

DAMAGE TO REINFORCED CONCRETE BOXED WALL-BUILDINGS IN THE 2011 GREAT EAST JAPAN EARTHQUAKE

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ABSTRACT: Post-earthquake damage evaluation for 634 public apartment buildings having boxed wall type structure (WRC, WPCa PS and ribbed panel) was conducted within the city of Sendai by AIJ Committee on boxed wall structures. Of the 496 buildings having a reinforced concrete boxed wall (WRC) structure, 97.4% were found to be undamaged or to have only slight damage. Among the remaining 2.6%, only one building had moderate damage and no buildings had severe damage. The others had minor damage. All of the 47 buildings having a precast prestressed reinforced concrete boxed wall (WPCa PS) structure in Sendai were found to have suffered no or slight damage. Of the 91 buildings having a boxed wall of thin ribbed concrete panel (ribbed panel) structure, 72.5% were found to have suffered no or slight damage. Among the remaining 27.5%, 11 buildings were moderately damaged and 1 building was severely damaged. The ribbed panel buildings suffered relatively higher damage. This is because 71 out of the 91 ribbed panel buildings were constructed before the new earthquake-resistance standards 1981.

INTRODUCTION

A committee on boxed wall structures, Architectural Institute of Japan (AIJ) conducted post-earthquake damage evaluation for the public apartment buildings in Sendai city on April 21 through 24, April 29 through May 2, and on June 26, 2011, and visual inspection for the public apartment buildings damaged by tsunami in the coastal areas in Miyagi Prefecture on June 5 and 6, 2011. This paper describes the results of the damage evaluation and the visual inspection.

SURVEYS AT PUBLIC APARTMENT COMPLEXES IN SENDAI CITY

Buildings surveyed

Surveys were planned at 64 public apartment complexes accommodating apartments built by the Miyagi prefectural government, Miyagi Prefecture Housing Supply Corporation and Sendai municipal government, and rental houses built by the Urban Renaissance Agency. Boxed wall structures amount to 638. Table 1 lists the numbers of buildings by area, structural type and number of stories. Five hundred buildings of 638 are two- to five-storied reinforced concrete boxed wall buildings (WRC buildings below), 47 are four- to five-storied precast prestressed reinforced concrete boxed wall buildings (WPCa PS buildings) and 91 are two-story mass-produced public apartments of middle size ribbed thin concrete panel structure (ribbed panel buildings). Surveys were conducted at 634 buildings in 63 complexes. No surveys have yet been made of four WRC buildings.

Survey method

Post-earthquake damage was evaluated using the inspection form for post-earthquake damage evaluation of reinforced concrete and SRC composite buildings prepared by the Japan Building Disaster Prevention Association, and damage to buildings was recorded. For WPCa PS buildings and ribbed panel buildings, the degree of damage at vertical and horizontal joints was taken into consideration in post-earthquake damage based on a newly prepared inspection form by AIJ Committee on boxed wall structures. Surveys were conducted from outside the building.

The seismic intensities in the apartment complexes where surveys were made are based on the data collected by the Japan Meteorological Agency, Building Research Institute [1], Tohoku University [2] and via K-net [3] and Small-Titan [4]. Figure 1 shows the locations of apartment complexes where surveys were conducted and seismic intensities. Seismic intensities in the apartment complexes where surveys were made ranged from 5 upper to 7.

Table 1 Number of boxed wall type public apartment buildings at each area in Sendai city

Type of structure	Aoba Ward	Miyagino Ward	Wakabayashi Ward	Taihaku Ward	Izumi Ward	Total
WRC buildings 2 F	2	0	0	0	0	2
WRC buildings 3 F	35	9	13	7	30	94
WRC buildings 4 F	39	43	4	25	16	127
WRC buildings 5 F	24	101	1	55	96	277
WPCa PS buildings 4 F	6	8	3	3	6	26
WPCa PS buildings 5 F	0	12	2	1	6	21
Ribbed panel buildings 2F	0	70	0	0	21	91
Total	106	243	23	91	175	638

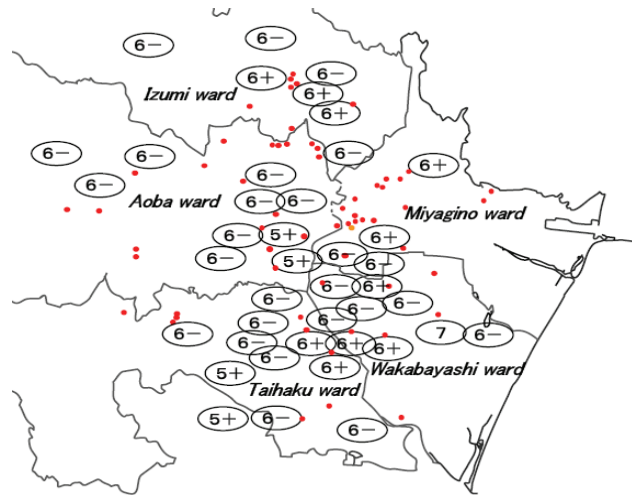


Fig. 1 Location of apartment complexes investigated and seismic intensity in Sendai city

Survey results

The tallies of the damage to the superstructure of 634 buildings surveyed are listed in Table 2 by structural type. There is no collapsed building. Of the WRC buildings, 97.4% were undamaged or slightly damaged. The buildings that suffered minor or higher level damage accounted for 2.6%. One building suffered moderate damage. None was severely damaged. All of the 47 WPCa PS buildings were undamaged or slightly damaged. As described below, however, a WPCa PS building was seriously damaged in Natori City. The percentage of undamaged or slightly damaged ribbed panel buildings is 72.5%. Those that suffered minor or higher level damage accounted for 27.5%. Eleven buildings were moderately damaged and one was severely damaged. The percentage of ribbed panel buildings that suffered minor or higher level damage is greater than that of other types of buildings. Thus, ribbed panel buildings suffered greater damage. One of the major reasons is that most of the ribbed panel buildings were constructed before the new anti-seismic design code was put into effect in 1981.

Table 2 Earthquake damage level of investigated apartment buildings in Sendai city

Type of structure	Damage level of super-structure					
	No damage	Slight	Minor	Moderate	Severe	Collapse
WRC buildings	369	114	12	1	0	0
WPCa PS buildings	31	16	0	0	0	0
Ribbed panel buildings	43	23	13	11	1	0
Total	443	153	25	12	1	0

CASE STUDIES OF DAMAGE TO REINFORCED CONCRETE BOXED WALL BUILDINGS

Apartment complex A in Aoba Ward, Sendai City

The complex is located on a slope. Six four-story buildings (buildings 1 through 6 referred to as “star houses” because of the Y-shape in plan) and an apartment building (building 7) with an ordinary rectangular plan exist in the complex. The complex was subjected to vibration of seismic intensity less than 6. The superstructure of building 7 was not damaged. Of the star houses, three buildings were slightly damaged, two suffered minor damage and one was moderately damaged. Photograph 1 gives an overview of a star-house apartment building.

In one of the star houses that was determined to have suffered minor damage, shear failure was observed in a bearing wall on the first floor. Photograph 2 shows the shear failure of the bearing wall on the first floor on the east side of the structure. On the south side of the building, ground settled along the slope. The ground deformation may have been one of the causes of the damage on the east side.



Photo 1 Overview of the star-house apartment



Photo 2 Shear failure of the bearing wall of the first floor at east side

Apartment complex B in Miyagino Ward, Sendai City

In the apartment complex, ground deformation caused part of the retaining wall to collapse and a five-story apartment building on the side of the retaining wall was inclined. Photograph 3 gives an overview of the inclined apartment building and the partially collapsed retaining wall. Photograph 4 shows the damage to the surrounding ground. The angle of inclination of the apartment building was 22/1000 on the short side and 9/1000 on the long side. The damage to the foundation was determined to be minor. Angle of inclination was measured at four corners of the building using one-meter-long inclinometers. Seismic intensity 6 upper was registered in the apartment complex.

As for the damage to the superstructure of the inclined apartment building, no cracks were observed on the exterior walls on the side of the balcony. Other exterior walls were covered with insulating panels and therefore no damage information was available.



Photo 3 Overview of the apartment inclined and the retaining wall collapsed partially



Photo 4 Damage of the ground around the apartment

CASE STUDIES OF DAMAGE TO PRECAST PRESTRESSED REINFORCED CONCRETE BOXED WALL BUILDINGS

Characteristics of precast reinforced concrete boxed wall buildings around Sendai

Surveys were conducted of precast reinforced concrete boxed wall buildings (WPCa buildings) in Natori City in addition to 47 apartment buildings in Sendai City. The WPCa buildings confirmed in the area consist of a rental house built by the Urban Renaissance Agency, 24 prefectural buildings and 31 municipal buildings. It is presumed that the precast prestressed reinforced concrete boxed wall structure (WPCa PS construction method) was adopted for all the buildings.

The WPCa PS structure, unlike the ordinary precast concrete boxed wall structure (WPCa), is formed by laminating cross-, T- and L-shaped three-dimensional precast members and compressing them using prestressing bars placed vertically.

Building *d* in apartment complex *F* in Natori City

Building outline

Apartment complex *F* accommodates two buildings, building *d* in the north and building *e* in the south. Both are of WPCa PS structure. Building *d* accommodates 30 five-story buildings and building *e* 20 five-story buildings. The construction of buildings *d* and *e* was started in October 1981 and completed in March 1982. Photograph 5 gives an overview of building *d* in apartment complex *F*.



Photo 5 Overview of d-apartment in Natori city

Damage outline

Relative settlement of 43 mm was observed between axes X8 and X9 (5100 mm span) on the first floor on the south side (balcony side). The inclined angle is 1/118 rad. Photograph 6 shows the settlement of the east side of the center.

Vertical and shear cracks were found in the foundation beam and vertical cracks at the end of longitudinal beams on the second to fifth floors between axes X8 and X9. The cracks are attributable to the settlement of the ground. The cracking at the end of axis X9 in a beam on the second floor are shown in Photograph 7.



Photo 6 View of ground subsidence around d-apartment



Photo 7 View of the crack at the beam of 2nd floor of d- apartment

Damage degree assessment

The damage degree of the superstructure was determined to be minor as a result of examination of the degree of damage to the first-floor bearing wall on the balcony side and second-floor floor beam where damage was visually confirmed. Subsequent detailed surveys found that there was a high possibility of piles failing and that settlement of more than 100 mm occurred. Then, the damage degree of the foundation was determined to be severe .

Other damage

Cracks and loss were found in part of the bracket on the precast wall supporting the precast slab in the staircase. It is, however, unknown whether the damage is attributable to the earthquake or not.

CASE STUDIES OF DAMAGE TO MASS-PRODUCED PUBLIC APARTMENT BUILDINGS

Outline of damage

Mass-produced public apartments are of middle size ribbed thin concrete panel structure developed in 1962 (ribbed panel buildings below). Precast concrete panels are bolt-connected to each other. The buildings became popular as semi-fireproof structures.

A total of 91 public apartment buildings were surveyed in four apartment complexes in Sendai City. All have two stories.

Of the 91 buildings, 43 (47%) were undamaged and 23 (25%) slightly damaged. Thirteen buildings (14%) suffered minor damage and 12 (13%) suffered moderate or higher-level damage and required large-scale structural repair (Table 3).

Most of the mass-produced public apartment buildings were constructed before the new seismic design code was put into effect in 1981. The buildings constructed after the enforcement of the code suffered relatively small damage. No damage was observed in 17 buildings out of 20 (85%).

Seismic intensity 6 upper was registered in the apartment complexes where surveys were conducted.

A building that was determined to have been severely damaged was built on a spread foundation on a fill above the retaining wall. The retaining wall collapsed (Photograph 8) and the building was deformed downward from the center.

Ten of the buildings that were determined to have been moderately damaged were also built on a landfill. In most cases, damage due to the fissure in the fill caused the building to suffer serious damage.

Municipal apartment houses are similar to the standard plan of a mass-produced public apartment house designed by the Japan Prefabricated Construction Suppliers & Manufacturers Association (JPA). The terrace-style houses accommodate four to eight houses. Most of the damage to the building occurred longitudinally. Little damage was incurred transversely.

Table 3 Earthquake damage level of mass production type public apartments investigated

Complex Name	Year of Construction	Number of buildings	No damage	Slight damage	Minor damage	Moderate damaged	Severe damage	Collapse
Complex G (Miyagino Ward)	1969~70	36	12	10	9	5(5)	0	0
Complex H (Miyagino Ward)	1970~71	14	5	1	2	5(5)	1(1)	0
Complex K (Izumi Ward)	1975	21	9	11	0	1	0	0
Complex L (Miyagino Ward)	1985	20	17	1	2(1)	0	0	0
Total		91	43	23	13	11	1	0
Ratio (%)			47.3	25.3	14.3	12.1	1.1	0.0

() : cause of damage is relating to embankment and retaining walls



Photo 8 Mass production type public apartments and damage of the retaining wall

Damage to structures

Figure 2 outlines a ribbed panel structure. Column forms were installed at intersections of longitudinal bearing wall and transverse wall. Damage to the ribbed panel structure was observed at the positions listed below.

- (i) Vertical crack at the vertical joint between the bearing and hanging walls (Photograph 9)
- (ii) Vertical crack at the vertical joint between the bearing and spandrel walls
- (iii) Flexural crack at the foot of the bearing wall where the wall thickness changes (boundary between a 120-mm-thick rib around the bearing wall and a 40-mm-thick area other than the rib)
- (iv) Shear crack in the bearing wall (Photograph 10)
- (v) Horizontal crack in the bearing wall at the height of the hanging wall
- (vi) Vertical crack at the vertical joint between bearing walls or at the vertical joint between the transverse bearing wall and column form
- (vii) Vertical crack in the foundation and failure of foundation beam due to ground settlement or fissure

Damage (i) and (ii) were confirmed most frequently. The results are the same as the damage to mass-produced public apartment buildings in the past earthquakes. In the buildings constructed after the enforcement of the new code, improvements have been made in detail and damage is incurred less frequently.

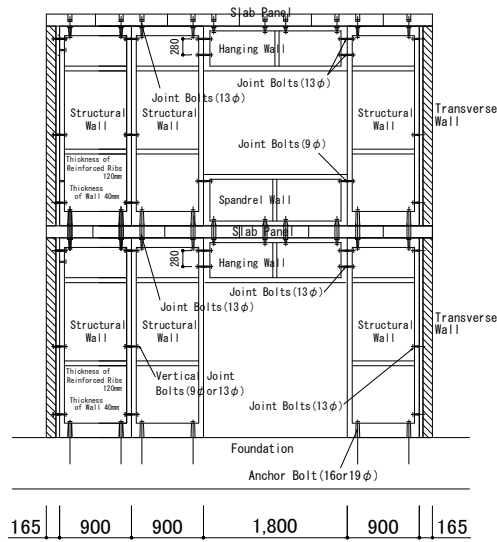


Fig. 2 Outline of ribbed panels structural system



Photo 9 Crack at vertical joint between bearing wall and hanging wall

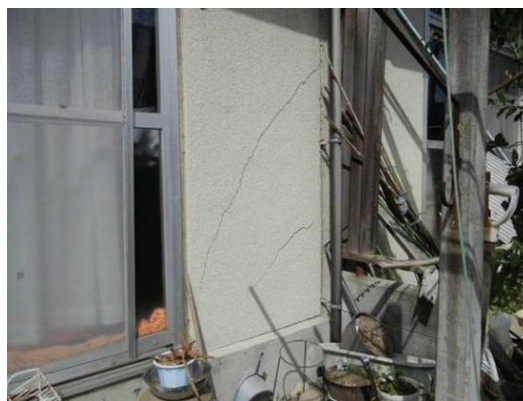


Photo 10 Shear crack of the bearing wall

CASE STUDIES OF TSUNAMI DAMAGE

Visual inspections were made for public apartment buildings that suffered tsunami damage in the coastal areas in Miyagi Prefecture. Photograph 11 shows the tsunami damage to a two-story mass-produced public apartment building in the Yuriage area in Natori City. The first floor was greatly damaged by the tsunami. Ribbed panels themselves were damaged in some cases. Photograph 12 shows the damage to a three-story WPCa PS building in the Yuriage area. No severe damage was found on the exterior wall. Photographs 13 shows the damage to three-storied WRC buildings in Minami-sanriku-cho. Debris from the tsunami remains on the roof, suggesting that the tsunami reached the top of the building. No severe damage was observed in the bearing wall or wall beam although partial damage was observed on the balcony.



Photo 11 Mass production type public apartment building damaged by tsunami in Natori



Photo 12 WPCa PS apartment building damaged by tsunami in Natori



Photo 13 WRC apartment building damaged by tsunami in Minami Sanriku

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*Surveys of damage to public apartment buildings in Sendai City

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