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.

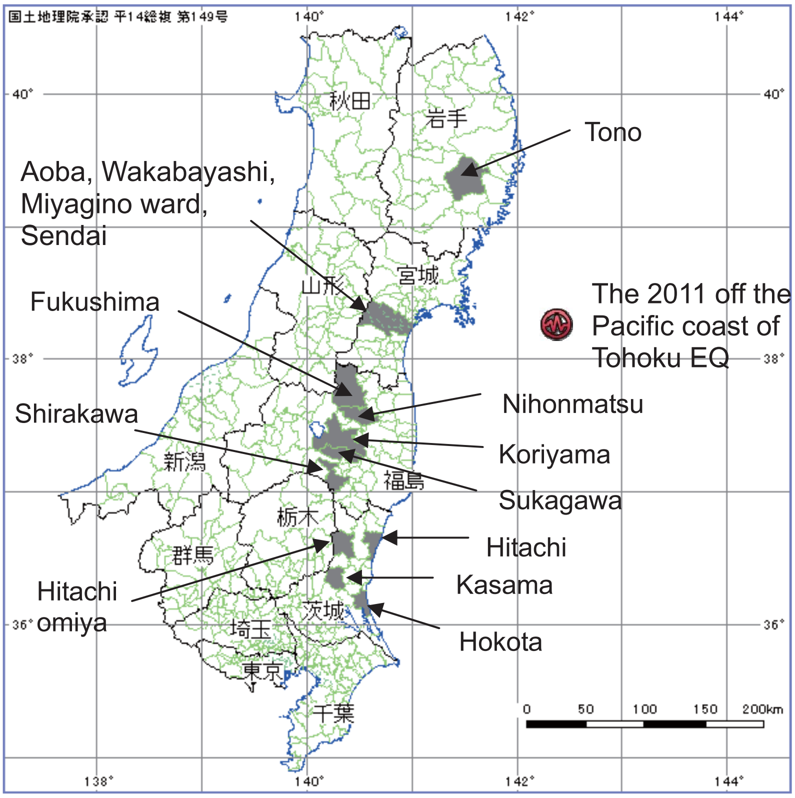

Fig. 6.3-1 Investigated Area (free mapping program, 'KenMap' was used)

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)

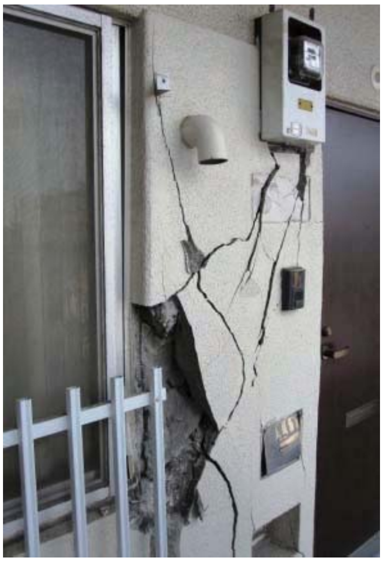

Photo 6.3-30 Shear cracks on nonstructural wall

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)

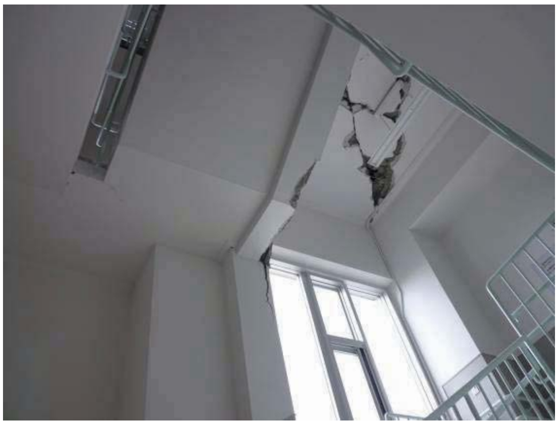

Photo 6.3-35 Damaged clock tower (Fukushima city)

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)