or missing. It was the worst natural disaster to strike Japan since the Great Kanto Earthquake of 1923. However, the damage caused by the ground motion of the earthquake has not received much attention because most lives were claimed by the tsunami. In fact, ground motions of the earthquake also caused various kinds of damage, and tracing what has occurred is the only way of the research of seismic hazard. We need to look at the fact revealed by the unprecedented disaster, and to draw lessons from the fact in a humble attitude.

The National Institute of Science and Technology Policy (NISTEP) held a seminar entitled "Damages Caused by the Great East Japan Earthquake and New Concept of Disaster Prevention" on February 7, 2012. One of main themes of the seminar was the building damage that ground motion directly causes. The speakers and their lecture titles were:

1) "Building Damage from Ground Motions and Problems with Disaster Prevention Systems" by Yuki Sakai (University of Tsukuba)
2) "Impact on Business Activity and the Effects of Seismic Isolation and Vibration Damper" by Shigeki Sakai (Hazama Corp.).

In this report, we present the characteristic features of the building damage caused by the 2011 Tohoku Earthquake based on the seminar lectures. The earthquake destroyed fewer houses and caused less building damage than the 1995 Southern Hyogo Prefecture Earthquake (i.e. the Great Hanshin-Awaji Earthquake) did. The 2011 Tohoku Earthquake mostly caused damage to non-structural members such as tiled roofs and walls. The main theme of this seminar was to clarify why the 2011 Tohoku Earthquake, which had a high seismic intensity, collapsed few buildings due to its shaking. To contribute to reducing damage in future earthquakes was also one theme of this seminar.

The 2011 Tohoku Earthquake generated the short-period ground motion in most of the Tohoku region near the hypocenter. In the Tokyo metropolitan area, however, long-period components were also observed, giving the first experience for the super-high rise building to sway widely for long minutes.

The Tokyo near-field earthquake, which is considered highly likely to occur with a maximum seismic intensity of 7 in the next few years, would cause more massive damage to buildings than the Southern Hyogo Prefecture Earthquake did. Are the buildings in the Tokyo metropolitan area, including the super-high rise buildings, safe enough for the coming earthquake? If there are countermeasures against the earthquake, what are they? The authors would like to try and find some approaches to address such problems and hope to reduce the earthquake damage as much as possible.

As mentioned above, the purpose of this paper is to present the contents of the seminar as well as to learn lessons on building damage caused by seismic shaking in case of a future massive earthquake.

2 Survey Methods and Results on Building Damage Caused by Ground Motion

It is desirable to conduct detailed investigation on damaged buildings in order to secure subsequent safety. However, even if we surveyed all damaged buildings, we cannot obtain the percentage of damaged buildings because it gives only the total number of damaged buildings. The damage rate or the collapse rate can only be derived by uniformly surveying all buildings in the whole area, irrespective of the damage status.

In practice, it is impossible to survey all buildings in a broad area, and even if one did, the indiscriminate survey would not reveal the relationship between the damage and seismic intensity or shaking. An effective approach to clarify such relationship is to select locations with reliable seismographs installed and to survey all buildings and houses around the seismograph within a few hundred meter radius.

Thus, there are two methods for surveying building damage; a method to survey only damaged buildings and thereby derive the total number of damaged buildings, and a method to survey all buildings around certain seismographs regardless of their damage and derive the relationship between the damage rate and the ground motion.

In Japan, the National Research Institute for Earth Science and Disaster Prevention (NIED) has seismograph networks called K-NET and KiK-net consisting of 1,381 strong-motion observation stations[1] installed at intervals of about 20 km nationwide (see Fig. 1). In addition, the Japan Meteorological Agency (JMA) and local governments each have strong-motion observation stations at 608 and 2,839 locations, respectively.

These observation stations are equipped with a strong-motion seismograph capable of recording strong shaking and a data transmission device, and all of them is enclosed in a sturdy case on the ground (see photo in Fig. 1). A KiK-net station is an observation station comprising a pair of a subsurface seismograph and a surface strong-motion seismograph. The records of seismic waveforms and other data obtained through the K-NET and KiK-net are released to the public or delivered through the internet.[2] When the 2011 Tohoku Earthquake struck, 200 stations of strong-motion seismograph recorded the seismic intensity larger than 6-weak.

Yuki Sakai and his research team selected 35 locations (shown in Fig. 2) out of the 200 strong-motion seismograph stations to survey, excluding locations where buildings or houses are too few. They conducted their field survey from March 16 to April 10, 2011 at 16 locations in Miyagi prefecture, 7 locations in Fukushima prefecture, 6 locations

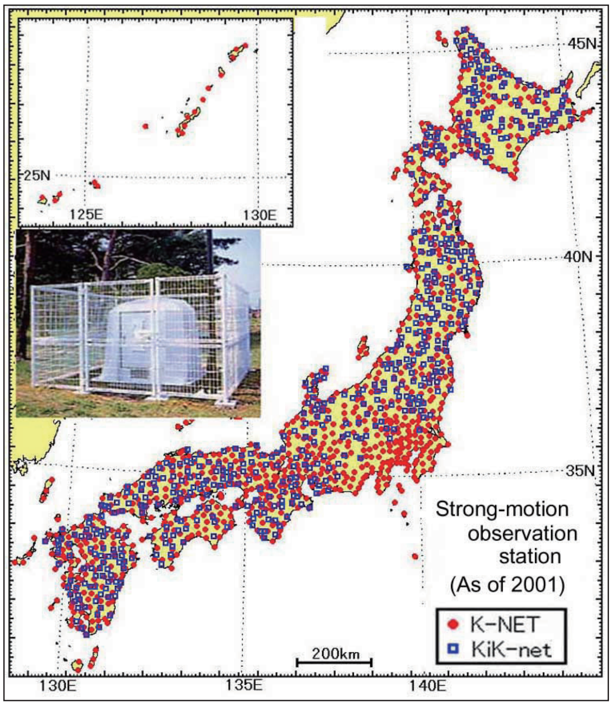

Figure 1 : Location of Strong-Motion Observation Stations K-NET and KiK-net. (Reprint from Ref. 1)

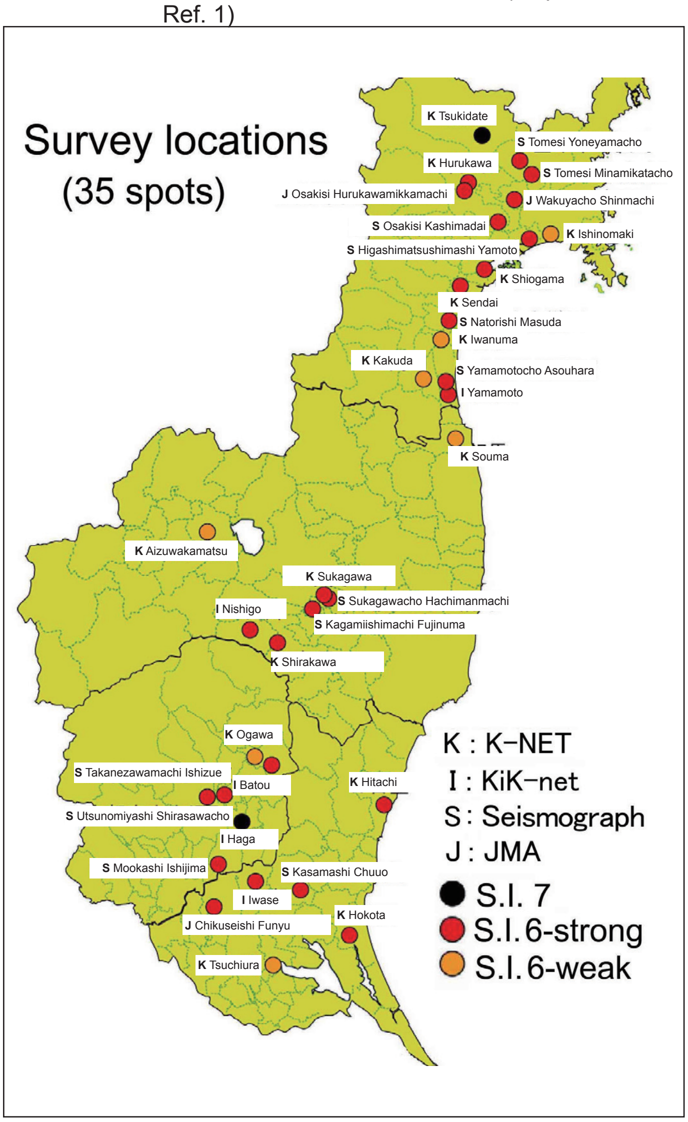

Figure 2 : 35 Locations of Building Damage Survey: (Provided by Y. Sakai)

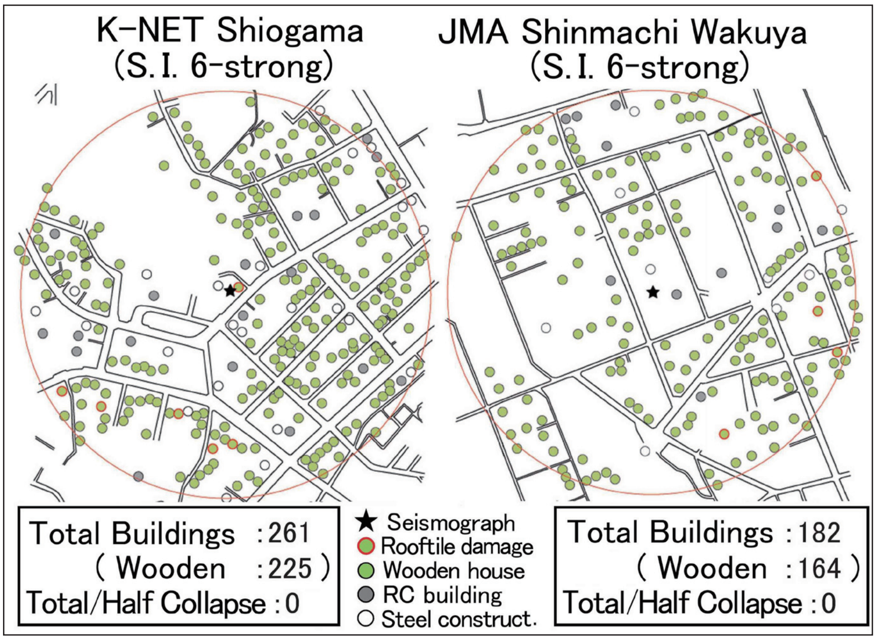

Figure 3 : Examples of Building Damage Survey (Provided by Y. Sakai)

in Tochigi prefecture, and 6 locations in Ibaraki prefecture. In terms of seismic intensity, the seismic intensity 7 was recorded at two locations, the intensity 6-strong at 26 locations, the intensity 6-weak at 7 locations.

Their method of field survey is a visual damage inspection of all buildings and houses in the area within a radius of 200 meters from the each strong-motion seismograph station. They, however, excluded the damage to warehouses and garages and the damage caused by landslides for the purpose of the accuracy. They limited the survey area within a radius of 200 meters from a strong-motion seismograph because the ground motion experienced in the area is expected to be the same as the recorded one. In some cases, however, a building may experience the stronger ground motion than the recorded one depending on the developing method of housing land.

In the field survey, from outward appearance, they judged all buildings in the area as total collapse, partial destruction, no damage or others. They also plotted them on a map, adding other information: the tiled roof damage, the number of floors, and the structural members such as wooden, reinforced concrete (RC) or steel framed structure. The maps in Fig. 3 show examples of field survey at the K-NET Shiogama observation station (left-side figure) and the JMA's observation station in Wakuya town (right-side figure). The boundary of surveyed area is denoted by the circle with a 200 meter radius from each observation station marked by a star. In these two areas, there were no buildings collapsed or seriously damaged, but some roof tiles were slightly damaged. The building damages were not serious also in other area surveyed by them.

Table I shows the overall results of their survey, including the numbers and percentages of building damage. Most surveyed locations experienced a seismic intensity larger than 6-strong (i.e., larger than 6.00), though some locations 6-weak (but almost 6-strong). They inspected a total of 2,954 buildings and houses, of which 0.47% collapsed or seriously damaged.

In Japan, we had defined the seismic intensity of 7 as a ground motion during which 30% or more buildings collapsed. After the definition was replaced by instrumental seismic intensity in 1996, the ground motion with a seismic intensity of 6-strong is supposed to destroy 8% to 30% of buildings, and that with a seismic intensity of 7 is supposed to destroy 30% or more buildings. However, the observed percentage of collapsed or seriously damaged buildings during the 2011 Tohoku Earthquake is as extremely low as 0.47% even in areas that experienced seismic intensity of almost 6-strong or greater.

The method of surveying all buildings within a radius of 200 meters around a strong-motion observation station enables us to obtain the collapse ratio of buildings or the percentage of damaged buildings. It also enables us to compare the collapse ratio to the ground motion there. In spite of such a merit, there is a demerit that buildings outside the

Table I : Results from the Building Damages Survey

Observation Station	Instr. Seismic Intensity	Bldgs.	Collapse	Collapse rate (%)	Observation Station	Instr. Seismic Intensity	Bldgs.	Collapse	Collapse rate (%)
JMA , Osaki (M)	6.21	257	7	2.72	K-NET Furukawa (M)	6.16	285	0	0.00
JMA Funyu, Chikusei (I)	6.06	27	0	0.00	K-NET Hokota (I)	6.41	17	0	0.00
JMA Shinmachi, Wakuya (M)	6.02	182	0	0.00	K-NET Tsuchiura (I)	5.63	161	0	0.00
KiK-net Iwase (I)	6.24	17	0	0.00	K-NET Hitachi (I)	6.46	108	0	0.00
KiK-net Nishigou (F)	6.00	8	0	0.00	Fujinuma, Kagamiishi (F)	6-strong	169	0	0.00
KiK-net Batou (T)	6.14	14	0	0.00	Hachiman, Sukagawa (F)	6-strong	229	5	2.18
KiK-net Haga (T)	6.50	59	0	0.00	Shirasawa, Utsunomiya (T)	6-strong	116	0	0.00
K-NET Ogawa (T)	5.97	146	1	0.68	Chuo, Kasama (Ib)	6-strong	101	0	0.00
K-NET Aizuwakamatsu (F)	5.86	199	0	0.00	Ishizue, Takanezawa (T)	6-strong	155	1	0.65
K-NET Iwanuma (M)	5.99	87	0	0.00	Asouhara, Yamamoto (M)	6-strong	108	0	0.00
K-NET Kakuda (M)	5.83	159	0	0.00	Ishijima, Moka (T)	6-strong	76	0	0.00
K-NET Shiogama (M)	6.02	261	0	0.00	Kashimadai, Osaki (M)	6-strong	123	0	0.00
K-NET Shirakawa (F)	6.11	85	0	0.00	Minamikata, Tome (M)	6-strong	3	0	0.00
K-NET Sukagawa (F)	6.00	75	0	0.00	Yoneyama, Tome (M)	6-strong	18	0	0.00
K-NET Sendai (M)	6.38	21	0	0.00	Higashimatsushima (M)	6-strong	200	0	0.00
K-NET Sohma (F)	5.85	159	0	0.00	Masuda, Natori (M)	6-strong	181	1	0.55
K-NET Tsukidate (M)	6.67	59	0	0.00	K-NET Ishinomaki (M)	5.93	—	—	—
					Total (but >S.I. 6.00)		2,954	14	0.47

M: Miyagi pref. F: Fukushima pref.
T: Tochigi pref. I: Ibaragi pref.

survey area cannot be inspected even if they collapsed. This is because arbitrary expansion of the survey area makes the statistical result unreliable.

In parallel to the above survey, another research group conducted a conventional survey where they closely inspected damaged buildings. Researchers of the National Institute for Land and Infrastructure Management (NILIM) and the Building Research Institute (BRI) jointly studied the damage status of RC buildings and steel-framed buildings within Fukushima prefecture[3] (Miharu town, Nihonmatsu city, Koriyama city, and Fukushima city) and Fukushima and Miyagi prefectures[4] (Shirakawa city, Sukagawa city, and Sendai city).

The survey results again showed that the earthquake with large seismic intensity did not cause heavy damage to many buildings aside from rare exceptions. There were some damages on exterior walls, but damages of the structural member were not serious. The group also reported that many of seriously damaged buildings were built before the 1978 Off Miyagi Prefecture Earthquake. In addition, they also indicated the influence of the ground conditions, because buildings in the area that was previously a paddy field were damaged more heavily.

Thus, two independent surveys clearly show that the damage to buildings caused by the 2011 Tohoku Earthquake was small in spite of the large seismic intensity. Was this the result of increasing earthquake-resistant buildings, or the result of some characteristics in the earthquake vibration? To figure this out, the next chapter attempts to draw comparisons with ground motion caused by the 1995 Southern Hyogo Prefecture Earthquake (the Great Hanshin-Awaji Earthquake), which inflicted considerable damage on buildings.

3 Comparison Between the 1995 Southern Hyogo Prefecture Earthquake and the 2011 Tohoku Earthquake

3-1 Comparison of Ground Motions

In Fig. 4, we compare the typical ground motion of the 2011 Tohoku Earthquake and that of the 1995 Southern Hyogo Prefecture Earthquake (hereafter, the 1995 Southern Hyogo Earthquake). These ground motions were observed at K-NET Tsukidate in Miyagi prefecture and the Takatori Station (of West Japan Railway Company) in Hyogo prefecture, respectively. While the building collapse rate for Tsukidate was 0% at seismic intensity 7, the rate for Takatori was 59.4% at seismic intensity 6-strong, showing a large difference.

The characteristics of the two ground motions shown in Fig. 4 are quite different from each other. While strong short-period ground motion continued for a long time in the 2011 Tohoku Earthquake, relatively long-period ground motion was observed in the 1995 Southern Hyogo Earthquake. The vertical axes of upper two graphs represent the acceleration of

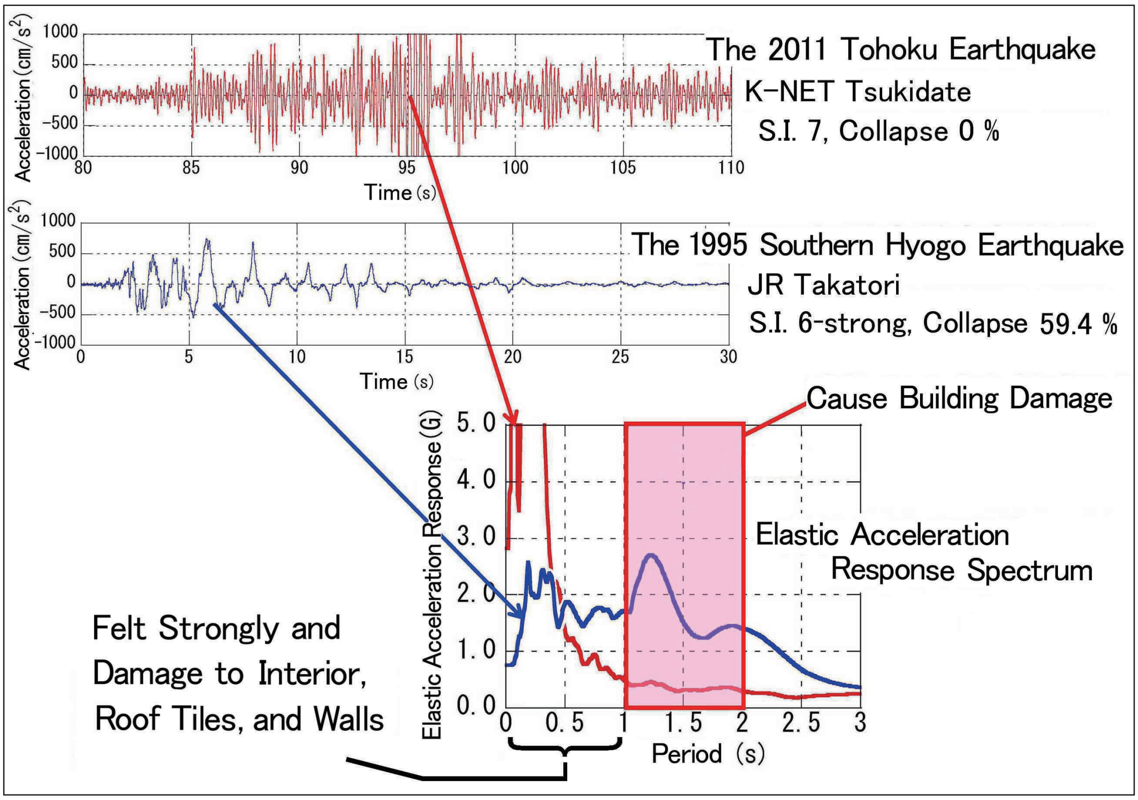

Figure 4 : Comparison of Ground Motions in the 2011 Tohoku Earthquake and the 1995 Southern Hyogo Prefecture Earthquake. (Provided by Y. Sakai)

ground motions in units of cm/s^2, which we usually call as "gal." Another unit "G," where 1G = 980 cm/s^2 (gravitational acceleration), is used for acceleration response in the lower figure. In the graph for the 2011 Tohoku Earthquake, the maximum acceleration exceeded 1,000 gal, but we have omitted the part beyond 1,000 gal to simplify the graph.

The difference between the characteristics of the two ground motions becomes apparent when we draw a graph showing the relationship between vibration intensity and vibration period (i.e., the elastic acceleration response spectrum). The elastic acceleration response of the 2011 Tohoku Earthquake was larger at a vibration period of 0 to 0.5 seconds, but that of the 1995 Southern Hyogo Earthquake was larger at a vibration period of 1 to 2 seconds. The ground motion with a period of 1 to 2 seconds will cause building damage, and it is suggested that there is a correlation between the intensity of this period vibration and the percentage of damaged buildings. On the other hand, ground motions with a period of 0 to 1 second are felt more by people and have a correlation with damages of room interior and non-structural materials such as roof tiles and walls.

Other observation stations in Tohoku region also showed that the elastic acceleration response was large in a period of 0 to 0.5 seconds and small in a period of 1 to 2 seconds (see Fig. 5). This result reveals the reason why the 2011 Tohoku Earthquake did not inflict so much damage to buildings. Namely, it was because the earthquake had little ground motion that affects buildings.

This fact does not mean that the earthquake safety of buildings was improved after the 1995 Southern Hyogo Earthquake. Thus, we cannot automatically expect that a building will withstand a large earthquake in the near future just because it survived the massive Tohoku Earthquake.

It is known that most wood-frame houses and low-

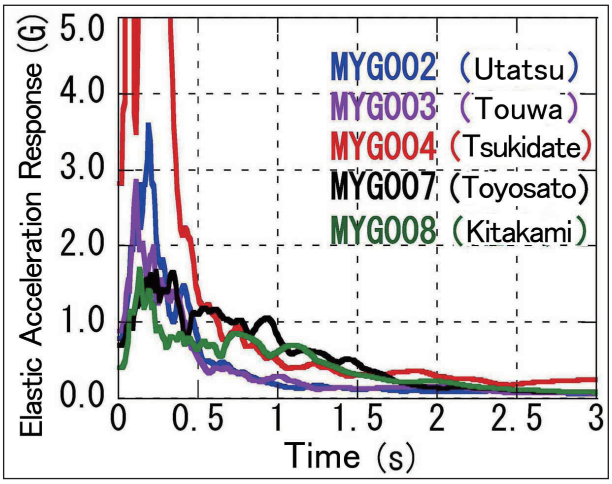

Figure 5 : Spectrum of the Elastic Acceleration Response at Other Observation Stations. (Provided by Y. Sakai)

and medium-rise buildings have their own natural periods of 0.3 to 0.4 seconds, at which they vibrate most easily. Therefore, it may seem strange that ground motion with 1 to 2 second periods, which are longer periods than own natural periods, would cause massive building damage.

The condition of natural period of 0.3 to 0.4 seconds is satisfied only within the elastic limit of buildings. When a building vibrates beyond the elastic limit, the plastic deformation of building starts to occur, and then the resonant period of the building would become longer. Thus, building damage is determined by the longer "equivalent period" at the time of plastic deformation. This has been confirmed by the results of both non-linear simulations and model experiments (see Fig. 6). Ground motion with a period of one to two seconds, even if it is a single cycle, can produce plastic deformation of a building and inflict heavy damage. For that reason, it is occasionally referred to as a "killer pulse" in media reports.

3-2 Comparison of Building Damage

The 1995 Southern Hyogo Earthquake inflicted heavy damage to buildings, fully or partially destroying approximately 250,000 buildings and houses. About 80% of the 6,432 people killed were, reportedly, crushed to death when their houses collapsed. In many cases, people sleeping on the first floor in a two-story house were crushed to death by the second floor dropped due to a broken post.

Ashiya city, a city with a population of about 90,000 people, published a detailed report titled "Ashiya City: Damage to Buildings and Restoration of Them[5]," which included results of all building survey in the city. Among all 15,421 buildings in the city 4,722 were fully destroyed and 4,062 were partially destroyed, accounting for 57% of all buildings in the city. There were 10,514 wooden houses, which were the most in number, and about 70% of them were fully or partially collapsed. Meanwhile, just over 20% of 2,577 RC buildings, which were the second in number, were fully or partially destroyed.

Many houses damaged by the earthquake were built before the June 1981 amendment to the Building Standards Act. Moreover, the older they are, the more houses are seriously damaged (see Fig.7). At some places in the belt zone of a seismic intensity of 7 stretching east to west on the center of the city, more than 90% of buildings and houses were fully or partially collapsed. Many people were also hurt or killed in the belt zone.

The phenomenon of the upper floor dropping due to the snap of posts is called "story collapse." The story collapse occurred not only in wooden houses, but in steel-framed and RC buildings (see Fig. 8). Fortunately, the story collapse in large buildings did not kill many people because the 1995 Southern Hyogo Earthquake struck in the early morning, at 5:46 a.m. We can easily imagine that the story collapse would have killed many people in large buildings such as department stores if the earthquake occurred during the daytime.

Y. Sakai found that the ground motions during the 2011 Tohoku Earthquake did not damage many buildings: the percentage of fully or seriously

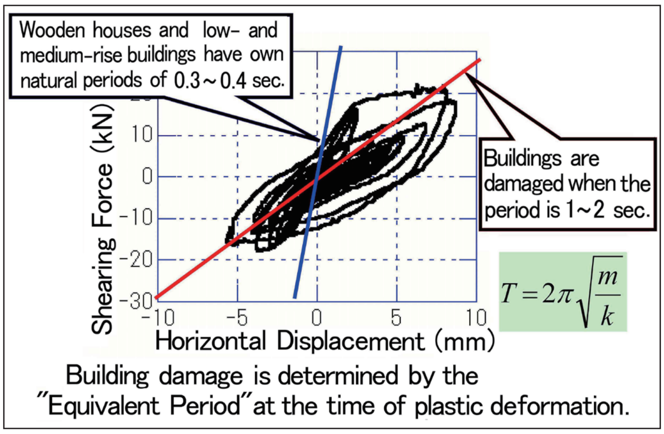

Figure 6 : Result of Model Experiment (Provided by Y. Sakai)

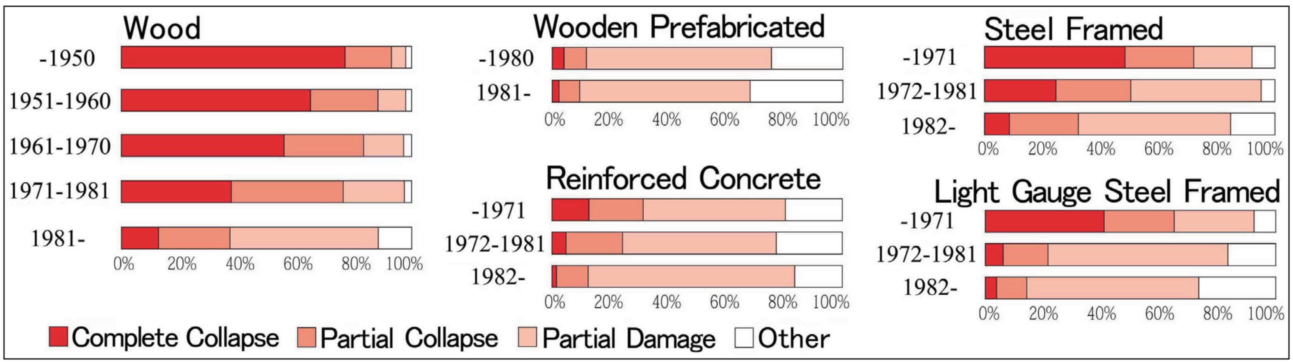

Figure 7 : Damage Situation of Buildings in Ashiya City (Reprint from Ref. 6)

destroyed buildings and houses was only 0.47%. In the meantime, the joint team of the NILIM and the BRI reported that some buildings suffered heavy damages such as story collapses.[3,4]

Figures 9(a) and 9(b) show two RC buildings that faced different intersections. Both buildings had stores on the first floor with "pilotis" structure (soft-first-story structure) which had few bearing walls. In both cases, the corner post facing intersection experienced shearing failure, which caused story collapse. However, a pilotis building with only pillars on the first floor hardly receives flowing water pressure if it can withstand the earthquake. In fact, there was a pilotis building escaping damage from the tsunami. Figure 9(c) shows a university building whose poor earthquake resistance had previously been pointed out. A reinforcement plan had been worked out when the earthquake struck. This building was seriously damaged, but an adjacent building on the same campus had no visible exterior damage. Figure 9(d) shows an example of wall damage that was the most commonly observed form of partial damage.

As discussed above, ground motions with a period shorter than 0.5 seconds were remarkable during the 2011 Tohoku Earthquake, and they mostly damaged interiors and non-structural members such as walls. Because of falling ceiling materials and light fixtures and because of collapsing parking garage ramps, there were casualties even in the Tokyo metropolitan area.

Figure 8 : Story collapse of Large Buildings. (Provided by Y. Sakai)

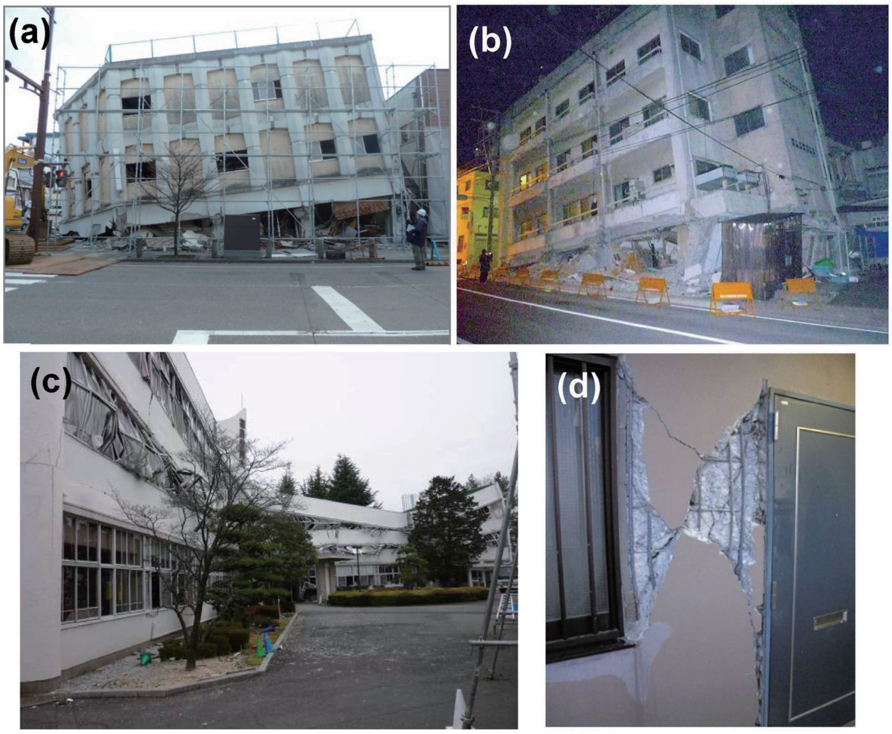

Figure 9 : Examples of building damage due to the 2011 Tohoku Earthquake. (Reprint from Refs. 3 and 4)

In the area, some houses experienced damage such as loosened roof tiles, and other damage was caused by soil liquefaction.

Some manufacturing buildings were also damaged with falling ceilings and broken interiors. An electronic component factory reported that air-tightness could not be maintained because the expansion joint of a clean room came lose. Many factories received large economic loss not only from damage to buildings, but also from damage to production facilities, such as the overturning of manufacturing equipment. Factory damage of a single company had substantial effects on many industries through the supply chain. For example, the shutdown of a semiconductor factory of Renesas Electronics Corporation heavily affected automobile production worldwide.

In order to prevent such an economic loss, industries should have “disaster resistance capability” for avoiding a decline of business activities at the time of a disaster as well as “disaster response capability” for quick recovery of business activity after a disaster. Business operators may need to prepare a “Business Continuity Plan (BCP)” that takes these two points into consideration and involves good practices.

4 Building Damage in Past Earthquakes

We refer to a ground motion where a period of one second or less is noticeable as “short period ground motion,” and that where a period of one to two seconds is noticeable as “slightly short period ground motion.” When a ground motion mainly involves vibrations with a period of two seconds or longer, it is referred to as “long period ground motion,” which has been observed in sedimentary plains such as the Kanto Plain, the Nobi Plain or the Osaka Plain. A long period ground motion is occasionally sorted into more detailed categories; “slightly long period ground motion” with a period of two to five seconds and “long period ground motion” with a period of five seconds or more.

Table II shows the situation of damage caused by past earthquakes larger than a seismic intensity of 6-weak. In the table, the earthquake that caused slightly short period ground motions (with a period

Table II : Damage Situation due to Past Earthquakes Lager Than Seismic Intensity (S.I.) of 6 weeks

Year	Name of Earthquake or Location of Hypocenter	M	Max. S.I.	Tsunami (meters)	Dead & Missing	Building Collapses		Vibration Period
						Compete	Partial	
1995	The Southern Hyogo Pref. Earthquake	7.3	7	Yes	6,437	104,906	144,274	☆
1997	Satsunan Region in Kagoshima Pref.	6.4	6-w	No	0	4	31	
1998	Northern Part of Iwate Pref.	6.2	6-w	No	0	0	0	
2000	Niijima, Kohzushima, and Vicinities (3 Times)	6.5	6-w	0.14	1	15	20	
2000	The Western Tottori Pref. Earthquake	7.3	6-s	No	0	435	3,101	○
2001	The Geiyo Earthquake	6.7	6-w	No	2	70	774	
2003	Off Miyagi Pref.	7.1	6-w	No	0	2	21	
2003	Northern Miyagi Pref.	6.4	6-s	No	0	1,276	3,809	Unknown
2003	The Off Tokachi Earthquake	8.0	6-w	2.55	2	116	368	
2004	The Niigata Pref. Chuetsu Earthquake	6.8	7	No	68	3,175	13,810	○
2005	West-off Fukuoka Pref.	7.0	6-w	No	1	144	353	
2005	Off Miyagi Pref.	7.2	6-w	0.12	0	1	0	
2007	The Noto Peninsula Earthquake	6.9	6-s	0.22	1	686	1,740	○
2007	The Niigata Pref. Off-Chuetsu Earthquake	6.8	6-s	0.32	15	1,331	5,709	○
2008	The Iwate-Miyagi Inland Earthquake	7.2	6-s	No	23	30	146	
2008	Northern Coast of Iwate Pref.	6.8	6-w	No	1	1	0	
2009	Suruga Bay	6.5	6-w	0.36	1	0	6	
2011	The Off the Pacific Coast of Tohoku Earthquake	9.0	7	9.3+	19,263	128,582	244,031	
2011	Near Border between Nagano and Niigata Prefs.	6.7	6-s	No	3	73	426	
2011	Eastern Shizuoka Pref.	6.4	6-s	No	0	0	103	

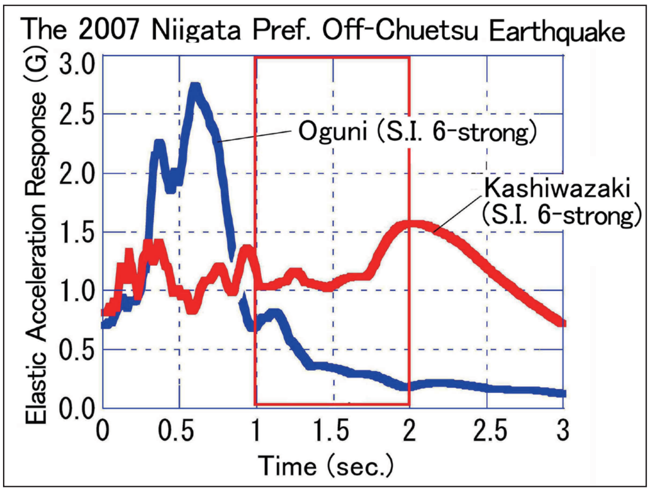

Figure 10 : Spectrum of Elastic Acceleration Response in the 2007 Niigata Pref. Off-Chuetsu Earthquake. (Provided by Y. Sakai)

of one to two seconds) at many locations is denoted by an asterisk, and at limited locations by a circle. It is unknown whether the 2003 earthquake with hypocenter in Northern Miyagi Prefecture caused slightly short period ground motions because some of the seismograph traces were lost. In Table II, we may find that there is a strong correlation between a star or circle and the number of buildings damaged. The 2011 Tohoku Earthquake seriously damaged a large number of buildings, but most of them were damaged by the tsunami rather than by ground motion. On the morning following the 2011 Tohoku Earthquake, however, the earthquake with hypocenter near the Border between Nagano and Niigata seriously damaged many houses in Sakae village (Nagano prefecture) and Tokamachi city (Niigata prefecture).

Though Table II marks earthquakes that caused slightly short period ground motions at some locations, the period is determined not only by the seismic source process but largely by the ground condition there and the propagation path of seismic waves. This is clear from Fig. 10 that shows the elastic acceleration responses observed in Nagaoka city (the Oguni district) and Kashiwazaki city during the 2007 Niigata Prefecture Off-Chuetsu Earthquake. While the short period ground motion was predominant in Oguni district, the ground motion with a period of two seconds or more was in Kashiwazaki city. In this way, the vibration period of ground motion differs by location even in the same earthquake. Therefore, when studying reduction of building damage caused by earthquakes, we must not study earthquakes alone, but study earthquakes, subsurface structure, the ground, buildings and other relevant elements comprehensively.

In the 2008 Iwate-Miyagi Inland Earthquake and the 2009 earthquake in Suruga Bay, most stations recorded short period ground motion, but certain stations such as K-NET Hurukawa and K-NET Naruko exceptionally recorded slightly short period ground motion and long period ground motion (see Fig. 11). The result of surveys on the building damage caused by these two earthquakes is summarized in Table III. In the survey areas, neither of these earthquakes caused serious building damages such as complete or partial collapse other than damage to tiled roofs.

Outside the survey areas, however, there were a total of 176 buildings collapsed and 23 people dead or missing at the time of the 2008 Iwate-Miyagi Inland Earthquake. Furthermore, the Ichinoseki-nishi observation station in Iwate prefecture recorded the seismic acceleration 4,022 gal that was the largest in recorded history. Earthquakes with a maximum seismic intensity larger than 6-weak, which have been believed to cause complete or partial collapses of buildings, occur 1.3 times a year in average. In terms of damage rate, however, the damage is clearly smaller than assumed in most earthquakes. Rather, the 1995 South Hyogo Earthquake that caused serious building damage corresponding to the seismic intensity is regarded as an exceptional case. This indicates that building damage caused by earthquakes cannot be explained by the single indicator of seismic intensity.

5 Relations between Seismic Intensity and Building Damage

The current seismic intensity scale used by the Japan Meteorological Agency (JMA) is a ten-level scale that goes from 0 to 4, followed by 5-weak, 5-strong, 6-weak, 6-strong and then 7. It was an eight-level scale from 0 to 7 before 1996, but strong and weak levels were added to both seismic intensities of 5 and 6 after the 1995 Southern Hyogo Earthquake. This was because the damage situation varied widely by areas with the same seismic intensity.

Seismic intensity is not a definite physical quantity such as acceleration or amplitude. It is a complicated quantity related to many factors such as vibration period, amplitude, acceleration, and duration time. For that reason, it was determined by body sensory or damage situation until 1995. In recent years, numerical

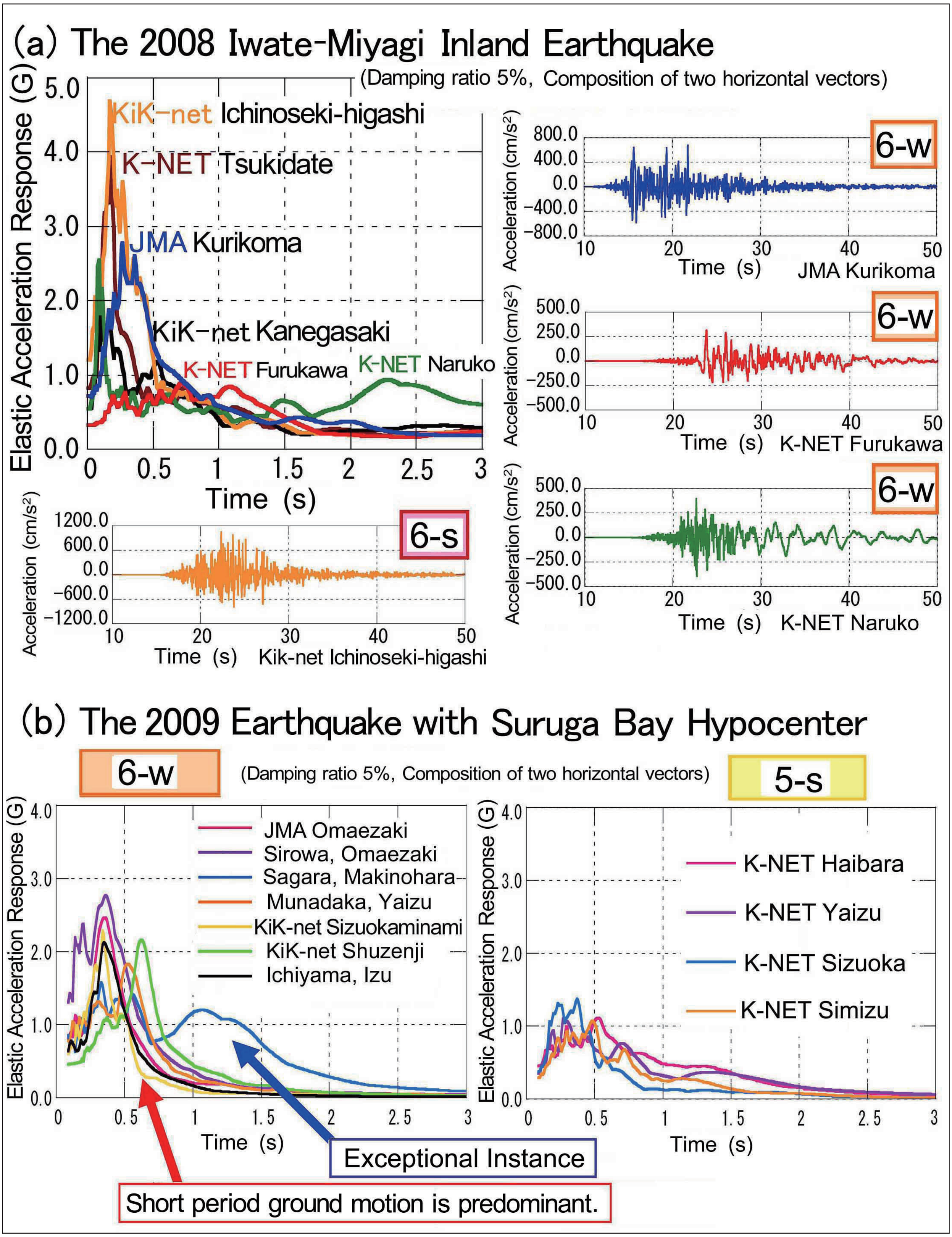

Figure 11 : The Elastic Acceleration Response Spectra in Two Major Earthquakes. (Provided by Y. Sakai)

Table III : Results of Surveys on Building Damage due to Two Earthquakes

(a) Building damage due to the 2008 Iwate-Miyagi Inland Earthquake

S.I.	Observation Station	S.I. Instr.	Damage Situation within 200 m Radius.	The number of buildings			
				All	Wood	Non-Wood	Col-lapse
6-s	Ichihasama,Kurihara (M),	6.2	Detached exterior materials, Block fence collapse, Roof tile damage, etc.	22	17	5	0
	Koromogawa, Oshu (I)	6.1	Exterior cracks in RC building, Roof tile damage, Ground damage, etc.	38	31	7	0
	KiK-net Ichinoseki-higashi (I)	6.0	Damage to public hall and gym exterior	4	4	0	0
6-w	JMA Kurikoma, Kurihara (M)	5.9	Small damage to exterior	14	13	1	0
	Uguisuzawa, kurihara (M)	5.8	Collapse of aged warehouse	40	32	8	0
	K-NET Tsukidate (M)	5.7	No Damage	53	47	6	0
	JMA Osaki (M)	5.6	Detached exterior materials	284	261	23	0
	Kannari, Kurihara (M)	5.6	Slanted warehouse, Detached exterior materials, Ground damage, etc.	26	14	12	0
	K-NET Furukawa (M)	5.5	Detached exterior materials, Broken glass windows, etc.	281	255	26	0
	K-NET Naruko (M)	5.5	No Damage	15	14	1	0
	KiK-net Kanegasaki (I)	5.5	Damaged block fence, Ground damage	12	11	1	0
	Tajiri, Osaki (M)	5.5	Detached exterior materials, Cracks in foundation of RC building, etc.	110	99	11	0
	Takashimizu, Kurihara (M)	5.5	Detached exterior materials, Other minor building damage	111	101	10	0
	Hanayama, Kurihara (M)	5.5	Detached exterior materials, Damaged block fence, etc.	38	30	8	0
	Shiwahime, Kurihara (M)	5.5	Exterior cracks in RC building, Detached exterior materials	57	43	6	0
	Isawa, Oshu (I)	5.5	No Damage	19	14	5	0
5-s	K-NET Ichinoseki (I)	5.0	No Damage	164	131	33	0

(I) Iwate Prefecture (M) Miyagi Prefecture

(b) Building damage due to the 2009 earthquake with Suruga Bay hypocenter

Observation Station	S.I. Instr.	Damage Situation within 200 m Radius	The number of buildings					Roof Tile Dmg. Rate (%)	Complete Collapse (%)
			Wood	Non-Wood	Complete Collapse	Partial Collapse	Roof Tile Damage		
JMA Omaezaki	5.7	Roof tile damage	131	7	0	0	6	4.8	0
Shirowa, Omaezaki	5.9	Roof tile damage to many buildings, Exterior damage	95	8	0	1	18	17.5	0
Sagara, Makinohara	5.9	Roof tile damage to many buildings	83	28	0	0	19	17.1	0
Sizunami, Makinohara	5.5	Roof tile damage to many buildings	154	33	0	0	17	9.1	0
Munadaka, Yaizu	5.6	Roof tile damage to many buildings	45	11	0	0	9	16.1	(0)
KiK-net Sizuokaminami	5.6	Roof tile damage, Interior damage to public swimming pool.	14	8	0	0	1	4.6	(0)
KiK-net Shuzenji	5.7	No Damage	1	0	0	0	0	0.0	(0)
Ichiyama, Izu	5.5	Roof tile damage	65	19	0	0	2	2.4	(0)
K-NET Haibara	5.4	Roof tile damage to many buildings	87	27	0	0	8	7.0	0
K-NET Yaizu	5.4	Roof tile damage	229	42	0	0	5	1.9	0
K-NET Shizuoka	5.1	Roof tile damage	334	214	0	0	1	0.2	0
K-NET Shimizu	5.2	No Damage	35	29	0	0	0	0.0	(0)

seismogram processing has been available, allowing for automated determinations by machines. This instrumental seismic intensity has been in use since 1996. For example, seismic intensity of 4 is defined by the automatically-determined values of 3.5 to 4.4, that of 5-weak by values of 4.5 to 4.9, that of 5-strong by values 5.0 to 5.4, and so on.

Automated determination of seismic intensity now allows TV and radio to report the seismic intensity at various locations within one or two minutes after an earthquake occurs. At present, only Japan has such a revolutionary system for prompt and detailed announcement of earthquake. In spite of the benefit from the system, a question arises as to whether the continuity between the former seismic intensity depending on body sensory and the current instrumental seismic intensity is well assessed or not. JMA documents say that the current instrumental seismic scale agrees well with the former scale up to the seismic intensity of 6 for earthquakes from 1988 to 1994. As yet, however, there has been no verification of consistency between the former and the current seismic scales for larger intensity than 6-strong after 1995. A possible inconsistency in seismic scales may cause the discrepancy between the current seismic intensity and percentage of building damage.

Since 1996, when the JMA adopted the instrumental seismic intensity, earthquakes with seismic intensities larger than 6-weak have increased in occurrence rate quite dramatically.[9,10] Figure 12 shows cumulated numbers of earthquakes with magnitude 6 and those with seismic intensities larger than 6-weak. In the figure, we can see that the occurrence rate of large earthquakes has not changed, but that of earthquakes with seismic intensities larger than 6-weak increased abruptly by 15 times after 1996.

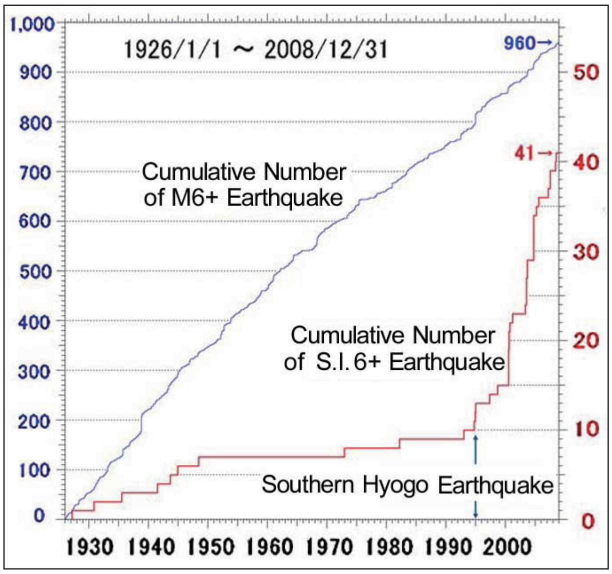

Figure 12 : Cumulative Number of Large Earthquakes. (Reprint from Ref. 10)

The increase in large-intensity earthquakes has been explained as a result of the increasing number of observation stations. It is because the network with many stations would not miss the area experiencing maximum seismic intensity. The explanation seems to be reasonable at first, but it is not obvious that it can explain a rate of occurrence that is 15 times higher. There is a possibility that a part of discrepancy in occurrence rate is caused by a difference between the current instrumental seismic scale and the former scale.

Yuki SAKAI proposed new indicator11 different from the instrumental seismic intensity, which will fit for the damage situation. The indicator is obtained by weighting the ground motions with certain vibration periods. If a clear discrepancy between seismic intensity and the damage situation frequently arises, the significance of the intensity as an indicator would be called into question. Certainly, there is an opinion that we should not change the current instrumental seismic intensity so lightly. If so, it may be a good idea to use another new index that would express structural damage of buildings.

Most ground motions have a short period of one second or less, and a slightly short period ground motion of one to two seconds does not necessarily occur often. Besides, the period of ground motion depends on both the ground structure and the propagation path of seismic waves. Because the shaking of the 2011 Tohoku Earthquake did not damage buildings seriously, many people may believe their houses not to be damaged by the ground motions with large seismic intensities such as 6-strong or 7. This is, however, a big misunderstanding, and it is quite dangerous for us to believe so. We should remind ourselves that an earthquake may cause enormous damages on buildings if it accompanies the large ground motion with a period of one to two seconds. The authors would like to stress that we should protect low- and medium-rise buildings against earthquake motions with a period of one to two seconds.

6 Super-high raise Buildings and Methods of Seismic Isolation and Vibration Damping

During the 2011 Tohoku Earthquake, a seismic intensity of 5-weak was recorded even in Tokyo distant from the hypocenter, and super-high rise buildings in the midtown swayed widely over a few minutes. Although the Japan Building Standards Act does not give a clear description of a super-high rise building, a building over 60 meters tall is often called a super-high rise building due to the prescription of Article 20, paragraph (1), in the act. The act requires that buildings taller than 60 meters must meet to quake-resistance standards by a certain analysis (time-history response analysis) using defined seismic waveforms.

The earthquake-resistant structure of buildings is classified roughly into three categories.

(a) Narrowly-defined earthquake-proof structure where the structure stiffness is increased for the purpose of enduring seismic force.

(b) Vibration damping structure where the motion of a building is suppressed by absorbing vibration energy.

(c) Seismic isolation structure where laminated rubber or sliding support prevent seismic force from reaching floors and upstairs.

Ordinary houses usually employ load-bearing walls or diagonal braces (i.e. narrowly-defined earthquake-proof structure) to enhance their earthquake safety, while super-high raise buildings employ vibration-damping and/or seismic-isolation structures. The own natural periods of low rise, high rise and super-high rise buildings are 0.5 seconds or less, 1 to 2 seconds, and 2 to 6 seconds, respectively. In general, the own natural period becomes longer for taller building. Consequently, a super-high rise building shows a large difference between the own natural period and the dominant period of ground motions, and thus the force and acceleration transmitted to the building become smaller (Fig. 13, left). Contrarily, the vibration amplitude and the building's deformation are increased in a super-high-rise building (Fig. 13, right).

In the vibration damping structure, seismic wave energy is absorbed by damper elements, which reduces both forces acting on the building and deformation of the building. Meanwhile, the seismic isolation structure reduces the forces transmitting to the building by prolonging the building's resonant period through the use of laminated rubber or spring dampers.

There are various types of vibration damping structures, but they are typically classified into the following three types.

(a) Inter-floor dampers: They prevent damage to a building by connecting the floor of the upper story to the ceiling (or the floor) of the lower story via dampers that can absorb vibration energy. Typical dampers are the oil damper and the low-yield steel damper as shown in Fig. 14.

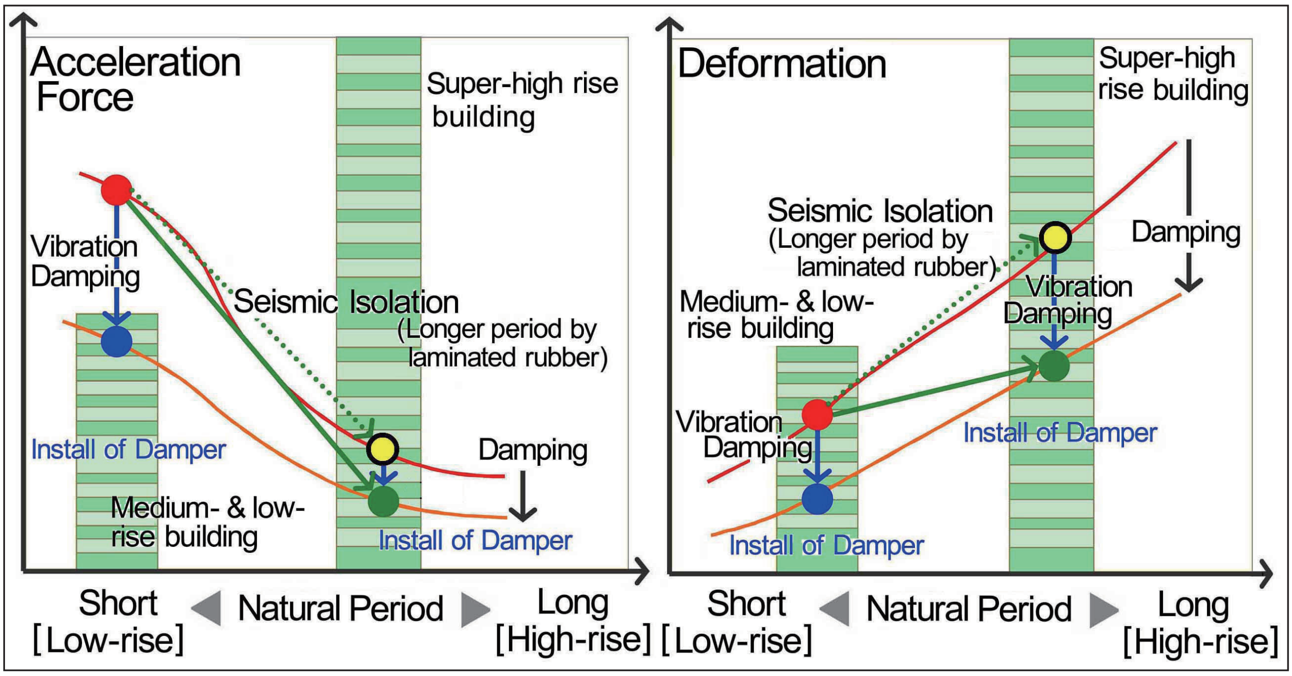

Figure 13 : Force Applied to Buildings and Deformation of Buildings. (Provided by S. Sakai)

Figure 14 : Types of Inter-Floor Dampers. (Provided by S. Sakai)

(b) Mass dampers: A "weight" is installed at the top of a building in order to suppress vibrations of the upper section of the building. In this case as well, the weight is connected to the building with dampers to absorb energy. In some cases, an actuator is used for the connection, providing active control by use of the force applied in the direction opposite to the sway of the building.

(c) Coupled vibration control structure: Separate structures (or separate buildings) with different natural periods are connected by dampers or bridge in order to suppress the vibrations. One example is the Harumi Island Triton Square where three buildings are connected by vibration control bridges. Another example is the Tokyo Skytree that has “Shin-Bashira,” a central column of the tower, connected to the main body by oil dampers.

Differently from vibration damping, a seismic isolation structure prevents ground motions from transmitting to the building by installing laminated rubber or steel dampers on the foundation of building as shown in Fig. 15. The seismic isolation structure makes it harder for ground motions to enter the building by prolonging a natural period of the whole building including seismic isolation equipment (see Fig. 13). When the natural period becomes long, the force acting on interior portions of the building becomes smaller while the deformation of the building becomes larger.

The structure concentrates such deformation on the laminated rubber or steel dampers so as to prevent damage to the upper part of the building. However, we need to pay sufficient attention to wind pressure when installing a seismic isolation system in a super-high rise building because a strong wind may cause the sway of the building. Careful consideration should also be paid to the joint area around entrances or the building's surroundings, as the floor or the building itself may move differently from the ground.

Figure 15 : Structural Members of Seismic Isolation. (Provided by S. Sakai)

Figure 16 shows the seismic motion observed in a super-high rise building adopting a seismic isolation structure at the time of the 2011 Tohoku Earthquake. The earthquake-induced vibrations were measured on three different floors: on the foundation, the first floor and the twenty-first floor. Three different waveforms at the same floor indicate two horizontal motions and one vertical motion in order from top to down. In Fig. 16, we find that the horizontal motions of the first

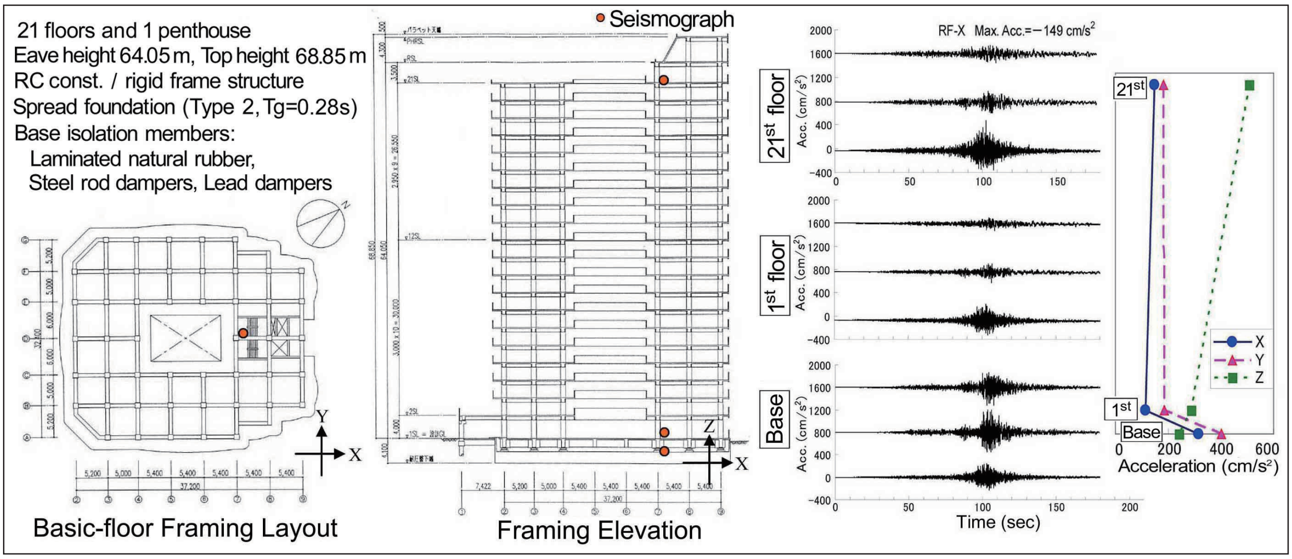

Figure 16 : Observed Motion of a Super-high Rise Building with Seismic Isolation during the 2011 Tohoku Earthquake. (Provided by S. Sakai)

floor are much smaller than those of the foundation. The acceleration of the first floor was about one-third of the seismic acceleration of the ground, which verified that the seismic isolation worked quite well. The vertical motion of the first floor, however, was not attenuated, and it turned out that the standard seismic isolation was not effective for vertical ground motion.

Since the earthquake-induced vibrations of the same building without a seismic-isolation cannot be measured, Shigeki Sakai and his colleagues just have to obtain them through computer simulation. The result showed that the seismic isolation structure reduced the vibration acceleration of the lower floors from 320 cm/s^2 to 100 cm/s^2, and that of the upper floors from 280 cm/s^2 to 160 cm/s^2.

The simulation also showed that the inter-story deflection angle, i.e. a relative story displacement divided by pillar length, would reach nearly 1/200 on many floors if the super-high raise building did not have the seismic isolation structure. In fact, the angle was 1/1000 or less on all floors thanks to the seismic isolation. When the angle reaches 1/200 or more, cracks supposedly start to develop in walls. Thus, it was confirmed that the seismic-isolation structure had a useful effect to protect a building against damage. Indeed, this building did not suffer any damages such as cracks in walls and pillar surfaces, nor furniture tipping accidents.

Both vibration-damping structure and seismic-isolation structure protect the whole building against damage by concentrating seismic force and deformation in dampers or laminated rubber. Hence, the strength and repetition tolerance of dampers or laminated rubber is a critical issue. After the 2011 Tohoku Earthquake, residual deformation in steel damper, cracks in lead damper, and loosened bolts were observed. Under such conditions, the effectiveness and reliability of vibration-damping or seismic-isolation largely decrease, and prompt repair or replacement may be necessary. Since these defects could be fatal particularly in the case of strong aftershocks, an emergency checkup should be conducted immediately after an earthquake. At present, we have neither methods of stress test against repeated vibrations nor evaluation standards for residual tolerance after an earthquake, which will be critical issues in the future.

The 2011 Tohoku Earthquake was the first case in which super-high rise buildings in the Tokyo metropolitan area swayed heavily for over 10 minutes. For instance, super-high rise buildings in Shinjuku experienced the swing up to 108 cm for 13 minutes. The scene has been video recorded and can be viewed on video websites. In the Tokyo metropolitan area, aftershocks accompanying "long period ground motion" were also observed. Figure 17 shows the ground motion observed in Shinjyuku at 3:59 a.m. on March 12. Though the acceleration of this aftershock is not large, the ground motion with a period of 5.6 seconds is clearly observed from 65 to 110 seconds in Fig. 17.

The long period ground motion got attention in Japan after an oil tank fire due to sloshing, a resonant phenomenon of fluid in a tank, at the Tomakomai industrial complex when the 2003 Off Tokachi Earthquake occurred. In the 2004 Niigata Prefecture

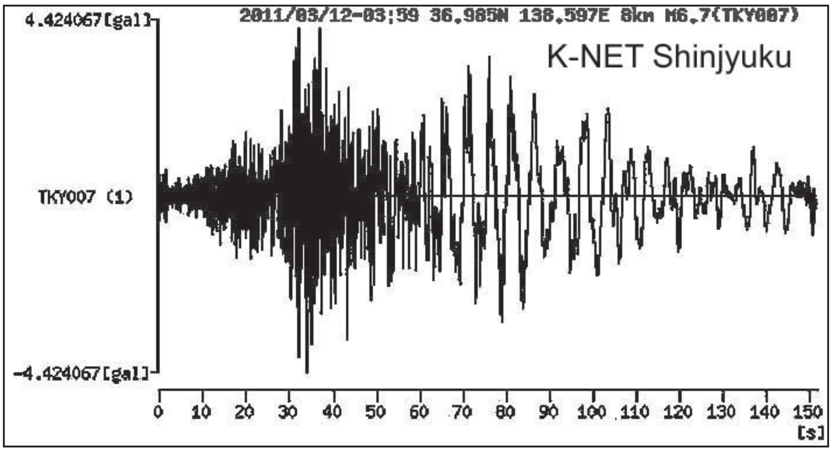

Figure 17 : Aftershock Ground Motion Observed at Shinjuku (from Ref.2)

Chuetsu Earthquake and the 2007 Niigata Prefecture Off-Chuetsu Earthquake, the long period ground motion damaged elevators of some super-high rise buildings in the Tokyo area. In addition, the oil tank fire that occurred in Niigata city at the time of the 1964 Niigata Earthquake was considered to have been caused by sloshing resulting from ground liquefaction, but today the cause is considered to have been the long period ground motion.

Modern super-high rise buildings in Japan, the first of which was the Kasumigaseki Building completed in 1967, had never experienced a large earthquake until the 2011 Tohoku Earthquake struck. Furthermore, many super-high rise buildings are located on the sedimentary ground layers such as Tokyo, Osaka, and Nagoya areas where the long period ground motion is commonly produced. The combination of a long period ground motion and super-high rise building is a largely unknown research region on earthquake damage. Based on this experience, we should address the critical issue of minimizing a possible damage caused by a future massive earthquake.

7 Summary and Conclusions

In this report, the authors want to draw out some lessons on disaster prevention from comparing building damages caused by two large earthquakes: the 2011 Tohoku Earthquake (the Great East Japan Earthquake) and the 1995 Southern Hyogo Prefecture Earthquake (the Great Hanshin-Awaji Earthquake).

The 2011 Tohoku Earthquake was a huge disastrous earthquake with large magnitude and large seismic intensities (6-weak and 7) over a wide area. Despite this, the ground motion did not cause serious damage to buildings differently from the 1995 Southern Hyogo Prefecture Earthquake. The reason is explained by the difference in the vibration period of the ground motion.

In the 2011 Tohoku Earthquake, “short period ground motions” with a period of one second or less were predominant, while “slightly short period ground motions” with a period of one to two seconds were rather quiet. The short period ground motion causes little structural damage like complete or partial collapses to buildings though people may experience it as a strong shaking. However, it causes damage to building walls and ceilings. Differently from the 2011 Tohoku Earthquake, the 1995 Southern Hyogo Prefecture Earthquake produced the slightly short period ground motion that seriously damaged many buildings.

Meanwhile, the 2011 Tohoku Earthquake and the aftershocks caused “long period ground motions” in Tokyo and swayed super-high rise buildings there. Seismic isolation and vibration damping devices worked well on a certain level, but their safety and effectiveness for the long period ground motion remain largely unknown. Hence, there are many issues to be studied in the future.

Slightly short period ground motion (with a period of one to two seconds) and long period ground motion (with a period longer than two seconds) cause quite different kinds of damages to different objects. The various causes dependent on vibration periods make the damage situation even more diverse than usual. It was just good luck in a sense that only little building damage was caused by ground motion in the 2011 Tohoku Earthquake. We need to note that a future earthquake with a similar level of seismic intensity may not necessarily cause the same degree of building damage. The disaster prevention plan for earthquakes based on predicted seismic intensity has only limited effectiveness and may serve as one of many guides. We must assume a situation where overall damage status cannot be fully identified by a single indicator of the JMA seismic intensity scale.

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