6. Damage to Buildings by Earthquake Motions

6.1 Policy on Earthquake Damage Investigation for Buildings

The 2011 Tohoku earthquake brought about building damage in a wide area of various prefectures on the Pacific coast in eastern Japan such as Iwate, Miyagi, Fukushima, Ibaraki and Chiba prefectures.

The epicentral area of this earthquake has a length of about 450 km and a width of about 150 km, almost in parallel with the Pacific coast in eastern Japan. Distance from the fault plane of the earthquake to the above prefectures is almost same. As indicated in Chapter 5, observed earthquake motions in Sendai City close to the epicenter are not much different from those in cities far away from Sendai, for instance, Tsukuba City.

Based on these circumstances, NILIM and BRI decided to widely survey damaged wooden buildings as a primary damage investigation in the northern part of Miyagi (Kurihara City) where JMA Seismic Intensity 7 was observed, and in a wide area of Miyagi to Ibaraki including inland Tochigi prefecture that suffered larger damage than coastal prefectures. In addition, as a secondary investigation, it was planned to select affected areas from those subject to the primary investigation to conduct a more detailed survey on buildings collecting building plans and wood-shear-wall layout.

In order to conduct a damage investigation of steel buildings, it was decided that mainly a primary visual inspection would be done in Sendai City since a large stock of steel buildings is accumulated, and also in Fukushima and Ibaraki prefectures. As mentioned later, severer damage to structural elements seemed to be limited, while there were so many types of damage to nonstructural elements such as falling of exterior cladding. Consequently, focusing not on private buildings that are difficult to investigate in detail but on school gymnasiums in Ibaraki prefecture where many damage cases were reported that enabled interior investigations, it was decided to continue the primary investigation. For reference, the school gymnasiums can be seen to be similar to factories and warehouses. If the structural damage in interior building is clarified in future, more detailed secondary investigation on buildings other than the gymnasiums will be considered.

Concerning damage investigation for reinforced concrete buildings, in addition to an investigation of reportedly collapsed buildings, a primary investigation was conducted on city halls and other public buildings that are located in a wide area of the north to the south as done in the damage investigation for wooden buildings, and damage patterns whether they are similar or different from previously grasped patterns are examined. If there are characteristic damage patterns that should be incorporated into technical standards, the secondary investigation will be considered.

A primary investigation for damage of building lands and foundations was conducted in Itako City, Ibaraki, and in Urayasu City, Chiba and its peripheral areas that were subject to severe liquefaction in the region of Kanto. The areas that had been affected by the 1978 Miyagi-Ken-Oki Earthquake were damaged again. In these areas, also a primary damage investigation that focuses on developed housing lands was conducted in some areas of Miyagi, Fukushima and Tochigi prefectures.

In order to survey the damage of nonstructural elements, a primary investigation was performed, altogether with damage investigation for steel and reinforced concrete buildings including a requested investigation of ceiling falls in the Ibaraki Airport Building as an administrative support.

6.2 Damage to Wood Houses

6.2.1 Objectives of damage survey

A lot of wood buildings were damaged by the 2011 Tohoku earthquake. NILIM and BRI surveyed the damage of wood building starting from March 14, three days after the earthquake occurrence for the purpose of grasping the general image of the damage. Because the disaster by the earthquake occurred in wide areas, we carried out the first survey for multiple times, but cannot grasp the whole aspect of the damage. In this chapter, results of these multiple survey were summarized as basic documents to devise a survey plan in afterward to consider about the damage cause.

6.2.2 The selection of the survey area and the outline of the survey

The survey area and the reasons of the selection are as follows;

Kurihara city in Miyagi pref. : The seismic intensity 7 was recorded,

Osaki city in Miyagi pref. : As a result of damage survey[6.2-1], heavy damage was reported,

Sukagawa city in Fukushima pref.: RC buildings were heavily damaged,

Nasu and Yaita cities in Tochigi pref., and Hitachiota and Naka cities in Ibaraki pref. : As a result of damage survey[6.2-1] by others, damage information has not been reported, at the time of our survey,

Ishinomaki city in Miyagi pref. : Although it was almost included in the inundation area, the selected area of the city was not inundated by the tsunami, and,

Joso and Ryugasaki cities in Ibaraki pref. : There was damage information and they are located close to NILIM and BRI.

The locations of the surveyed cities and towns are shown in Fig. 6.2-1, and the schedules of the survey are shown in table 6.2-1.

Table 6.2-1 Schedules of survey.

Month/Day	Surveyed area
3/14～16	Kurihara and Sendai in Miyagi prefecture
3/23	Joso and Ryugasaki in Ibaraki prefecture
3/24～25	Sukagawa in Fukushima prefecture and Nasu and Yaita in Tochigi prefecture
3/25	Hitachiota, Naka, and Mito in Ibaraki prefecture
4/21	Hitachiota and Naka in Ibaraki prefecture
4/27～29	Osaki, Misato, and Ishinomaki in Miyagi prefecture

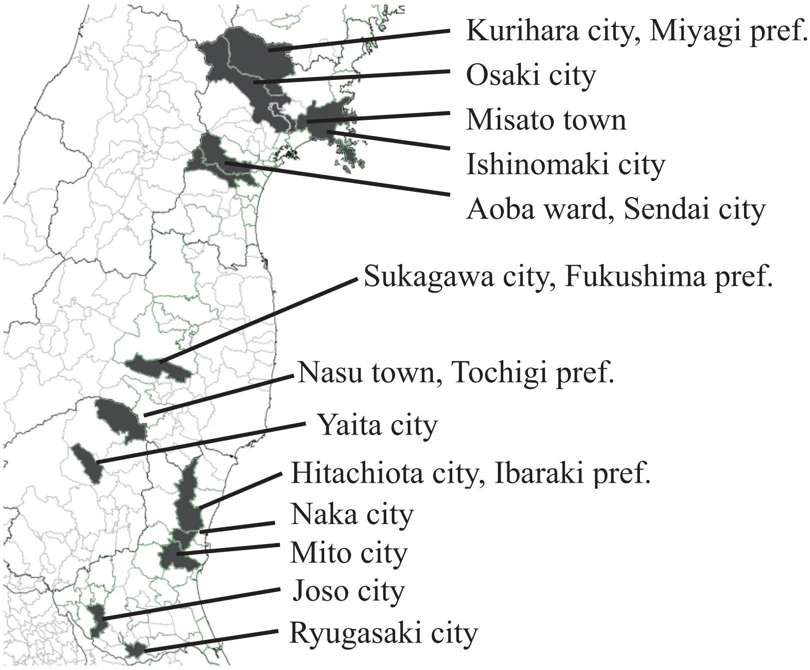


Fig. 6.2-1 Locations of surveyed cities and towns.

6.2.3 Results of the survey

(1) Kurihara city, Miyagi prefecture

According to the Kurihara city office, Miyagi where seismic intensity 7 was recorded, post-earthquake quick inspection of damaged buildings was conducted for 590 wood houses (excluding warehouses) in greatly damaged areas: Wakayanagi-Kawakita (139), Wakayanagi-Kawaminami (246), Wakayanagi-Fukuoka (80), Semine (187), Kurikoma-Sakurada (70), as of March 15. Location of these places is shown in Fig. 6.2-2. Unsafe wood houses in danger, wood houses with limited entry and inspected (safe) wood houses accounted for 18%, 29% and 54% of the total, respectively. The number of collapsed houses was only one, and the number of completely

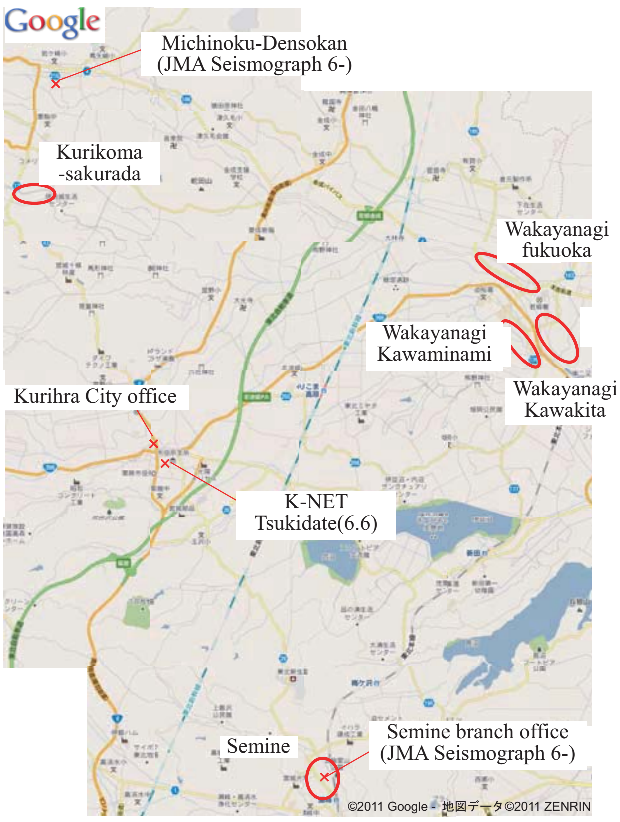


Fig.6.2-2 Surveyed areas in Kurihara city

destroyed houses and almost-destroyed houses were 42. The ground conditions in Wakayanagi and KurikomaSakurada are poor, and most of the houses in the north and south side of Wakayanagi, KurikomaSakurada and Semine had age of about 30 to 40 years. On the other hand, since the ground conditions are good near the city office, structural damage was not observed in the city office.

K-NET Kurihara Tsukidate (MYG004 : Instrumental seismic intensity 6.6) is set up on the hillock 3m higher (by eye measurement) than south of parking lot of Kurihara lyceum. There was a possibility of the amplification of earthquake motions (Photo 6.2-1). In Wakayanagi district, the ground was bad and sand boil due to liquefaction was observed (Photo 6.2-2). Damage to houses caused by ground transformation (Photo 6.2-3) and damage to houses with store were also observed (Photo 6.2-4).

A large residual deformation was observed in the longitudinal direction in the large-scale wood building used as a movie theatre then renovated to a factory (Photos 6.2-5, 6.2-6)

According to the observation of overturning of tombstones in three places in Wakayanagi district, the ratio of overturning was from 10% to 40%, and it seemed that there were a lot of overturnings in north to south direction (Photo 6.2-7).

In Kurikomasakurada district, collapse of work hut, drop of the mud plasters of Nagaya-mon gates (Photo 6.2-8), damage of plastered storehouses were observed, but any heavy damage in house was not observed.

The Seismograph of Kurikoma (JMA seismic intensity 6-) is set up on the parking lot in the west of “Michinoku-Densokan（Photo 6.2-9）”. From the exterior damage investigation, damage was not observed in “Michinoku-Densokan” and Kurikoma Branch office (Glulam frame structure: Photo 6.2-10).


Photo 6.2-1 K-NET KuriharaTsukidate


Photo 6.2-2 Sand boil due to liquefaction

Photo 6.2-3 Damage of houses caused by ground transformation

Photo 6.2-4 Damage of houses with store

Photo 6.2-5 Large-scale wood building renovated to a factory

Photo 6.2-6 Inside of the building shown in Photo 6.2-5

Photo 6.2-7 Overturning of tombstones

Photo 6.2-8 Drop of mud plasters of Nagaya-mon gate (Kurikomasakurada)

Photo 6.2-9 Seismograph of Kurikoma

Photo 6.2-10 Kurikoma Branch office (Glulam frame structure)

(2) Osaki city, Miyagi prefecture

According to the Osaki city office, it was informed that the damage concentrated in the neighbourhood of the city office and the northwest of JR Freight Company Furukawa Station, as shown in Fig. 6.2-3. In the other areas, it was informed that there was damage on building along the old main road in Furukawa-Araya, but damage on buildings in the mountain region including Naruko district and so on, had not been reported.

Heavy damage including the collapse of houses was confirmed on the way to the northwest of JR Freight Company Furukawa Station from the Osaki city office. Besides the damage reported by the other institutions[6.2-2)], a largely deformed house, a damaged house with store, a partially collapsed house, and so on were observed.

For example, warehouse with the mud walls renovated as store or gallery (Photo 6.2-11) was damaged heavily or slightly. There was the one whose roof system with roof tiles collapsed and fell down, as shown in Photo 6.2-12. In the area of these warehouses, there was a Japanese traditional post and beam construction house with large deformation (Photo 6.2-13) which was renovated as a store. On the opposite side of this house, there was the house with store (Photo 6.2-14) with story shear deformation whose exterior mortar came off and wood lath under the mortar near the opening of the ventilation fan was deteriorated and attacked by termites, as shown in Photo 6.2-15. Such damage was confirmed in the other buildings. Most of these damage occurred along a small river, except for a few case, and it was considered that the soft ground near the river might amplify the earthquake ground motion.

Seismograph at JMA Furukawa (Photo 6.2-16) which recorded seismic intensity 6+ was located in the northeast corner of the Mikkamachi park. There were the former school buildings around it. One of them was not almost damaged (Photo 6.2-17), while the other was damaged on roof tiles and exterior mortar without story drift. In addition to them, a rare damage example (Photo 6.2-18) that only the 2nd story collapsed was observed. On the other hand, a wood school building (Photo 6.2-19) in the west of the Osaki city office seemed not to be damaged in the appearance. Besides these, the house with store with large story drift in 1st story (Photo 6.2-20), those with large story drift in 2nd story (Photo 6.2-21), and 1-story wood house with large story drift caused by the land liquefaction were observed.

In the northwest of JR Freight Company Furukawa Station, a collapsed steel frame building, an RC structure apartment house with rocking drift caused by the land deformation, and a temple building (Photo 6.2-22) with large story deformation were observed.

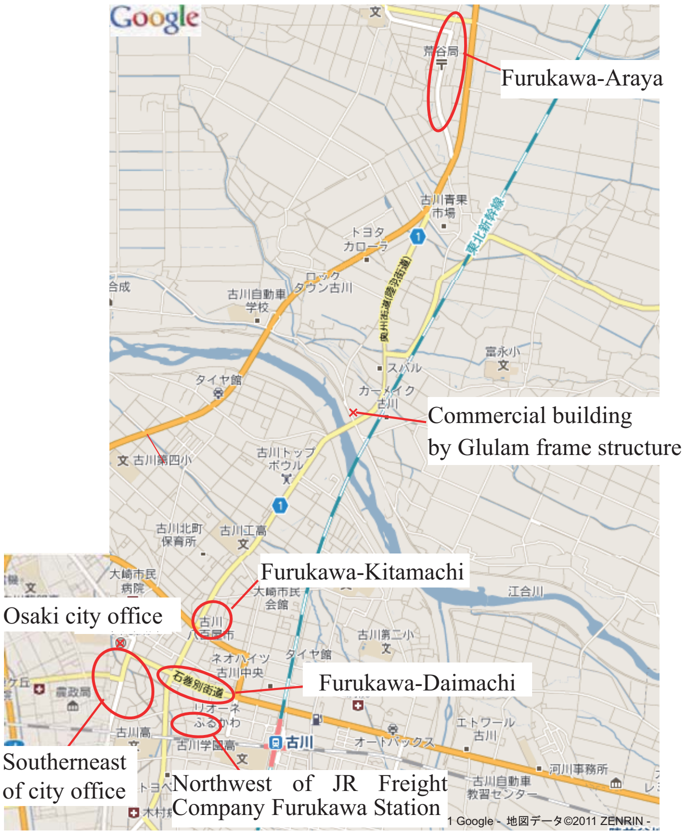


Fig. 6.2-3 Surveyed areas in Osaki city

Photo 6.2-11 Warehouse with mud walls damaged heavily or slightly

Photo 6.2-12 Warehouse with mud walls whose roof system with roof tiles fell down

Photo 6.2-13 Damaged Japanese traditional house with large story deformation

Photo 6.2-14 House with store with large story deformation

Photo 6.2-15 Deterioration in building of Photo 6.2-14

Photo 6.2-16 JMA seismic station at Furukawa (Seismic Intensity 6+)

Photo 6.2-17 School building suffering damage on roof tiles and exterior walls

Photo 6.2-18 School building whose 2nd story collapsed

Photo 6.2-19 Seemingly slightly damaged School building

Photo 6.2-20 House with store with large story deformation

Photo 6.2-21 House with store with 2^{nd} story drift more than that of 1^{st} story

Photo 6.2-22 Heavily damaged temple building

(3) Misato town, Miyagi

According to the Misato town office, the number of damaged structure was shown in table 6.2-2. There were a lot of damaged structures in Nakazone and Hirabari of Kogota area in this town.

Table 6.2-2 Number of damaged structures in Misato town as of April 28

Damage		Kogota area	Nango area	Total
Residential	Fully destroyed	60	17	77
	Half destroyed	243	70	313
	Partially destroyed	1,577	307	1,884
Non-residential		1,193	232	1,425

In Hirabari of Kogota area, there were a lot of wood houses which tilted largely in the east-west direction along the Eaigawa river (Photo 6.2-23). Photo 6.2-24 shows the wood house which leans to the fence. Most of the tombstones in this area fell toward in the east-west direction (Photo 6.2-25). Photo 6.2-26 shows the tilted wood house of which two-story might have been extended. In the southern side of Eaigawa river, there were log house without damage (Photo 6.2-27), wood house which tilted largely at first story (Photo 6.2-28) and tilted shrine building (Photo 6.2-29).

In Nango area, ground deformation was observed in the branch town office (Photo 6.2-30), but there were few damaged houses. Photo 6.2-31 shows the tilted wood house in Nango area. The structures in this area were damaged in a certain level during the 2003 northern Miyagi prefecture earthquake. There is a possibility that damaged buildings were retrofitted or rebuilt after the 2003 earthquake, because structures in this area seemed to be new.

Photo 6.2-23 Largely tilted house

Photo 6.2-24 Collapsed wood house

Photo 6.2-25 Tombstones in Hirabari

Photo 6.2-26 Tilted two-story house

Photo 6.2-27 Log house without damage

Photo 6.2-28 Largely tilted wood house

Photo 6.2-29 Damaged shrine

Photo 6.2-30 Ground deformation in Nango branch town office

Photo 6.2-31 Heavily damaged house

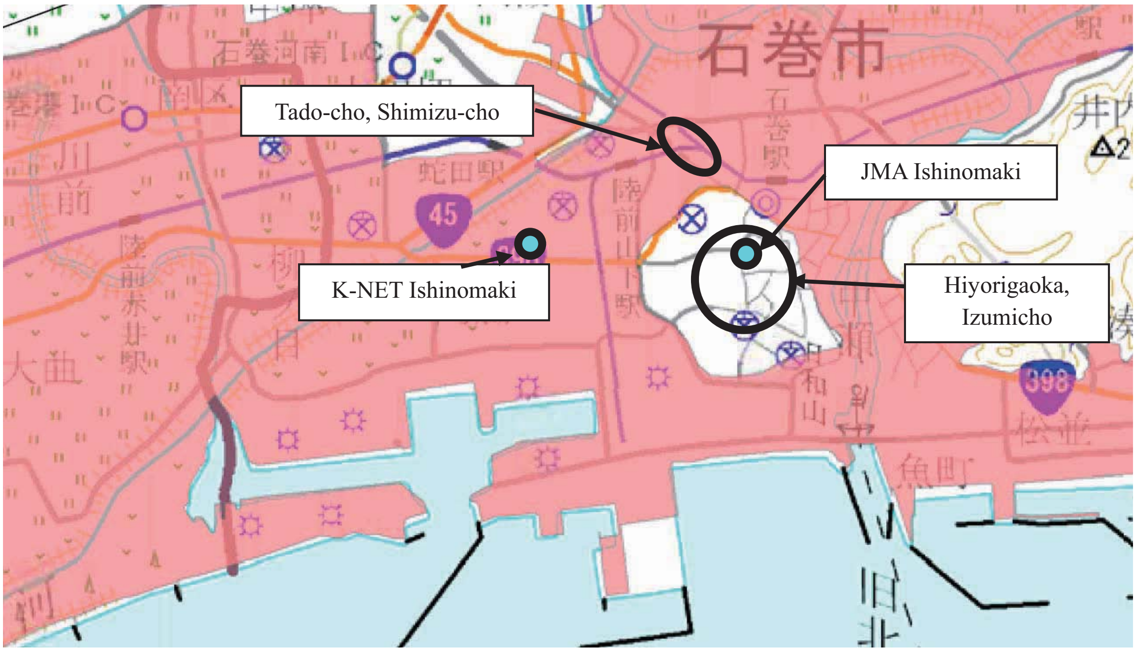
Photo 6.2-32 Inside of the house in Photo 6.2-31

(4) Ishinomaki city, Miyagi prefecture

Hiyorigaoka and Izumi-cho in Ishinomaki city are located on a hill (max. Altitude, 56.4m) at the western side of Kyu-kitakami river, almost all of the buildings are residence without public facilities (Photo 6.2-33). There were not heavily damaged wood houses and a few wood houses of which roof tile damaged (Photo 6.2-34).

Tado-cho and Shimizu-cho are located at the northern side of Hiyorigaoka hill and the area inundated by the tsunami according to the information[6.2-5)] of GSI (Fig. 6.2-4). There are a lot of low-rise wood houses with store which have big opening along the street between Ishinomaki-kaido and Ishinomaki-betsukaido street. The inundation depth estimated by the trace was 80-150cm. The inhabitant said that the fluid velocity of the tsunami was very slow and the inundation depth increased like flood. So it was estimated that the damage of the buildings was caused by the earthquake motion.

On the both sides of the street, there were collapsed wood house by earthquake (Photo 6.2-35) and tilted wood house with store (Photo 6.2-36). It was estimated that the wood houses with store which have less seismic elements at the first story were heavily damaged.



Colored area: inundated area

Fig. 6.2-4 GSI Inundation area map of Ishinomaki city [6.2-5)]

Photo 6.2-33 Appearance of Izumicho

Photo 6.2-34 Damaged roof tile in Hiyorigaoka

Photo 6.2-35 Collapsed wood house

Photo 6.2-36 Tilted wood house with store

(5) Sendai city in Miyagi prefecture

According to the Tohoku Regional Bureau, Ministry of Land, Infrastructure Transport and Tourism and Aoba ward office, Sendai city, the regions, where post-earthquake quick inspection of damaged buildings was conducted, were Asahigaoka 1, 2, 3, 4 chome(2, 250), Oritate 4, 5, 6 chome (470), Kaigamori 1 chome (400), Seikaen 1, 2chome (540) in Aoba ward, and Higashikuromatsu, Kuromatsu 1 chome and 3 chome in Izumi ward and so on. Location of those places was shown in Fig.6.2-5.

From the results of investigations on Oritate and Seikaen where the damage of the houses were serious, it was found that almost all of the damage of house were caused by ground transformation. Moreover, ground transformation caused retaining wall collapse (Photo 6.2-37, 6.2-38), landslide and damage of houses (Photo 6.2-39). On the other hand, there were some sloping lands in Kaigamori and Asahigaoka where the number of damage of retaining wall was minor, and damage of roof tile, collapse of concrete block wall and outer wall were observed. In Komatsujima, Aoba ward, drop off the mortar wall and damage of columns and biodeterioration by termites were observed in the house with store (Photo 6.2-40). Moreover, the house with large residual deformation on the 1st floor was observed (Photo 6.2-41). In Mukaiyama, Taihaku ward, collapse of a Japanese-style hotel was observed because of the sudden fall of stone of hillback (Photo

6.2-42, 6.2-43).

Fig. 6.2-5 Observation points in Sendai city
(◯:observation completed, ◌: not completed)

Photo 6.2-37 Damage of retaining wall and houses（Oritate, Aoba ward）

Photo 6.2-38 Damage of house in Photo 6.2-37

Photo 6.2-39 Damage of house caused by the ground transformation (Oritate)

Photo 6.2-40 Drop off the mortar wall (Komatsujima)

Photo 6.2-41 House with large residual deformation (Komatsujima)

Photo 6.2-42 Collapse of Japanese-style hotel (Mukaiyama)

Photo 6.2-43 Hillback of the hotel

(6) Sukagawa city, Fukushima prefecture

According to the Sukagawa city office, it was said that the damage of buildings was concentrated on around the city office at Hachiman-machi, Kaji-machi and Minami-machi. The post-earthquake quick inspection of damaged buildings (Table 6.2-3) was conducted only around the city office and finished by March 24.

There was a little damage on the upper timber construction of wood houses, and the damage of several residential lands was reported in the east part of the city. A lot of Japanese traditional warehouse with wood structural members and mud walls were built and left at present because Sukagawa city prospered as a merchant town. A lot of warehouses with mud wall and stone built about 30 years ago suffered heavy damage.

A lot of damaged wood houses were observed around the collapsed RC structure building. Examples are as follows: the failed exterior mortar wall of the 2nd floor in a house with store (Photo 6.2-44), deterioration and damage by Reticulitermes on a part of structural member and wood lath of exterior mortar wall (Photo 6.2-45), a wood house whose stair hall was removed and collapsed (Photo 6.2-46), and so on.

The wood warehouses with mud wall were heavily damaged near the hotel with the window glass broken. For example, the warehouses which deformed much (Photo 6.2-47) and whose roof system collapsed (Photo 6.2-48) were observed. A few wood houses with roof tiles damaged (*e.g.* Photo 6.2-49) were found. On the other hand, roof tiles of temple gate (called as “*Sanmon*”) were damaged, while the main hall of the temple was not so damaged (Photo 6.2-50 and 51). The sand eruptions caused by the soil liquefaction and the damage on the roof tiles were seen here and there in Minami-machi, Sukagawa city. In addition, on the web site of the city, the collapsed house was reported (Photo 6.2-52, From the city website).

Another collapsed building with uncertain structural type was found (Photo 6.2-53). According to the damage overview seen from the east of Minami-machi (Photo 6.2-54), it was observed that the wood houses with roof covered temporarily with blue vinyl sheet which was guessed to be damaged to roof tiles were relatively many.

Table 6.2-3 Results of Post-earthquake quick inspection of damaged buildings in Sukagawa city as of March 24

Structural type	Checked number	Unsafe	Limited Entry	Inspected
Timber	1,023	245	315	463
Steel	188	51	44	93
Reinforced concrete	73	25	16	32
Total	1,284	321	375	588
Ratio	100 %	25.0 %	29.2 %	45.8 %


Photo 6.2-44 Fallen mortar of wall (Wood house with store)


Photo 6.2-45 Deterioration and damage due to termite on column and wood lath of exterior mortar


Photo 6.2-46 Collapsed stair hall


Photo 6.2-47 Failed warehouse with mud wall

Photo 6.2-48 Fallen roof of warehouse with mud wall

Photo 6.2-49 Damage of roof tile

Photo 6.2-50 Minor damage of temple gate

Photo 6.2-51 No damage on main hall of temple

Photo 6.2-52 Collapsed wood house at Minami-machi (From Sukagawa city website)

Photo 6.2-53 Collapsed building (Unknown structure type)

Photo 6.2-54 Damage overview from the east of Minami-machi (Many roofs covered with blue vinyl sheet)

(7) Nasu town, Tochigi prefecture

According to the Nasu town office, the post-earthquake quick inspection of damaged buildings had not been carried out. The primary damage survey was conducted only by the town officials. With the survey, 32 wood houses were found totally collapsed.

It was said that the damage on buildings was concentrated in the area of Nishi-Ohkubo near the town office, although there was no collapsed wood house. It was reported that there was little damage in Nasu-kogen highland area in the west of national road route 4. On the other hand, it was said that damage on many wood houses were found in Toyohara-Otsu area where many cottages built on slope lands.

The damaged houses were in the area of Shio-akutsu, Chausu, Hoshibata, Akiyamasawa, Nigashimuro, Yanome, Higashi-Iwasaki, Numanoi, Hongo, Nishizaka, Ishizumi, Muronoi etc. and most of them were developed as residential lands. The locations of surveyed areas are shown in Fig. 6.2-6.

The stone-built warehouse was heavily damaged near the town office (Photo 6.2-55). The exterior stonewall of the former post office was failed (Photo 6.2-56).

Toyohara-Otsu area is in the north of Nasu town, and cottages are built along the path on slightly elevated hills. The movement and collapse of the wood deck (Photo 6.2-57) and collapse of the stone exterior were often observed. Several damages on wood houses caused by the slope land or the embankment were observed. The damage on the wood house due to large ground deformation caused by the earthquake motion was also found (Photo 6.2-58). It was confirmed that the metal fasteners were installed in the column end joint and the brace end joint of this house. (Photo 6.2-59). Besides the story drift, crack of concrete foundation (Photo 6.2-60), crack and loss of the exterior siding board, broken window glass, and failed ceiling of eaves (Photo 6.2-61) were observed.

In Nishi-Ohkubo area, several wood houses whose exterior mortar wall in the 1st floor was almost failed were found (Photo 6.2-62). And, the wood house with large story drift (Photo 6.2-63) and the other one damaged due to deformation of the residential land (Photo 6.2-64) were found.

Photo 6.2-55 Damage of stone-built warehouses

Photo 6.2-56 Damage of an old post office

Fig. 6.2-6 Surveyed area in Nasu town

Photo 6.2-57 Damage of wood deck in Toyohara-Otsu, Nasu town

Photo 6.2-58 Heavily damaged wood house

Photo 6.2-59 Metal fastener at the end of column and brace

Photo 6.2-60 Crack of foundation

Photo 6.2-61 Failed ceiling of eave

Photo 6.2-62 Damage of exterior mortar wall

Photo 6.2-63 Wood house with large story drift

Photo 6.2-64 Damaged house due to deformation of residential land

(8) Yaita city, Tochigi

According to the Yaita city office, the post-earthquake quick inspection of damaged buildings was limited to the houses at the request of residents and all houses in evacuation zone due to deformation of the residential land. By March 23, 108 buildings (including 3 buildings, such as stone warehouse, which couldn't be evaluated) were surveyed by the post-earthquake quick inspection of damaged buildings. The numbers of "Unsafe", "Limited Entry" and "Inspected" were 40, 42 and 23, respectively.

Evacuation was announced officially to the east of Lobin-city due to the deformation of the residential land. It was said that many damage were observed in the northeast area of Narita-Happy-Highland, Arai, Hariu, and Koshiwata where development was made by sharpening slope lands and filling up swamps. The locations of the above areas are shown in Fig. 6.2-7.

In Lobin-city (Photo 6.2-65), cracks of fence and retaining wall, caving of road bed, ups and downs of the residential land (Photo 6.2-66) and cracks of the foundation concrete (Photo 6.2-67) were often observed. In addition, damage on the roof tile, especially top of the roof, and collapsed concrete block fences were observed.

Narita-Happy-Highland located at the north of Lobin-city was a developed residential land. Most of the damage on buildings was due to the deformation of the residential land. A wood house with 1/10 radian shear deformation (Photo 6.2-68) was found.

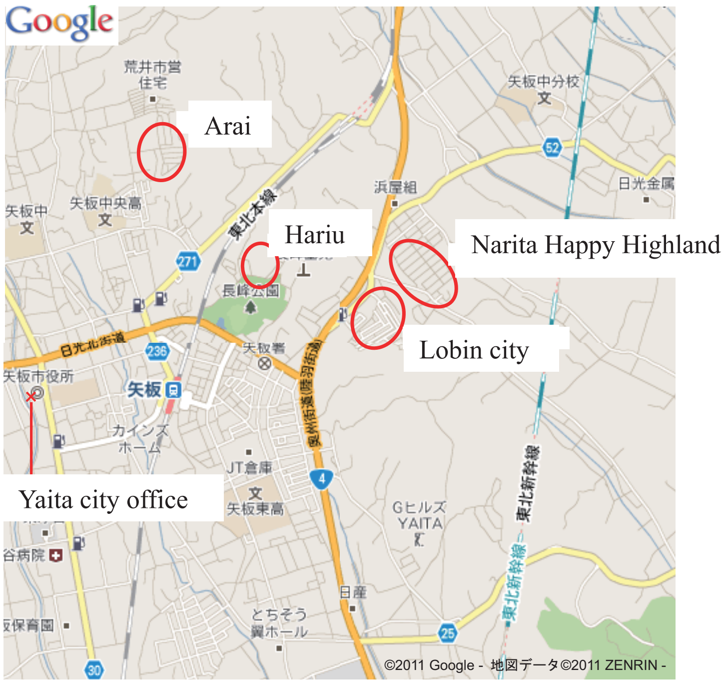


Fig. 6.2-7 Research area in Yaita city

Photo 6.2-65 No damaged houses at Lobin-city area

Photo 6.2-66 Ups and downs of residential land

Photo 6.2-67 Crack of foundation

Photo 6.2-68 Wood house with large shear deformation

(9) Hitachiohta city, Ibaraki prefecture

According to the post-earthquake quick inspection of damaged buildings, the number of “Unsafe” was 199, “Limited Entry” was 549 and “Inspected” was 574 in the city. The number of “Unsafe” was 87, “Limited entry” was 235 and “Inspected” was 97 in the Matsuzaka-cho. There were a lot of damaged buildings at the Kanasago area (Matsuzaka-cho and Nakano) in the Kujigawa river basin. Hitachiohta city office had made the hazard map that considers the subduction-zone earthquake. The seismic intensity was from 5+ to 6- at the Kujigawa river basin area.

There were a lot of damaged fence made by the Ohyaishi stone. A collapsed farm type house was observed (Photo 6.2-69, 6.2-70). The mortar plastered wall finish of the wood house at the land filled paddy field fell down (Photo 6.2-71).

Photo 6.2-69 Collapsed wood house

Photo 6.2-70 Breakage of entrance part.

Photo 6.2-71 Falling down of mortar plastered wall

(10) Naka city, Ibaraki prefecture

Naka city is surrounded by the Nakagawa river and the Kujigawa river and the center of the city is located on the plateau. A lot of damaged buildings were located at the Kujigawa river basin. The number of totally collapsed houses was 4 at Kadobe-shimogawara, 1 at Motoyonezaki as of March 25. By the post-earthquake quick inspection of damaged buildings, the number of “Unsafe” was 88. The damage information was reported at Kadobeakutsu and Urizura.

At Kadobe-shimogawara in Naka city, there were a lot of collapsed barns (Photo 6.2-72) and heavily damaged nagayamon gates (Photo 6.2-73). A damaged house with store was observed (Photo 6.2-74). A lot of collapsed barns were observed at Kadobe-akutsu.

A two story wood house with mortar finish collapsed at the urban area of Urizura in Naka city (Photo 6.2-75).

At the wood gymnasium (Photo 6.2-76, Photo 6.2-77) with curved glue laminated timber built in 1985-1989 in Urizura, buckling and tensile failure of the steel braces, the breakages of the foundation concrete at the brace joint were observed (Photo 6.2-78). At the wood school building (Photo 6.2-79), the slip of wood braces (Photo 6.2-80), the deformation of steel roof plate, wood flooring and interior material due to the contact with the stairway made by reinforced concrete were observed.

Photo 6.2-72 Collapsed nagayamon gate (Kadobe)

Photo 6.2-73 Tilted nagayamon gate (Kadobe)

Photo 6.2-74 Damaged house with store (Kadobe)

Photo 6.2-75 Collapsed house (Urizura)

Photo 6.2-76 Wood gymnasium

Photo 6.2-77 Inside of the gymnasium

Photo 6.2-78 Breakage of the foundation concrete

Photo 6.2-79 Wood school building

Photo 6.2-80 Slip of the wood brace

(11) Mito city, Ibaraki prefecture

According to the Mito city office, the number of totally collapsed building was 34 (residential 2, non-residential 32), half destroyed building, 66 (residential 34, non-residential 32) as of March 25.

The damaged buildings were mainly located around the city hall and in Motomachi, Yoshinuma-cho, Aoyagi-cho, Yanagawa-cho, Kamikochi-cho, Taya-cho, Joto and Sannomaru. The number of the collapsed residential house was two at Motomachi.

In the southern part of the Mito railway station, the ground settlement occurred and the gap between the high-rise building and ground was observed. This area had been a part of the Senbako lake and was developed as residential land in 1965-1974. The ground settlement was also observed at the city hall and the entry to the building was restricted.

There was a heavily damaged Nagayamon gate at Yoshinuma-cho (Photo 6.2-81). The damaged barns were observed at Aoyagi-cho, Yanagawa-cho, Taya-cho (Photo 6.2-82).


Photo 6.2-81 Heavily damaged Nagayamon gate (Yoshinuma-cho)


Photo 6.2-82 Damaged barn (Aoyagi-cho)

(12) Joso city, Ibaraki prefecture

According to the Joso city office, Ibaraki prefecture, structural damage was not observed for houses. An announcement of collapsed house immediately after the earthquake, was the damage to a wood hut in a resting place. The house built in the side of Lake of crescent was inclined because of the soil liquefaction (Photo 6.2-83, 6.2-84). Although there were several inclined houses because of the soil liquefaction, a lot of damage to the roof tile were observed, and it seemed that the ratio of the damage of the roof tile was comparatively high.


Photo 6.2-83 Damage of resting place (Joja-machi, offered by Joso city office)


Photo 6.2-84 Damage of ground near the resting place（offered by Joso city office）

(13) Ryugasaki city, Ibaraki prefecture

According to the Ryugasaki city office, Ibaraki prefecture, structural damage was not observed in houses, and information about collapsed house immediately after the earthquake, was the damage of barn in the Takasu-cho. The post-earthquake quick inspection of damaged buildings was conducted for 58 wood houses based on the request from the citizens. According to the department, unsafe wood houses in danger and wood houses with limited entry accounted for 12, and 29 respectively. Most of the damage of houses was damage of roof tile and outside wall. There was no damage due to inclination of structural building frame. Though 6 houses and 1 barn were judged as partial collapse, the sites of those buildings were not located in concentrated specific region. The surrounding of the city office and JR Sanuki station are old urban areas, grounds of those areas are low and weak, and have a lot of damage of the roadbed. On the other hand, two new towns in the east and the west areas in the city are located on the hill, the ground is sound, and the damage of houses was not reported. Sand eruption by soil liquefaction was partly observed in the Takasu-cho area.

6.2.4 Conclusions

From the damage survey on the wood houses due to ground motion in Kurihara city, Osaki city, Misato town, Ishinomaki city, Sendai city in Miyagi prefecture, Sukagawa city in Fukushima, Nasu town, Yaita city in Tochigi prefecture, and Hitachiota city, Naka city, Mito city, Joso city, Ryugasaki city in Ibaraki prefectue, the followings were summarized.

1) The damage on many wood houses due to ground motion was confirmed in Osaki city in Miyagi prefecture, Sukagawa city in Fukushima prefecture, Nasu town in Tochigi prefecture, and Hitachiota city and Naka city in Ibaraki prefecture.
2) Although the seismic intensity 7 was recorded in Kurihara city, Miyagi prefecture, it was observed that the damage on wood houses was minor.
3) The heavy damage on wood houses caused by the failures of residential land was confirmed in Sendai city, Miyagi prefecture, and Yaita city, Tochigi prefecture. The number of wood houses suffering such damage was quite large.
4) The damage of the roof tile in Fukushima and Ibaraki prefectures seemed much larger than that in Miyagi prefecture where large earthquakes occurred frequently.
5) The possibility that the ground motion was amplified on the land filled up from swampland or rice field, even if the residential land did not fail, was suggested in Kurihara city, Osaki city in Miyagi prefecture, Nasu town in Tochigi prefecture, Hitachiota city, Naka city, Joso city, Ryugasaki city in Ibaraki prefecture, and so on.
6) In Osaki city, several rare damage examples that residual story deformation of 2nd floor was larger than that of 1st floor were confirmed.

The selected houses will be surveyed in detail and each damage cause will be discussed in future, based on the results of the damage summary of the above-mentioned wood houses.

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6.2-2) Naohito KAWAI：Quick Report of Damage Survey on Buildings Due to The 2011 Off The Pacific Coast of Tohoku Earthquake by Kogakuin University Survey Team for Wood Buildings, Quick Report of Damage Summary Survey in Osaki City and Ichinoseki City on April 11. (draft), non-publication document.

6.2-3) The Japan Wood Research Society: (non-publication document)

6.2-4) NILIM and BRI：Quick Report of The Field Survey and Research on “The 2011 off The Pacific coast of Tohoku Earthquake” http://www.nilim.go.jp/lab/bbg/saigai/h15miyagi/chousa.pdf

6.2-5) Geographical Survey Institute: Figure of inundation range general condition http://www.gsi.go.jp/common/000059847.pdf

6.3 Damage to Reinforced Concrete Buildings

6.3.1 Introduction

The 2011 Tohoku earthquake caused a lot of damage to buildings in a wide area of Tohoku and Kanto regions of Japan. The Joint Survey Team investigated the damage to reinforced concrete (RC) buildings and reinforced concrete buildings with embedded steel frames (referred to as steel reinforced concrete, or SRC) in the affected areas where seismic intensities were classified as 6 lower (6-) and over by the Japan Meteorological Agency (JMA) in Iwate, Miyagi, Fukushima and Ibaraki. The objective of the field investigation was to see the picture of the overall damage to the buildings and to classify their damage patterns. The surveys were conducted several times from March 14 to the middle of May in the districts as shown in Fig. 6.3-1. This report presents the outline of the field investigation.

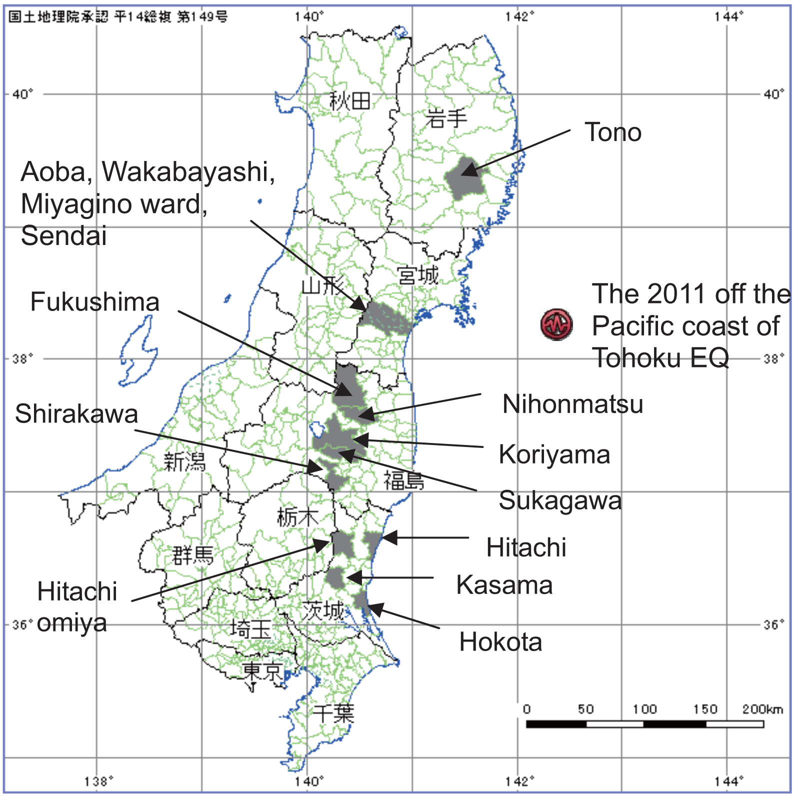

Fig. 6.3-1 Investigated Area (free mapping program, 'KenMap' was used)

6.3.2 Characteristics of damage on RC buildings

In the 2011 Tohoku earthquake, strong earthquake motions were recorded in various locations of Tohoku and Kanto regions and caused various patterns of damage in a wide area. At the same time, the damage concentrated on a specific area was not seen generally. As a rule, it would appear that structural damage to buildings was not particularly heavy in comparison with the measured JMA seismic intensities. Consequently, there was not a significant difference in damage situations among the locations. However, the damage to structural members was somewhat concentrated on limited areas, such as Wakabayashi ward in Sendai city and Sukagawa city. It is known that these areas were formed on paddy fields or moats. Therefore, it can be well estimated that ground conditions in the areas possibly contributed to the damage.

The patterns of structural damage on RC buildings identified by the field surveys were almost the same with those that had been observed in past earthquake damage investigations. Some serious types of damage were observed, such as story collapse of low-rise buildings, collapse of soft-first story (pilotis), and the loss of vertical load carrying capacity of columns due to shear failure. Most of severely damaged buildings were designed with the previous seismic design code that was enforced before June 1981. Some SRC buildings designed under the current seismic design code enforced after June 1981, caused damage of buckling of their longitudinal reinforcements near base plates at the bottom of column. The same damage is known to have occurred also in the Hyogoken Nambu Earthquake in 1995 (Kobe Earthquake). In addition, buildings designed under the current seismic design code were confirmed to have no collapse but some damage like shear cracks at their beam-column joints or horizontal cracks at their concrete placing joints. The patterns of the damage of RC and SRC buildings that were observed through the site investigation are classified into those for structural and nonstructural elements in the following.

A) Damage of structural elements
- A-1) Collapse of first story
- A-2) Mid-story collapse
- A-3) Shear failure of columns
- A-4) Flexural failure at the bottom of column and base of boundary columns on multi-story shear walls
- A-5) Pullout of anchor bolts and buckling of longitudinal reinforcements at exposed column base of steel reinforced concrete (SRC) buildings
- A-6) Shear failure or bond splitting failure of link beam of multi-story coupled shear walls
- A-7) Building tilting
- A-8) Destruction, failure or tilting of penthouses
- A-9) Damage of seismic retrofitted buildings

B) Damage of nonstructural elements
- B-1) Flexural failure at the bottom of column with wing wall
- B-2) Damage of nonstructural wall in residential building
- B-3) Damage and falling of cladding

B-4) Tilting or dropout of components projecting on the roof
B-5) Collapse of concrete block wall and stone masonry wall

6.3.3 Damage of Structural Elements

A-1) Collapse of first story

The first story in a two-story RC office building shown in Photo 6.3-1 was completely collapsed in Wakabayashi ward, Sendai city. In addition, the shear failure and the axial deformation of the columns on the second floor of this building caused the buckling of the longitudinal reinforcements and the fracture of the hoops of columns in the first story.

Photo 6.3-1 First-story collapsed building (Wakabayashi ward, Sendai city)

The soft-first story collapse occurred on a four-story RC residential building with a shop in the first floor in Koriyama city, and was attributed to the shear failure of the columns on the first story and the torsional deformation (Photos 6.3-2 and 6.3-3). The RC shear wall on the first story was collapsed out-of-plane with buckling of reinforcing bars.

Photo 6.3-2 First-story collapsed building (Koriyama city)

Photo 6.3-3 Close-up view of the fallen story

A three-story RC building shown in Photo 6.3-4 was severely damaged on the first story, which was located at the intersection in Sukagawa city, had a few walls on the facade on the first story and many walls on the back of the first story and the second story and higher. The corner columns faced to the intersection were significantly destroyed as shown in Photo 6.3-5. The loss of axial load carrying capacity of the first-story columns caused the drop of the second and higher stories.

Photo 6.3-4 First-story collapsed building (Sukagawa city)

Photo 6.3-5 Close-up view of the fallen story

A-2) Mid-story collapse

A three-story office building shown in Photo 6.3-6 in Wakabayashi ward, Sendai city partially collapsed on the second story and the building tilted. Only the second story has openings on the wall at the gable side, as shown in the left of Photo 6.3-6. For this reason, it was assumed that the openings were intensively deformed and resulted in shear failure of the short columns formed by the hanging and spandrel walls. The shear failure of the long columns on the third story was observed possibly due to the effect of the collapse of the second story. The damage to the columns and beams on the first story was not seen, while shear cracks were observed on the nonstructural walls.

Photo 6.3-6 Mid-story collapsed building (Wakabayashi ward, Sendai city)

Photo 6.3-7 shows a three-story RC school building, which was constructed in

1966 and has a Y-letter shape plan in Fukushima city. The mid-story collapse occurred on the second story, and the part of the third story was heavily damaged. In addition, the shear failure also occurred on the columns in the first story, as shown in Photo 6.3-8. Visual damage was not seen in other school buildings and the gymnasium on the same site. The seismic indices of the structure, I_S on the first and second stories of the building were below the seismic demand index of structure, I_{S0} by the seismic evaluation method [6.3-1)], therefore the seismic retrofit of the building had been planned.

Photo 6.3-7 Mid-story collapsed building (Fukushima city)

Photo 6.3-8 Shear failure of the first-story column

A-3) Shear failure of columns

A three-story RC building constructed in 1963 was suffered from the shear failures of columns in Tono city of Iwate prefecture, where the JMA seismic intensity was 5 upper (5+) (Photo 6.3-9). Two extremely short columns on the first-story, four columns on the northern plane of structure and an interior shear wall were failed in shear as shown in Photo 6.3-10, and short columns with spandrel wall, some long columns on the southern plane of structure had shear cracks. The post-earthquake damage evaluation [6.3-2)] was conducted for the building in the longitudinal direction. In the result, the building was determined to represent heavy damage (residual seismic performance ratio, R=57.8%). The building had been damaged in the South Sanriku Earthquake in 2003 (JMA seismic intensity 6 lower). For this reason, cover concrete was then recast on the shear-cracked columns, and the existing columns were temporary strengthened with H-shaped steel, as shown in Photo 6.3-11. However, the 2011 Tohoku earthquake affected these columns again.

Photo 6.3-9 Appearance of the damaged building (Tono city)

Photo 6.3-10 Shear crack on shear wall

Photo 6.3-11 Column strengthened with H-shaped steel

The next case is that the shear failure occurred on the first-story columns in a two-story RC building in Aoba ward, Sendai city (Photos 6.3-12 and 6.3-13). Some columns of the building were intact after the mainshock on March 11, but aftershocks caused shear failure to some of them, as shown on the right of Photo 6.3-13. It was confirmed that the aftershocks accelerated the damage level of this building.

Photo 6.3-12 Appearance of the damaged building (Aoba ward, Sendai city)

Photo 6.3-13 Shear cracks of first-story columns

Photo 6.3-14 shows the four-story RC building that was constructed in 1970 in Sukagawa city. The columns with the spandrel wall on the first story were heavily damaged in shear and shorten in the axial direction as shown in Photo 6.3-15. The same damage was observed on the second-story exterior columns. Some of the reinforcing bars of the damaged columns that were raised from the foundation were anchored with a 180-degree hook near the mid height of story. It is considered that the shear failure began at this point. Two shear walls were severely damaged, which were arranged in the center core of the building to resist mainly horizontal forces. In particular, the second-story core wall was failed in shear in both of the span and longitudinal directions, and the longitudinal reinforcements in the boundary column of shear wall were heavily buckled as shown in Photo 6.3-16.

Photo 6.3-14 Appearance of damaged building (Sukagawa city)

Photo 6.3-15 Shear failure of short column

Photo 6.3-16 Failure of shear wall

A three-story RC building constructed in 1964 on a hill in Kasama city of Ibaraki prefecture shown in Photo 6.3-17 also suffered damage. Cracks in the ground were observed around the building. As seen in the photo, the RC structure on the first story was severely damaged. Shear failure occurred on many exterior columns, which were made shorter in clear height by the hanging and spandrel walls without structural slit, as shown in Photo 6.3-18. In addition, the failure of the shear wall with opening was observed (Photo 6.3-19).

Photo 6.3-17 Appearance of damaged building (Kasama city)

Photo 6.3-18 Shear failure of column

Photo 6.3-19 Shear failure of wall with opening

A-4) Flexural failure at the bottom of column and base of boundary columns on multi-story shear walls

A building that consists of nine-story SRC and two-story RC structures in Aoba ward, Sendai city suffered from the earthquake (Photo 6.3-20). In the high-rise building, the multi-story shear wall of the gable side was subject to flexural failure at the third floor. Crushing of concrete and buckling of the longitudinal reinforcements was observed at the bottom of the boundary column of shear wall, as shown in Photo 6.3-21. This building was also damaged by the Miyagiken-oki Earthquake in 1978 and had been retrofitted.

Photo 6.3-20 Appearance of damaged building (Aoba ward, Sendai city)

Photo 6.3-21 Crushing at the bottom of column of the multi-story shear wall

A-5) Pullout of anchor bolts and buckling of longitudinal reinforcements at exposed column base of steel reinforced concrete (SRC) buildings

Photo 6.3-22 shows the appearance of a damaged building, which is the nine-story SRC residential building constructed in 1991 in Koriyama city of Fukushima prefecture. Pullout of anchor bolts, buckling of reinforcing bars and compressive failure of concrete occurred at the corner column and the bottom of multi-story shear wall in the first story, as shown in Photo 6.3-23, and shear cracks and bond splitting cracks were observed on the first story columns.

Photo 6.3-22 Appearance of damaged building (Koriyama city)

Photo 6.3-23 Damage at the bottom of SRC column

The damage at the bottom of SRC column and shear wall was also observed on a building in Shirakawa city shown in Photos 6.3-24 and 6.3-25, which was composed of RC and SRC structures. Pullout of anchor bolts of the exposed-type column base occurred. In consequence, the reinforcing bars were forced to stretch large and the buckling of them occurred around the base plate, as shown in Photo 6.3-26.

Photo 6.3-24 Appearance of damaged building (Shirakawa city, Fukushima pref.)

Photo 6.3-25 Damage of the bottom of SRC column and shear wall

Photo 6.3-26 Close-up view of the bottom of SRC column

This type of damage was observed not only in buildings designed under the previous seismic design code but also in some buildings constructed under the current seismic design code.

A-6) Shear failure or bond splitting failure of link beam of multi-story coupled shear walls

The shear failure or bond splitting failure occurred on the link beam connecting coupled shear walls from low-rise to high-rise stories on a eight-story RC building in Aoba ward, Sendai city, as shown in Photo 6.3-27. The link beams have two openings at the center of them, and were damaged around these parts (Photo 6.3-28).

Photo 6.3-27 Appearance of damaged building (Aoba ward, Sendai city)

Photo 6.3-28 Damage of boundary beam with opening

A-7) Building tilting

A fourteen-story RC building shown in Photo 6.3-29 was settled down and was tilted about 1/70 radian. The building is one of two residential buildings located in L-shape with expansion joint in Miyagino ward, Sendai city. The shear cracks on the nonstructural walls over every story and some parts of mullions occurred in both buildings as shown in Photos 6.3-30 and 6.3-31, which damage was classified as B-2). Though the other building without inclination had same shear cracks on the nonstructural walls from first to sixth story in the Miyagiken-oki Earthquake in 1978 and had been repaired with concrete replacement, almost same damage was happened on the similar part.

Photo 6.3-29 Appearance of tilted building (Miyagino ward, Sendai city)

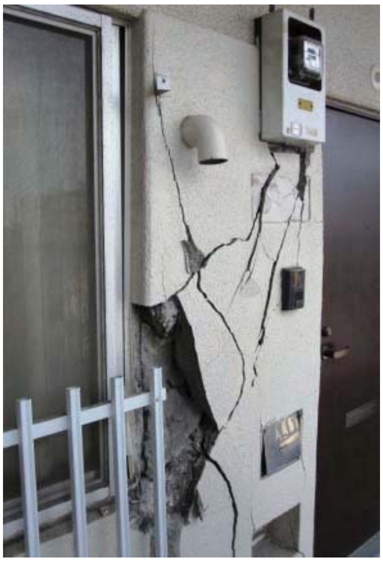

Photo 6.3-30 Shear cracks on nonstructural wall

Photo 6.3-31 Shear cracks on mullion

Photo 6.3-32 shows a residential building that sank and leaned in the longitudinal direction in Shirakawa city. The balcony, of which height above ground level was about 77cm, went down to ground surface in the gable side, as shown in Photo 6.3-33.

Significant settling was also observed on a sidewalk in surrounding area.

Photo 6.3-32 Appearance of sunken and leaned building (Shirakawa city)

Photo 6.3-33 Sunken balcony

A-8) Destruction, failure or tilting of penthouses

The damage on penthouses was observed everywhere, like tilting of it in Aoba ward, Sendai city, as shown in Photo 6.3-34. The clock tower attached to a five-story RC building constructed in 1954 was destroyed at the bottom of it, despite the building was heavily damaged in Fukushima city (Photos 6.3-35 and 6.3-36).

Photo 6.3-34 Damaged penthouse (Aoba ward, Sendai city)

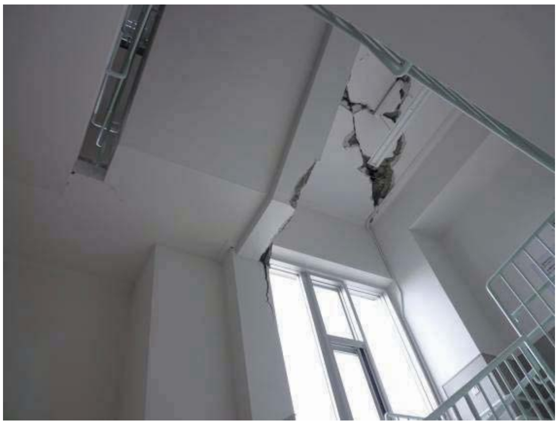

Photo 6.3-35 Damaged clock tower (Fukushima city)

Photo 6.3-36 Bottom of the tower

A-9) Damage of seismic retrofitted buildings

Photo 6.3-37 shows a two-story RC office building constructed in 1969 in Hitachiomiya city of Ibaraki prefecture. The building had been retrofitted with framed steel braces in the longitudinal direction in 2003, because the seismic index of structure, I_S on the first story of the building was below the seismic demand index of structure, I_{S0} by the seismic evaluation method [6.3-1)]. Meanwhile, the building in the span direction was not retrofitted, as a consequence the seismic index of structure in the direction satisfied the seismic demand index of structure. The steel braces had been eccentrically installed to the center axis of the beams and columns.

Shear cracks occurred on the columns with the framed steel braces at the 2011 Tohoku earthquake as shown in Photo 6.3-38, although the remarkable damage such as yield of steel was not seen on the braces. Flexural cracks at the beam ends of the second-story in the span direction and shear cracks at the beam ends of the third-story were observed, respectively. A maximum deflection of 128mm was happened at the center in the span direction with a span of 12m. It would appear that the deflection was increased due to the damage occurred on the beam end by the earthquake, thought the under-surface of the beam has been strengthened. Because the beam had cracks caused by the past earthquake, it had been reinforced with steel plates in the range of quarter beam length from the column.

Photo 6.3-37 Appearance of damaged building (Hitachiomiya city)

Photo 6.3-38 Shear crack on column with framed steel braces

There were many seismic retrofitted buildings including school buildings in the affected areas where the strong earthquake motions were observed. Based on the results of the investigation, these retrofitted buildings were heavily damaged or slightly harmed, it means that the seismic strengthening of existing buildings act effectively against the earthquake.

6.3.4 Damage to nonstructural elements

B-1) Flexural failure at the bottom of column with wing wall

The separation of cover concrete at the bottom of wing wall was observed on a five-story RC building constructed in 2007 in Sukagawa city of Fukushima prefecture, as shown in Photos 6.3-39 and 6.3-40. In this report, that case is classified as the damage of nonstructural elements, because the wing wall is generally designed as the nonstructural element, which is not expected to resist the external force.

Photo 6.3-39 Appearance of damaged building (Sukagawa city)

Photo 6.3-40 Separation of concrete of wing wall

B-2) Damage of nonstructural wall in residential building

The nonstructural walls around the front doors from lower to top floors were subject to shear failure, while the doors were deformed on a ten-story SRC residential building constructed in Aoba ward, Sendai city in 1996, as shown in Photos 6.3-41 and 6.3-42. In addition, shear cracks were observed on the mullion walls on balconies in some of the lower floors.

Photo 6.3-41 Appearance of damaged building (Aoba ward, Sendai city)

Photo 6.3-42 Shear failure of nonstructural wall

In a nine-story SRC residential building shown in Photo 6.3-22 in Koriyama city, damage of the nonstructural elements was seen (Photo 6.3-43). In addition, large shear cracks occurred on the nonstructural wall in the longitudinal direction. For this reason, the front door was deformed out-of-plane as shown in Photo 6.3-44, and could not be opened and closed. The shear cracks on the mullion walls also occurred in a eight-story RC hotel building in Sukagawa city (Photos 6.3-45 and 6.3-46).

The cases where shear cracks occurred on the nonstructural walls around the front door or on the mullion wall of the balcony were relatively often observed in urban residential buildings, regardless of application of the seismic design codes.

Photo 6.3-43 Damage of nonstructural wall in same building shown in Photo 6.3-22 (Koriyama city, Fukushima pref.)

Photo 6.3-44 Damage of nonstructural wall and deformed door in same building shown in Photo 6.3-22

Photo 6.3-45 Appearance of damaged building (Sukagawa city)

Photo 6.3-46 Shear crack on nonstructural wall

B-3) Damage and falling of cladding

Photos 6.3-47 and 6.3-48 show the case where the AAC (Autoclaved lightweight Aerated Concrete, the abbreviated term 'ALC' is commonly used in Japan.) panel on the upper floor in a eight-story building fell down, and Photo 6.3-49 is the case where the tile on exterior wall was dropped, in Aoba ward, Sendai city.

These kinds of damage relatively often occurred in buildings without structural damage, not limited to specific areas. Despite of the construction period and the seismic design codes application, these damage were often observed in many buildings.

Photo 6.3-47 Damaged building with AAC panels (Aoba ward, Sendai city)

Photo 6.3-48 Dropped AAC panels

Photo 6.3-49 Damage of tile on exterior wall

B-5) Collapse of concrete block wall and stone masonry wall

The collapse of concrete block wall and stone masonry wall are well known as earthquake damage caused by strong seismic motion. The damage of that type was often observed in the field investigation, as shown from Photo 6.3-50 to Photo 6.3-53.

Photo 6.3-50 Collapse of concrete block wall (Koriyama city)

Photo 6.3-51 Collapse of concrete block wall (Sukagawa city)

Photo 6.3-52 Collapse of stone masonry wall (Fukushima city)

Photo 6.3-53 Collapse of stone masonry wall (Shirakawa city)

6.3.5 Concluding Remarks

In this report, the patterns of damage of reinforced concrete (RC) and steel reinforced concrete (SRC) buildings caused by earthquake motions under the 2011 Tohoku earthquake were classified as the damage on structural and nonstructural elements and the examples of them were described. As previously stated, almost all of the patterns of damage were observed in past destructive earthquakes such as the Hyogoken Nambu Earthquake (Kobe Earthquake) in 1995 and the Mid Niigata Prefecture Earthquake in 2004. However, the following patterns of structural damage that had been observed in the Hyogoken Nambu Earthquake have not been confirmed within the scope of the investigation conducted so far.

- Story collapse of soft-first story building designed under the current seismic design code
- Mid-story collapse in mid-rise and high-rise buildings
- Overturning of buildings

- Failure of beam-column joint in building designed under the current seismic design code
- Fracture of pressure welding of reinforcements
- Falling of pre-cast roof in gymnasium

In general, there were only a few cases of serious structural damage that were caused by the earthquake motions. On the contrary, it was the remarkable cases caused by the earthquake that public buildings like city hall under the past seismic design code suffered from severer damage and could not be continuously used. The main cause of the damage on these buildings was the loss of the vertical load carrying capacity due to shear failure of short columns. The fact makes us reconfirm that seismic retrofit of these public buildings is particularly important, which must be operated as the disaster management facilities.

References

6.3-1) The Japan Building Disaster Prevention Association: Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings, 2001 (English Version in 2005)

6.3-2) The Japan Building Disaster Prevention Association: Guideline for Post-earthquake Damage Evaluation and Rehabilitation, 1991 (revised in 2001). (in Japanese)

6.4 Damage to Steel Gymnasiums

6.4.1 Introduction

The damage to steel buildings such as offices and shops caused by the 2011 Tohoku earthquake in the areas of Ibaraki, Fukushima and Miyagi prefectures with JMA seismic intensity around 6 was investigated for two weeks after the earthquake. Structures of steel buildings are generally covered with exterior cladding and interior finishing. For this reason, the real situations of the damage to columns, beams and braces may not be correctly determined under the visual damage observation. Therefore, the damage investigation on steel gymnasiums whose structural members are generally exposed was considered and conducted. The damage investigation for such steel gymnasiums was carried out in the areas of Ibaraki prefecture with JMA seismic intensity around 6. This section describes the outline of the damage investigation of the steel gymnasiums.

6.4.2 Outline of damage investigation of steel gymnasiums

(1) Outline of damage investigation of high school gymnasiums in Ibaraki prefecture

Gymnasiums designed under the seismic code before June 1981 (hereinafter referred to as previous seismic code) were heavily damaged in the Mid Niigata Prefecture Earthquake in 2004, but most of gymnasiums designed under the current seismic code were not damaged[6.4-1)~6.4-3)]. Consequently, as the subject of the damage investigation, steel gymnasiums constructed under the previous seismic code were mainly chosen. The investigation covered a wide range of areas in Ibaraki prefecture where JMA seismic intensities 5 (+) to 6 (+) were recorded (Ooarai town, Shirosato town, Hitachi city, Mito city, Naka city, Hitachinaka city, Chikusei city, Kasama city, Hokota city, Tsuchiura city, Bando city, Koga city, Shimotsuma city and Joso city). The main purpose of the investigation is to determine what damage pattern was often observed in these areas and in which area the pattern was often distributed. A total of 44 gymnasiums in high schools were chosen and investigated.

(2) Outline of damage investigation of elementary and junior high school gymnasiums in Mito city

In general, building size (total floor area) of high school gymnasiums seems to be larger than the size of elementary and junior high school gymnasiums. In order to know an effect of building size on earthquake damage situation, damage investigation of elementary and junior high school gymnasiums was considered and conducted. The result of the damage investigation for the high school gymnasiums in Ibaraki prefecture showed that the areas around Mito city suffered relatively larger structural damage than other areas. Then, Mito city was chosen as the survey area of the damage investigation for gymnasiums in elementary and junior high school. A total of 22 gymnasiums in elementary and junior high schools constructed under the previous seismic code in Mito city were investigated.

6.4.3 Results of damage investigation of steel gymnasiums

(1) Results of high school gymnasiums in Ibaraki prefecture

1) Outline of structure of investigated gymnasiums

A total of 44 gymnasiums were investigated in Ibaraki prefecture. The number of gymnasiums constructed under the previous seismic code is 41. There are 4 two-story gymnasiums, and 40 one-story gymnasiums. The number and percentage of structural types of the investigated gymnasiums are shown in Table 6.4-1. In general, the structural types of gymnasiums are classified into 3 classes as shown in Table 6.4-1, but the percentages of the types seem to strongly depend on the regions. For example, in the damage investigation[6.4-1)~3)] of the Mid Niigata Prefecture Earthquake in 2004, the percentage of the mixed structure consists of lower RC frame and upper steel frame was 75%, and the percentage of steel moment-resisting frames was 6%. From table 6.4-1, it is found that the percentage of the mixed structure in Ibaraki prefecture is smaller than Niigata prefecture, and the percentage of steel moment-resisting frames is larger.

Table 6.4-1 Structural types of investigated high school gymnasiums

<table>
<tr><td colspan="2">Mixed structure consist of lower RC frame and upper steel frame</td><td colspan="2">Steel frame structure</td><td rowspan="3">RC frame structure having steel roof frame</td><td rowspan="3">Unidentified</td></tr>
<tr><td colspan="2">20（45%）</td><td colspan="2">15（34%）</td></tr>
<tr><td>Steel brace frame</td><td>Steel moment-resisting frame</td><td>Steel brace frame</td><td>Steel moment-resisting frame</td></tr>
<tr><td>15（34%）</td><td>5（11%）</td><td>7（16%）</td><td>8（18%）</td><td>6（14%）</td><td>3（7%）</td></tr>
</table>

2) Structural damage

The types of observed structural damage in this investigation include a) buckling and fracture of brace member and fracture of its joint, b) buckling of diagonal member of latticed column, c) damage of connection (bearing support part) between RC column and steel roof, d) deflection, buckling and fracture of roof horizontal brace, and e) cracking of column base concrete. The a) and b) damage types are included as the type of severe structural damage based on the damage evaluation standard of earthquake damaged buildings[6.4-4)]. However, the number of these severe damaged gymnasiums is 2 and 1 corresponding to the damage type a) and b), respectively. Buckling of diagonal member of latticed column is damage to the column in span direction frames, and was not observed under the damage investigation of the Mid Niigata Prefecture Earthquake in 2004[6.4-1)~6.4-3)].

From the results of this investigation, it seemed that structural damage in Mito city, Hokota city and Naka city was relatively larger than in other areas.

3) Nonstructural damage

The types of nonstructural damage observed in this investigation include dropping of ceilings and exterior walls and breakage of windows, etc. In four of the investigated gymnasiums, ceiling materials were extensively dropped, which is classified into the severe damage category based on the damage evaluation standard[6.4-4]. In five gymnasiums, breakage of many windows was observed.

4) Damage situations of seismic retrofitted buildings

Seismic retrofitting was performed in five of the investigated gymnasiums. One of the five retrofitted gymnasiums was constructed in the area where relatively severe damage was observed. Structural and nonstructural damage of this gymnasium were not observed.

(2) Results of elementary and junior high school gymnasiums in Mito city

1) Outline of structure of investigated gymnasiums

A total of 22 gymnasiums were investigated. 20 of the gymnasiums were constructed under the previous seismic code. All of the investigated gymnasiums are one-story. The structural types of the gymnasiums are shown in Table 6.4-2, as the case of the high school gymnasiums. The percentage of the mixed structure that consists of lower RC frame and upper steel frame is 19%, and the percentage of RC frame structure having steel roof frame is 41%.

Table 6.4-2 Structural types of investigated elementary and junior high school gymnasiums

<table>
<tr><td colspan="2">Mixed structure consist of lower RC frame and upper steel frame</td><td colspan="2">Steel frame structure</td><td rowspan="3">RC frame structure having steel roof frame</td><td rowspan="3">Unidentified</td></tr>
<tr><td colspan="2">4(19%)</td><td colspan="2">7(32%)</td></tr>
<tr><td>Steel brace frame</td><td>Steel moment-resisting frame</td><td>Steel brace frame</td><td>Steel moment-resisting frame</td></tr>
<tr><td>3(14%)</td><td>1(5%)</td><td>1(5%)</td><td>6(27%)</td><td>9(41%)</td><td>2(10%)</td></tr>
</table>

2) Structural damage

Five types of the structural damage, shown in the result of the investigation of high-school gymnasiums, were also observed in the elementary and junior high school gymnasiums. However, the degree of structural damage in the elementary and junior high school gymnasiums seems to be smaller than in the case of high school gymnasiums.

3) Nonstructural damage

Severe nonstructural damage in which ceiling members were widely dropped, as observed in the investigation for the high school gymnasiums, was not observed in the elementary and junior high school gymnasiums. However, 20 of the gymnasiums suffered some sort of nonstructural damage. The degree of nonstructural damage in the elementary and junior high school gymnasiums seems to be smaller than in the case of high school gymnasiums.

6.4.4 Classification and characteristics of damage to steel gymnasiums

During this earthquake damage investigation, a total of 66 gymnasiums in the high schools within Ibaraki prefecture and in the elementary and junior high schools within Mito city were surveyed. The damage to the gymnasiums was classified into the types of (1) to (7). The types of (1) to (6) and the type of (7) represent structural damage and nonstructural one, respectively.

(1) Buckling and fracture of brace member and fracture of its joint
(2) Buckling of diagonal member of latticed column
(3) Damage of connection (bearing support part) between RC column and steel roof frame
(4) Deflection, buckling and fracture of roof horizontal brace
(5) Cracking of column base concrete
(6) Other (Overturning of floor strut, etc.)
(7) Nonstructural damage such as dropping of ceilings and exterior walls and breakage of windows

Each damage photograph shows each damage type in the following pages.

(1) Buckling and fracture of brace member and fracture of its joint

Buckling of brace member (Photo 6.4-1) and fracture of brace joint (Photos 6.4-2 ~ 6.4-4) were observed. Angle section was often used for many brace members, but circular hollow section steel (Photo 6.4-3) was also used for brace members. Fractured sections include steel plate inserted into steel pipe, end of bracing member and section loss part by bolt hole. These types of the damage are classified into the severe damage category based on the damage evaluation standard[6.4-4)]. The number of the gymnasiums of this type is 3. The gymnasiums constructed under the previous seismic code that had been severely damaged by the Mid Niigata Prefecture Earthquake in 2004 had accounted for about 30% of the total[6.4-1)~6.4-3)]. It is impressed that a rate of the gymnasiums severely damaged by the 2011 Tohoku earthquake was lower than by the Mid Niigata Prefecture Earthquake in 2004.

Photo 6.4-1 Buckling of brace

Photo 6.4-2 Net section fracture at bolt hole

(a) Fracture at column top

(b) Fracture at brace crossing

Photo 6.4-3 Fracture of brace welded connection

Photo 6.4-4 Fracture of bolts

(2) Buckling of diagonal member of latticed column

In one of the investigated gymnasiums, buckling of diagonal members in some latticed columns was observed (Photo 6.4-5). Damage of column buckling caused in steel frames for span direction had not been observed under the damage investigations of the Mid Niigata Prefecture Earthquake in 2004[6.4-1)~6.4-3)].

(a) Latticed column (b) Buckling of diagonal member

Photo 6.4-5 Buckling of diagonal member of latticed column

(3) Damage of connection (bearing support part) between RC column and steel roof frame

In the investigated gymnasiums, exposure of anchor bolts due to spalling of the concrete at connection (bearing support part) between the RC column and steel roof frame (Photos 6.4-6 and 6.4-7), spalling of finish mortars on the RC column at the roof bearing support part, and pullout of hole-in anchors (Photo 6.4-8) were often observed.

Photo 6.4-6 Spalling of concrete

Photo 6.4-7 Spalling of concrete

Photo 6.4-8 Pullout of hole-in anchors

(4) Deflection, buckling and fracture of roof horizontal brace

Roof horizontal braces were damaged in two high school gymnasiums and five elementary and junior high school gymnasiums. Such damage mainly occurred at horizontal braces with turnbuckles; obvious deflection of the horizontal brace (Photo 6.4-9) and fracture at thread and fracture of bolt connections were observed (Photo 6.4-10).

Photo 6.4-9 Deflection of horizontal braces

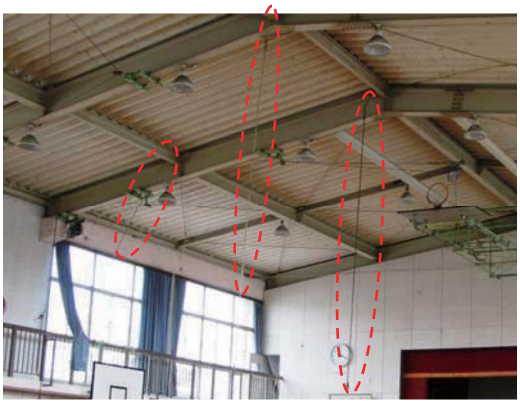

Photo 6.4-10 Fracture of horizontal braces

(5) Cracking of column base concrete

Damage of cracking of the column base concrete and mortar in the gallery of some gymnasiums was observed (Photo 6.4-11). Concrete and mortar of steel column base at a ground level was also cracked (Photo 6.4-12). However, almost all of these cracking are classified into minor or slight damage.

Photo 6.4-11 Cracking of column base concrete

Photo 6.4-12 Cracking of column base concrete

(6) Other (Overturning of floor strut, etc.)

As the other types of the structural damage, the following damage was observed; (a) overturning of floor strut (Photo 6.4-13), (b) tilting of concrete block self-standing wall and (c) peeling of paint of beam members which was observed near the top of the V-shaped roof beams or arch beams (Photos 6.4-14 and 6.4-15). In terms of the peeling of paint, it was uncertain whether yielding of the beams occurred or not.

Photo 6.4-13 Overturning of floor strut

Photo 6.4-14 Peeling of paint of beams

Photo 6.4-15 Peeling of paint of beams

(7) Nonstructural damage such as dropping of ceilings and exterior walls and breakage of windows

The types of nonstructural damage of gymnasiums included dropping of ceilings and lighting equipment (Photos 6.4-16 ~ 6.4-18), breakage of windows (Photo 6.4-19), dropping of exterior walls (Photo 6.4-20), dropping of interior walls and eave soffit (Photo 6.4-21). In particular, the severe damage such as dropping of extensive ceiling in the high school gymnasiums was observed more than in the elementary and junior high school gymnasiums.

Photo 6.4-16 Dropping of extensive ceiling components

Photo 6.4-17 Dropping of extensive ceiling components

Photo 6.4-18 Dropping of extensive ceiling components

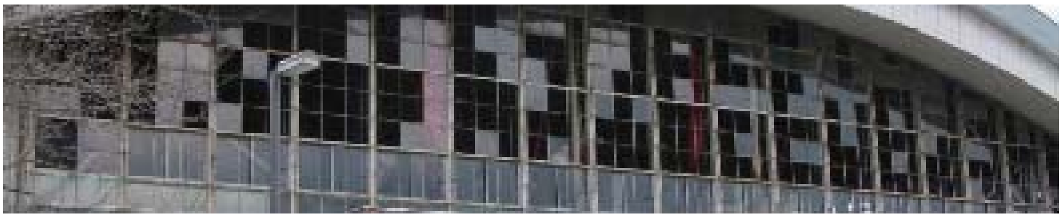

Photo 6.4-19 Breakage of windows

Photo 6.4-20 Falling of exterior finish components

Photo 6.4-21 Falling of eave soffit

6.4.5 Conclusions

The damage to the steel gymnasiums constructed under the previous seismic code in the areas with JMA seismic intensity around 6 in Ibaraki prefecture was investigated, and the outline of the investigation was described in this section. The results of the damage investigation of the steel gymnasiums are summarized as follows.

a) Structural damage to the steel gymnasiums

1) The types of observed structural damage to the gymnasiums are classified into the following six categories. (1) Buckling and fracture of brace member and fracture of its joint, (2) Buckling of diagonal member of latticed column, (3) Damage of connection (bearing support part) between RC column and steel roof frame, (4) Deflection, buckling and fracture of roof horizontal brace, (5) Cracking of column base concrete, and (6) Other (overturning of floor strut, etc.).
2) In three among the 66 investigated gymnasiums, severe structural damage such as "fracture of brace member and joint" occurred. This rate of the damage seems to be smaller than that in the Mid Niigata Prefecture Earthquake in 2004.
3) Severe structural damage was observed in Mito city, Hokota city and Naka city than in other areas.

b) Nonstructural damage to the steel gymnasiums

1) The types of observed nonstructural damage include dropping of ceilings, dropping of exterior and interior walls, falling of eave soffit and breakage of windows.
2) In four of the investigated gymnasiums, ceiling materials were extensively dropped, which is classified into the severe damage category. In some of the gymnasiums, many windows were broken.
3) Severe nonstructural damage was observed in Mito city, Hokota city and Hitachi city than in other areas.

4) Severe structural and nonstructural damage seemed to have occurred in the high school gymnasiums rather than in the elementary and junior high school gymnasiums.

References

6.4-1) NILIM, MILT, Japan and BRI, Japan: Report on the Damage Investigation of Buildings Due to the Mid Niigata Prefecture Earthquake in 2004, pp.305-353, October, 2006 (in Japanese)

6.4-2) Takashi Hasegawa, Akiyoshi Mukai, Kazuo Nishida and Tadashi Ishihara: Damage Investigation of Steel Gymnasiums Due to the Niigataken-chuetsu Earthquake (Part1 Study on structural damage), Summaries of Technical Papers of Annual Meeting, AIJ, B-2, pp.569-570, September, 2005 (in Japanese)

6.4-3) Kazuo Nishida, Akiyoshi Mukai, Takashi Hasegawa and Tadashi Ishihara: Damage Investigation of Steel Gymnasiums Due to the Niigataken-chuetsu Earthquake (Part2 Study on nonstructural damage), Summaries of Technical Papers of Annual Meeting, AIJ, B-2, pp.571-572, September, 2005 (in Japanese)

6.4-4) The Japan Building Disaster Prevention Association: Damage evaluation standard and repair technology guidelines of earthquake damaged buildings, August, 2002 (in Japanese)

6.5 Damage to Residential Land

6.5.1 Introduction

The outline of damage situations associated with liquefaction in the alluvial plain area along the Tone River on the border between Ibaraki and Chiba prefectures and in Urayasu city, Chiba prefecture is reported. Furthermore the outline of damage situations of developed housing areas in Miyagi and Fukushima prefectures is also reported.

6.5.2 Damage due to Liquefaction in alluvial plain area along Tone River

Damage associated with liquefaction has occurred in the same areas as in the areas where liquefaction had been reported in the past earthquakes, such as abandoned river channel, back marsh and reclaimed paddy field. This section describes the damage situations in Nishishiro, Inashiki city, Hinode, Itako city and Kamisu city in Ibaraki prefecture. Liquefaction damage in Nishishiro, Inashiki city and Hinode, Itako city had been reported in the 1987 East Off Chiba Prefecture earthquake.

(1) Nishishiro, Inashiki city, Ibaraki prefecture

Large-scale and extensive damage occurred within the area of 500 m by 500 m that route 51 of national highway and the Yokotone River on the east of the road enclose. Route 11 of prefectural road was closed to vehicles, and sand boiling, large-scale road upheaval or severe fissure that was associated with liquefaction were seen mainly along the road. As a ground deformation, the ground subsided up to about 40 cm, and lateral displacement was up to about 1 m. An automobile was buried in boiled sand to the extent of a half of height of their tires.

Finishes of the sidewalks around a large-scale commercial establishment along Route 11 were scattered. The subsidence of the surrounding ground was about 40 cm, and the settlement of the facility itself was slight. The commercial building was tilted about 0.7/100 in the longitudinal direction. The pile foundation of the building was observed from an opening between surrounding fissures (Photo 6.5-1).

Photo 6.5-1 Situations around the commercial building and state of pile head

A boiled sand was seen everywhere on the roads or sites also in surrounding residential area. A house constructed on an embankment was tilted to an adjacent warehouse with sand boiling. An angle of tilting was 5.0/100 (Photo 6.5-2).

(2) Hinode, Itako city, Ibaraki prefecture

In Hinode, large-scale damage occurred in the area of about 200 m by 200 m along the Hitachi-tone River. Boiled sand, uplift of buried structures, and subsidence or tilting of utility poles, which were caused by liquefaction, were seen everywhere on the site. Many houses facing to the road subsided 20 to 30 cm from the front sidewalk (Photo 6.5-3). Foundation cracks or gaps were not observed.

Photo 6.5-2 House tilted 5.0/100

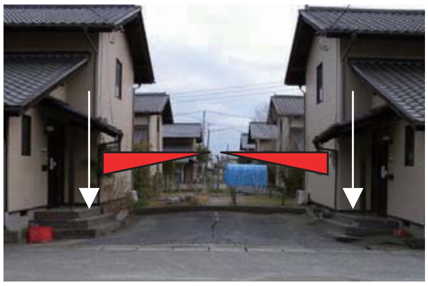

Photo 6.5-3 Subsidence of two houses enclosing vacant land

(3) Kamisu city, Ibaraki prefecture

This section describes the damage situations around Yokose Elementary School, and in Tsutsui, Horiwari and Fukashiba areas.

1) Around Yokose Elementary School

Yokose Elementary School is located about 3 km southeast from the Kamisu city office. The boiled sand by liquefaction was seen on the ground near the school. The ground subsidence was caused about 15 cm of difference in level on the rim of the building, and about 40 cm of difference in level at the outer slope (Photo 6.5-4). The building is supported by pile foundation. The outer slope and stairs were spread foundations, and the differential settlement was caused in this building.

2) Tsutsui area

The types of damage, such as sand boiling, uplift of buried structures, road gaps and subsidence or tilting of utility poles which were caused by liquefaction, occurred in the area of about 300 m by 300 m near Sotonasakaura in the area of Tsutsui that is located in the western part of Kamisu city. Due to damage to residential land, a severe fissure was generated, a house subsided approximately 15 cm from the surrounding ground and caused about 30 cm of difference in level from the ground (Photo 6.5-5). Cracking or crack fissures on the foundations were not visually observed.

3) Horiwari area

The uplift and the gap caused by site ground subsidence were occurred in the area of about 500 m by 500 m along Route 124 of national highway in Horiwari area that is located in the western part of Kamisu city. Along a street in the center of the area, uplift of the sidewalk or subsidence of the housing site caused a 25 to 30 cm of difference in level, and a side ditch around the house was damaged (Photo 6.5-6). A case where the ground around a house subsided about 15 cm without settlement of the house was observed. It is considered that the lower part of the sidewalk was damaged by the uplift of culverts.

4) Fukashiba area

Fukashiba is located in the western part of Kamisu city and on the opposite side of Horiwai along Route 124. In this area, many houses were damaged due to ground deformation and embankment deformation. Most of the damage patterns of the houses seem to have included their movement, subsidence and tilting without structural damage on their upper structures and foundations (Photo 6.5-7).

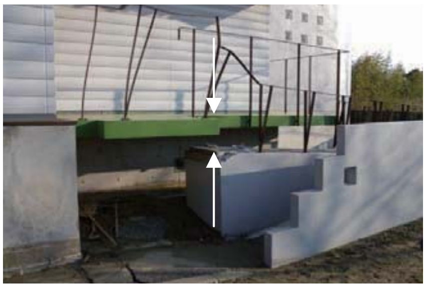

Photo 6.5-4 Slope difference in level

Photo 6.5-5 Crack in the site

Photo 6.5-6 Damage to side ditch

Photo 6.5-7 Damage situations by liquefaction

6.5.3 Damage due to Liquefaction in Urayasu city, Chiba prefecture

Area of reclaimed ground accounts for 3/4 of a total area in Urayasu city at present. The southern part of the city is the area that was developed under a reclamation project using sea sand. In the result, the area consists of soft layers up to GL-40 m. For reference, liquefaction damage was also reported in the 1987 East Off Chiba Prefecture earthquake. The damage situations are given below.

(1) Mihama area

In Mihama, subsidence and tilting were observed in houses that have a dry area in the basement (Photo 6.5-8). An angle of tilting of the house was about 3 degrees. It is considered that the basement was uplifted and another remaining parts of the house was subsided. Around the house, in-site of house was totally covered with boiled sand by liquefaction, and a foundation of fence at site boundary was deformed. In addition, carport in a house was ruptured and moved (Photo 6.5-9). The carport and the house was separated and moved about 50 cm due to the movement of the ground associated with liquefaction.

(2) Benten area

Significant tilting and subsidence of houses were observed at a zone in Benten (Photo 6.5-10). In another zone, the ground subsided by liquefaction, damage to the road that was waved and a 10 cm of difference in level was generated between a side ditch and the road. These types of damage were concentrated on an extension line of the boundary between the sites of tilted houses. Inhabitants told us that there was an old river on a straight line where the damage was concentrated.

Photo 6.5-8 Tilted house

Photo 6.5-9 Moved carport

Photo 6.5-10 Settled and tilted house

(3) Irifune area

In Irifune, a difference in settlement between adjacent buildings on spread and pile foundations was observed. The building on spread foundation settled about 35 cm from the front sidewalk, while the case of building on pile foundation was about 30 cm of difference in level from the front sidewalk (Photo 6.5-11).

(4) Hinode area

In Hinode, the ground subsidence was observed (Photo 6.5-12). This building is considered to have a pile foundation. A relative gap between the building and ground was about 50 cm. Building lifeline was damaged due to ground subsidence and displacement.

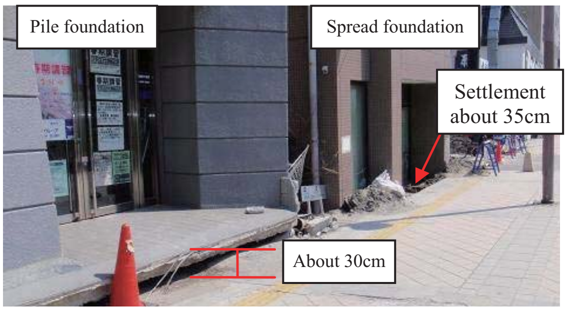

Photo 6.5-11 Difference in damage due to support mechanisms

Photo 6.5-12 Building with subsidence of surrounding ground

6.5.4 Damage to Developed Housing Area

The damage investigation for developed housing area was conducted in several areas of Miyagi, Fukushima and Tochigi prefectures, while only the damage in Miyagi and Fukushima prefectures is reported in this section.

(1) 5-chome, Oritate, Aoba-ku, Sendai city, Miyagi prefecture

In one corner of a large-scale housing area, where a slope in the N-NE direction had been developed, ground deformation due to sliding of the reclaimed area by banking to the slope direction, and damage to the retaining walls due to ground deformation were often observed (Photo 6.5-13). Houses on the site were recognized to have different damage patters, such as movement, subsidence and tilting without structural damage, severe structural deformation and fractured foundation.

(2) 2-chome, Aoyama and 4-chome, Midorigaoka, Taihaku-ku, Sendai city, Miyagi prefecture

This area is located at one corner of the large-scale housing area where a hill was developed. Ground deformation due to sliding of the reclaimed area by banking to the slope direction, and damage to the retaining walls due to ground deformation, were often observed. The damaged area in 4-chome, Midorigaoka during the 2011 Tohoku earthquake was almost same as that during the 1978 Miyagi-oki earthquake. The land in 2-chome, Aoyama is wavier than in 4-chome, Midorigaoka. Near the zone of 2-chome, Aoyama, large-scale sliding of the embankment occurred (Photo 6.5-14). In this zone, large deformation and damage were seen on both of upper structures and foundations of houses in the housing area. In other places with embankment sliding, deformation and damage to upper structures of houses were observed, but it seemed that there was limited significant damage to foundations. In 2-chome, Aoyama, a retaining wall for the housing area with a height of over 5 m was damaged.

Photo 6.5-13 Damage to retaining wall and house due to sliding and ground deformation

Photo 6.5-14 Group of houses damaged due to sliding and ground deformation

(3) 1-chome, Futabagaoka, Aoba-ku, Sendai city, Miyagi prefecture

This area is located at one corner of a large-scale housing area where a slope in the eastern direction was developed. The area suffered ground deformation due to sliding of the reclaimed area by banking to the slope direction. Large structural deformation (Photo 6.5-15) was relatively often seen in houses in the area, but houses without structural damage were sporadically observed. In addition, a gap between the house foundation and surrounding ground that was caused by ground subsidence and transformation, and damage to the lifeline, were observed. Damage to a retaining wall in the area was hardly seen, while traces of flaking and falling of block fences on the upper part of the wall were sporadically observed.

(4) 1 to 2-chome, Midorigaoka, Shiroishi city, Miyagi prefecture

This is a housing area where a hill was developed. Fissures on the slope of the hill and near the top of the hill, and damage to housing foundations and retaining walls due to deformation of the reclaimed area by banking, were observed in the area. The slope in 1-chome, Midorigaoka had been significantly collapsed under the 1978 Miyagi-oki earthquake. A level of ground deformation on the slope under the 2011 Tohoku earthquake was lower than that during the 1978 earthquake. Near the top of the hill, ground deformation of the reclaimed area by banking caused fracture of the embankment retaining wall, damage to house foundations (Photo 6.5-16) and push-out of the retaining wall on embankment.

Photo 6.5-15 Damage to houses due to sliding and ground deformation

Photo 6.5-16 Houses damaged near the top of hill

(5) Shimomiyamae, Asohara, Yamamoto Town, Watari-gun, Miyagi perfectere

This is a housing area where a hill was developed. Land sliding of the slope at the end of the hill, and ground deformation that seemed to be related with the sliding were observed. This ground deformation caused serious damage to houses. In the result, some houses were in a state of sliding on the slope of the hill (Photo 6.5-17). On the other hand, there was no ground deformation in a house located in the flat part of the hill, while paper sliding doors on the first-story of the house were only broken during the earthquake.

(6) Numanoue, Fushiogami, Fukushima city, Fukushima prefecture

This area is located at one corner of a large-scale housing area where a hill was developed. The result of investigation was revealed ground deformation due to land sliding on the slope of the hill. This ground deformation caused serious damage to houses. In the result, several houses were in a state of sliding on the slope of the hill (Photo 6.5-18). On the other hand, houses near the top of the hill suffered only damage associated with slight deformation of the reclaimed area by banking.

Photo 6.5-17 Fracture of embankment retaining wall and houses tilting due to land sliding on the slope of hill end

Photo 6.5-18 Land sliding of slope on the southwest of hill and sliding houses

6.5.5 Conclusions

The outline of the damage situations in the investigate scope is as follows.

(1) Damage due to liquefaction:

In the alluvial plain area of the Tone River and the coastal area of Tokyo Bay, extensive damage such as sand boiling or ground deformation associated with liquefaction was confirmed. Heavily tilted houses were seen, while cracks or fissures on the foundations were not observed.

(2) Damage to developed housing area:

Severe damage with ground deformation such as slope sliding was observed mainly in the elevated and developed housing area (particularly marginal part of development). In several areas, ground deformation occurred again in the developed area that had been affected by the past earthquakes.

6.6 Damage to Nonstructural Components

6.6.1 Introduction

This section is based on the surveys by the Joint Survey Team after March 11th 2011. External surveys were conducted to various buildings in three prefectures of Miyagi, Fukushima and Ibaraki, and external and internal ones were also done in Ibaraki prefecture to gymnasiums and an airport passenger terminal building. This section describes the outline of the damage to exterior walls, openings, suspended ceilings, interior walls focusing on the buildings without severe structural damage patterns such as story collapse.

6.6.2 Damage to exterior walls

Many damaged exterior walls, including walls finished with ceramic wall tiles, cement mortar and metal lath wall and AAC (Autoclaved lightweight Aerated Concrete) panel walls, were observed.

Detachment of ceramic wall tiles was often observed at buildings of RC nonstructural exterior walls. Types of the detachment were classified according to existence or nonexistence of crack on the damaged RC wall.[6.6-1) 6.6-2)] In Photo 6.6-1, ceramic wall tile detached from RC exterior wall. Cracks were observed on the damaged RC wall. Photo 6.6-2 shows detachment of ceramic wall tiles installed on a cylindrical RC wall above the building entrance (within a circle). No crack was externally observed on the undersurface RC wall. A net was placed over the damaged area to catch falling tiles.

Photo 6.6-1 Detachment of ceramic wall tiles from damaged RC exterior wall

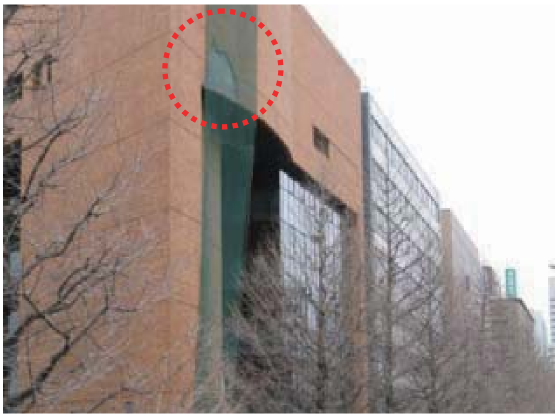

Photo 6.6-2 Detachment of ceramic wall tiles from RC wall

Damage to cement mortar and metal lath exterior walls was often observed in steel buildings. Photo 6.6-3 shows detachment of cement mortar and metal lath exterior wall in a 3-story building. Damage to the window glass was not observed, but cement mortar and metal lath fell from the exterior wall (shown in Photo 6.6-3) and from the parapet on another side. Photo 6.6-4 shows a one-story steel building in which cement mortar and metal lath detached from an exterior wall and from an eaves soffit. Photo 6.6-5 shows a damaged gable end wall of a gymnasium. This wall consisted of two layers. The undersurface wall was cement mortar and metal lath exterior wall. The surface one was exterior boards nailed to furring installed on the undersurface wall. Both were damaged and fell by the earthquake.

Photo 6.6-3 Falling of cement mortar and metal lath wall

Photo 6.6-4 Falling of cement mortar and metal lath from eaves soffit

Photo 6.6-5 Damage to gymnasium gable end wall

Photo from 6.6-6 to 6.6-7 shows damage to AAC panel exterior walls. Photo 6.6-6 shows falling of finishing ceramic wall tiles on AAC panels and broken light-weight aerated concrete in a 3-story building. Ceramic wall tiles on all faces of the exterior walls detached and the corners of the AAC panels were chipped. AAC panel was broken and internal iron wires were exposed at the circular broken line in the photo. AAC panels fell from another side. The construction method of the AAC panel exterior wall was not observed in the external survey. Photo 6.6-7 shows falling of AAC panels from the top-floor of a 5-story building. The damaged AAC panels were observed to be installed to the support metal with cement mortar and steel bar. This AAC construction method appeared in 3rd edition of Japanese Architectural Specification Standard JASS 12 as one of standard construction methods for AAC panel exterior wall but not included in its 4th edition.[6.6-3)] [6.6-4)] AAC panels installed with this AAC construction method were frequently observed to be damaged.

Photo 6.6-6 Falling of ceramic wall tiles and breakage of AAC panels

Photo 6.6-7 Detachment of AAC panels

6.6.3 Damage to openings

Damage to openings was observed in window glasses and window frames.

Photo 6.6-8 shows broken window glasses in the upper area of a windbreak room on the ground level of a 5-story building. Exterior ceramic wall tiles fell from another side.

Photo 6.6-8 Broken window glass

Photo 6.6-9 shows damaged window glasses installed to the upper fixed window with hardening putty at a gymnasium gable end wall. Cracked wired window glasses were also observed at the lower double sliding window with hardening putty. Flaking of paints was observed on the center of an arch beam of the gymnasium. Photo 6.6-10 shows breakage of window glasses in a gymnasium. The window glasses were installed to fixed window frames with glazing bead and twelve window glasses were broken at three exterior surfaces. Flaking of concrete at the roof bearing support part, deformation of almost all roof horizontal braces and fracture of one roof horizontal brace in the gymnasium were observed.

Photo 6.6-9 Breakage of window glasses installed to fixed window frame with hardening putty

Photo 6.6-10 Breakage of window glasses installed to fixed window frame with glazing bead

Photo 6.6-11 shows broken window glasses on the longitudinal surface in a gymnasium. Twenty-six wired window glasses were broken, which were installed to double sliding window frames with glazing bead. On the windows of opposite side, there were no damage to the frosted window glasses and a detachment of a mullion cover of a window. No damage was observed in the structure.

Photo 6.6-11 Breakage of wired window glass installed to double sliding window frame with glazing bead

Photo 6.6-12 shows a damaged glass wall system at the 1st floor of a 6-story building. A glass mullion was broken in an area circled by a broken line (steel pipe adjacent to the broken glass were installed after the earthquake for the repair work).

Photo 6.6-13 shows damage to window frame in a gymnasium. The photo shows the window frames near the center of the longitudinal surface of the gymnasiums. The upper part of the window frame was dislocated and leaned to the outside. The same damage was observed also at the opposite side. Fracture or buckling was observed in most of the section loss parts by bolt holes on longitudinal direction frame braces. Braces were fractured in three of four frames.

Photo 6.6-12 Breakage of glass mullion of glass wall system

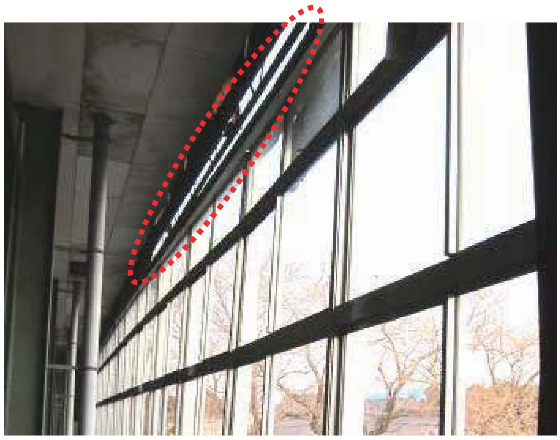

Photo 6.6-13 Dislocation of window frame

6.6.4 Damage to suspended ceilings

Many damaged suspended ceilings were observed in the damage investigation of gymnasiums and an airport passenger terminal building. The damaged suspended ceilings included wooden suspended ceilings faced with wooden boards, metal furring ones faced with plaster boards and absorption boards of rock wool, ones with exposed T system and glass wool boards and others.

Photo 6.6-14 shows a damaged wooden suspended ceiling in a gymnasium. The ceiling almost fell with light fittings except at perimeter. Partial falling of an eaves soffit, dislocation of a window frame and 33 broken window glasses were also observed.

Photo 6.6-14 Falling of wooden suspended ceiling

Photo 6.6-15 shows a metal furring suspended ceiling broken at the center of a pitched ceiling. Damage was also observed at interior walls above the stage. No damage was observed to the steel roof and supporting RC columns. Photo 6.6-16 shows damage to a high ceiling above the lobby of an airport passenger terminal building. There were five metal furring suspended ceilings of 3m x 11m. The metal-sheet clips hanging the metal furring channels were damaged by the earthquake and one of the ceilings fell. In the ceiling plenum, vertical diagonal members were unevenly installed and the members were complicatedly installed near the connection with the surrounding wall. No damage to the structure was observed.

Photo 6.6-15 Falling of metal furring suspended ceiling

Photo 6.6-16 Falling of metal furring suspended ceiling

Photo 6.6-17 shows damaged ceilings in a gymnasium. The horizontal ceiling marked with red dotted lines was composed of corrugated steel plates and steel members and the pitched ones were composed of metal furring channels and other steel members faced with gypsum board. Both ceilings fell. The broken window glasses and the leaned interior wall above the stage were also observed. Many roof horizontal braces were fractured.

In the gymnasium shown in Photo 6.6-18, many glass wool boards on exposed T system fell. Flaking of concrete was observed in the structure.

Photo 6.6-17 Falling of metal furring suspended ceiling and corrugated steel plates

Photo 6.6-18 Falling of glass wool board of T system ceiling

Photo 6.6-19 shows a damaged metal furring suspended ceiling in a gymnasium. Significant visual damage was not observed, but the ceiling board sagged near the center of pitched ceiling marked with a red dotted oval line in the photo. This was possibly due to the displacement of ceiling members in the plenum. Cement mortar finish of interior wall above the stage was flaked as shown in Photo 6.6-23, and the exterior boards were broken at the gable end wall. No damage to the structure was observed.

Photo 6.6-20 shows damaged ceiling at the connection with surrounding wall in a gymnasium. Bending of the metal furring channels and detachment of ceiling boards were observed. In the corner of the ceiling, the sheet-metal clips were damaged and the ceiling sagged in several meters long. The gymnasium is composed of lower RC frame and upper steel frame.

Photo 6.6-19 Sagging of metal furring suspended ceiling

Photo 6.6-20 Damage to metal furring ceiling at the connection wall

Photo 6.6-21shows damaged ceiling boards at the connection with the structure of a gymnasium. It was reported that one window glass was broken. No damage to the structure was observed.

Photo 6.6-22 shows damaged ceilings at an office building. The ceiling was damaged at the connection with the partition. Bending of a metal furring channels and falling of ceiling boards were observed.

Photo 6.6-21 Damage to metal furring suspended ceiling at the connection

Photo 6.6-22 Damage to metal furring suspended ceiling at the connection

6.6.5 Damage to interior walls

Photo 6.6-23 shows damaged walls above the stage in the gymnasium shown in Photo 6.6-19. Cement mortar finishes on the studs were broken and fell. Damage to the walls above the stage was observed also in some gymnasiums such as shown in Photo 6.6-15 or Photo 6.6-17.

Photo 6.6-23 Falling of cement mortar finish above stage

Photo 6.6-24 shows a lift of the nail fixing interior wall boards to the studs in the arena of gymnasium.

Photo 6.6-25 shows damaged interior walls in a gymnasium. Interior walls around the supports leaned at two of three basketball hoops. The damaged hoops were temporarily supported with ropes.

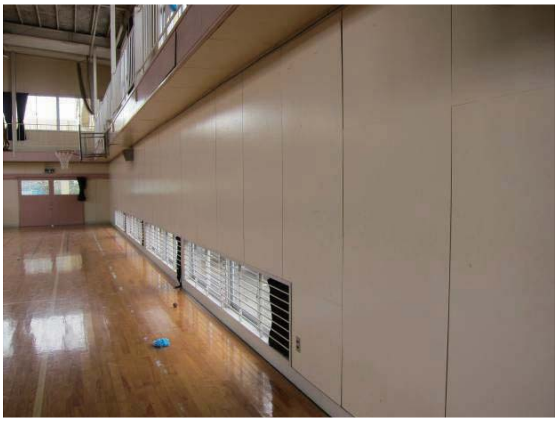

Photo 6.6-24 Loosen nails fixing board

Photo 6.6-25 Damaged interior wall

6.6.6 Conclusion

This section described the outline of damage to nonstructural components. Damage to nonstructural components constructed with relatively older building methods was often observed. Breakage and falling of nonstructural components placed on relatively higher parts were also observed.

The frequently observed damage to each nonstructural component is summarized as below:

Exterior wall

Ceramic wall tiles were detached from RC nonstructural walls. Cement mortar and metal lath were detached from steel buildings. AAC panels installed to support metal with cement mortar and steel bar were also detached from steel buildings.

Openings

Glasses of fixed window were broken, mostly installed with hardening putty.

Suspended ceiling

Various types of suspended ceilings were damaged. Breakage at connection with interior walls was frequently observed at gymnasiums.

Interior wall

Walls were broken and fell above the stage of gymnasiums.

References

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6.6-2) Akio BABA and Hiroshi ITO, Full Scale Experiment on the Seismic Safety of Exterior Finishing Material and Construction Method, Cement & Concrete No.376, published by the Cement Association of Japan, 1978

6.6-3) Japanese Architectural Standard Specification JASS 21 AAC Panel Work, 3rd edition, Architectural Institute of Japan, 1998

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