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DAMAGES TO REINFORCED CONCRETE BUILDINGS OBSERVED IN FUKUSHIMA AFTER THE 2011 EAST JAPAN EARTHQUAKE

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ABSTRACT: This paper reports on structural damages to reinforced concrete buildings observed in Fukushima prefecture after the 2011 East Japan Earthquake. The survey was conducted as part of reconnaissance activity of AIJ, Architectural Institute of Japan. Typical severe damages to reinforced concrete school buildings are outlined, both by the ground motions and the tsunami waves, based on the detailed field observation and with ground motions recorded at K-net stations nearby. The causes of the damages are discussed with problems peculiar to the buildings.

Key Words: damage survey, reinforced concrete, school buildings, damage evaluation, ground motion, collapse

INTRODUCTION

Typical damages to reinforced concrete school buildings observed in Fukushima region, especially relatively heavy damages such as collapse or near collapse, were reported here with the specific reasons in the structures. The survey was conducted as the reconnaissance activity of AIJ, Architectural Institute of Japan, combined with the damage level evaluation requested from MEXT, Ministry of Education. The details of investigation methods and the other results such as the damage rates in the selected area will be analyzed and discussed elsewhere based on the statistical data of the inventory damage rates on the school buildings not only just with the ages of buildings but also on the effects of retrofit or strengthening as well as in relation with calculated seismic performance indices. Heavy and typical damages are reported below with the ground motions recorded at K-net stations nearby (NIED, 2011).

DAMAGES TO SCHOOLS IN NORTH FUKUSHIMA

K-net records at Fukushima city

The JMA intensity of the ground motion was defined as V+ at Fukushima city, but VI- at north Fukushima, while the response spectrum was calculated as shown in Fig. 1 from the record at K-net station of Fukushima (FKS003). The maximum acceleration response was close to 1G and the maximum velocity response was close to 100kine, which may be regarded as close to or a little less than the very rare level, the level 2 of BSL.

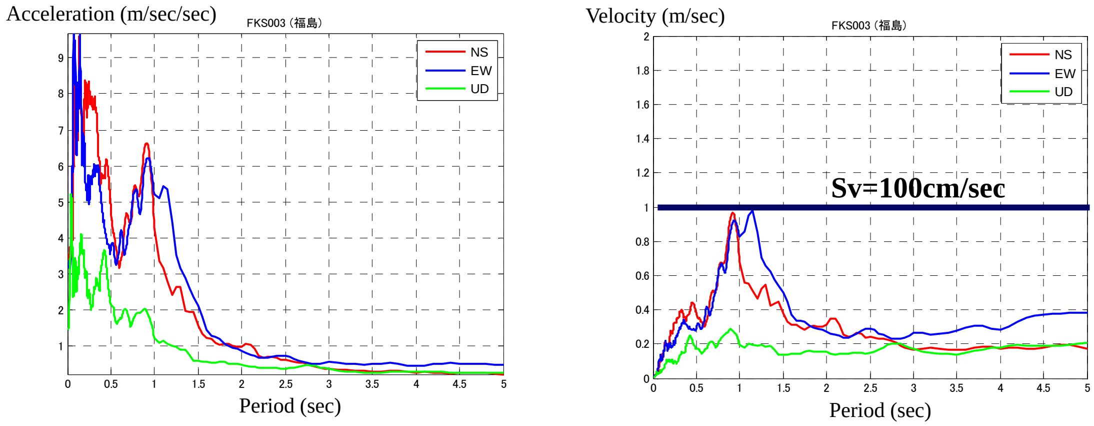

Fig. 1 K-net records at Fukushima city

F-College in north Fukushima city

Collapse of a building, so-called pancake crush, was observed in F-college located north of Fukushima city, which was three-story reinforced concrete building for administration built in 1965. The building is located in the campus of the north area of Fukushima city, which is on a shallow hill with an adjacent drain on north end of the site. Relatively heavy damages were observed in the neighborhood area, which are now crowded with wooden houses, but were marshes in the old days.

The building had a Y-shaped plan with a stair hall in the center and three longitudinal blocks spread to north, east and west directions as equivalent triangular as shown in Figure 3.2.3. The foundation bases are PC piles with the depth of 6m. A continuous shear wall is located only at each end of three blocks, while the walls along the stair in the center were not continuous and the other walls were non-structural partitions. The columns are located with 11m in the span and 5m in the longitudinal direction, respectively.

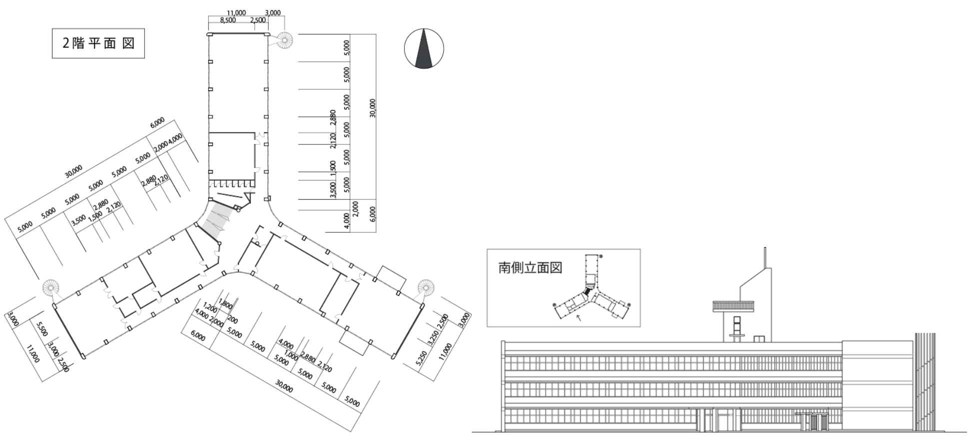

Fig. 2 Second floor plan and south elevation of administration building in F-college

The typical columns in the second story had the sectional size of 500x750mm, 12-D25+2-D16 main bars, the 9mm hoop bars set with the spacing of 250mm. The story height was 3800mm, though the inner height of the columns in the longitudinal direction was 2000mm due to the spandrel walls, as shown in an elevation in Figure 3.2.4, while the column inner height in the span direction was longer up to 3000mm. Therefore, it is estimated that the concentration or unequal distribution of the lateral earthquake loads might have occurred among the three blocks, due to the difference of the inner column heights, because when one of the blocks is in the longitudinal, the others are mostly in span directions, both skewed in thirty degrees, where the shear distribution ratios might have been relatively smaller. The unequal shear distributions might have been one of the reasons why the severe collapse was induced peculiar to this building.

As shown in the Photos 3.2.16 and 3.2.17, most of the slabs around the center stair hall in the third floor had fallen down due to the shear and axial failure of columns in the second story, while the walls at the ends could support the slabs though they inclined towards inside. Also as shown in Photos 3.2.18 and 3.2.19, the spandrel walls in the longitudinal direction could support the floor slabs so that there are spaces enough to survive inside. As shown in Photo 3.2.20, the first-story did not collapse probably owing to a wall in the center hall and amount of main bars increased in the first-story columns. At the time of the earthquake, most of the college staffs working in the building could evacuate before the collapse. It is estimated from the interview that the collapse might have occurred at the end of the main shock, probably around two minutes after they first felt the shaking. Three of them were confined but rescued several hours later so that no casualties were reported. A two-story reinforced concrete building, attached nursery school, in the adjacent area suffered relatively severe damage with axial compression at the column base. The other buildings in the college have been constructed with the current code or retrofitted, which had no damages, slight or minor. The collapsed building was the only one to be retrofitted in the near future.

Photo 1 South overviews of west wing and east wing

Photo 2 Collapse of the second story

SCHOOLS IN MIDDLE FUKUSHIMA

K-net records at Koriyama city

The JMA intensity of the ground motion was defined as VI- at Koriyama city, while the response spectrum was calculated as shown in Fig. 3 from the record at K-net station of Koriyama (FKS018). The maximum acceleration response was close to 2.5G and the maximum velocity response was close to 120kine, which may be regarded as exceeding the very rare level, the level 2 of BSL. The intensity in the region might have been higher than in north Fukushima.

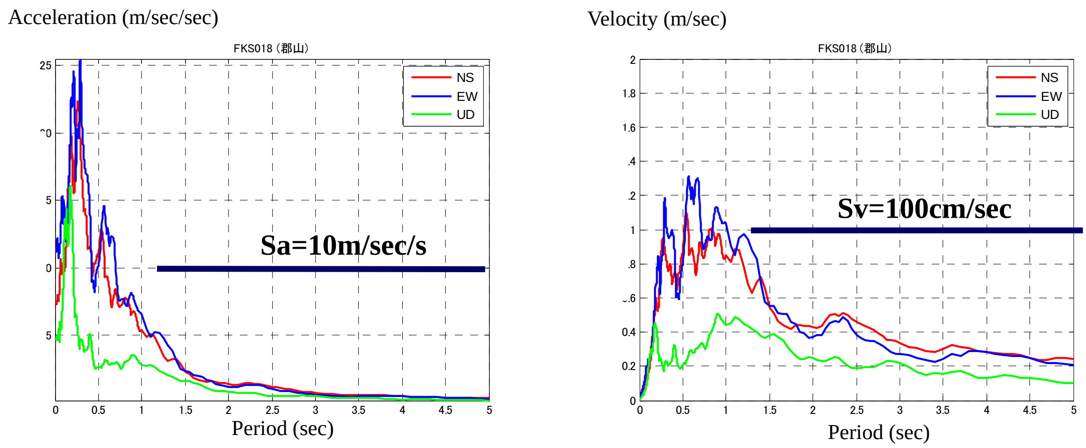

Fig. 3 K-net records at Koriyama city

M-junior high school in Motomiya city

Motomiya city is in the middle area of Fukushima Prefecture where the JMA seismic intensity recorded as V+. M-junior high school is located in a wide field area with a shallow hill rather close to north Koriyama. Therefore, the intensity might have been higher than V+ around the site. Figure 4 shows a plan view of the site with a section of the collapsed building. The school consists of two reinforced concrete buildings, one steel gymnasium and one steel works. Photo 3(a) shows two reinforced concrete buildings, both of which are 3-story buildings built in 1966. One building located in the south of the site, called south building, nearly collapsed and the other building located in the north, called north building, suffered heavy damage due to the earthquake.

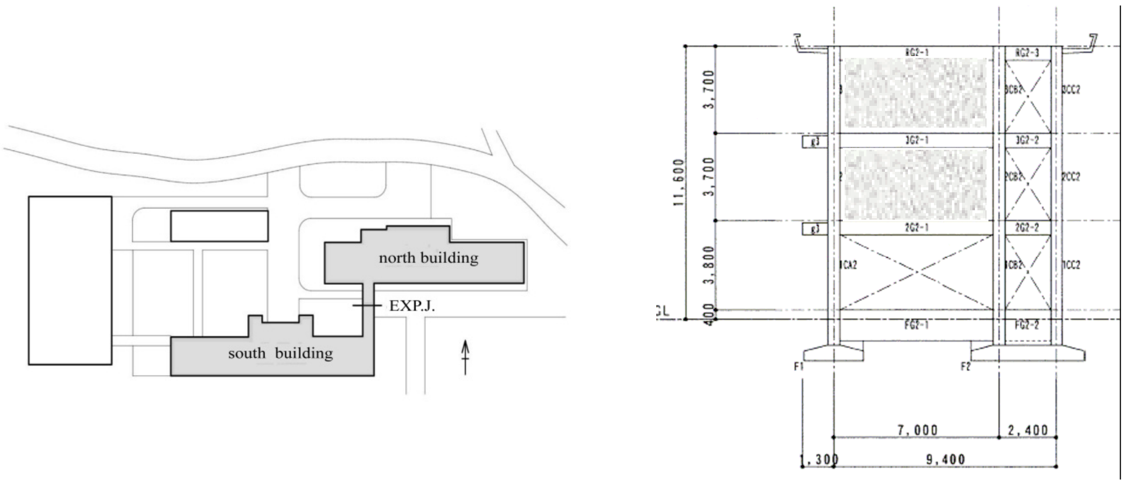

Fig. 4 Plan view of M-junior high school

The south building has typical floor plan as school buildings in the age with five classrooms in a floor. The foundation bases are piles. The structure in the longitudinal direction is moment resisting frame without shear walls. On the other hand continuous shear walls from base to top are located as partitions between classrooms in the span direction except for two frames of the first floor. In other words the shear walls of these two frames are not continuous and isolated columns of the first floor support all axial load generated by walls of upper floors, which could become very high during earthquakes.

The columns are located only at the corners of each classroom with 9m in the longitudinal and 7m in the span direction, respectively. The typical columns in the first floor have the sectional size of 750x500mm and 14-ϕ22 (longitudinal south frame) or 20-ϕ22 (longitudinal middle frame) main bars (SR235). 9mm round hoop bars (SR235) with 90degree hooks are arranged for shear reinforcement with the spacing of 250mm (column center) or 150mm (column end).

Photo 3(b) shows the southern view of the south building. As shown in the photo, the slabs around the center of the building in the second floor had fallen due to the shear and axial failure of columns of the first floor. These columns were isolated columns in the first floor supporting upper shear walls. Therefore, the failure was supposed to be caused by very high axial load generated by walls of upper floors. Photo 4 shows the damage of the isolated column located in the corridor side of the classroom. Although the inner height of the column was long, the column suffered severe damage showing crush of concrete and broken hoop reinforcement around the center of the column with hoop spacing of 250mm. On the other hand, Photo 4 shows the damage of a side column of a barbell type shear wall in the first floor. As shown in the photo the column failed in shear severely in the longitudinal direction but the damage was light comparing to isolated columns due to the presence of the shear wall in the span direction. Photo 3(c) shows the damage of a column with a wing wall of the northern frame in the longitudinal direction. The inner height of the column was short due to the spandrel walls and the column failed in shear severely. The damage grade of the south building may be regarded as near collapse, while the grade of north building was rated as severe from the residual seismic capacity ratio.

Photo 3 (a) South view of the buildings

Photo 3 (b) Collpase of south building

(a) isolated column under walls

(b) side column of barbell wall

(c) column with sidewalls

Photo 4 Shear failure of columns in the first story

K-net records at Sukagawa city

The JMA intensity of the ground motion was defined as VI+ at Sukagawa city, while the response spectrum was calculated as shown in Fig. 5 from the record at K-net station of Sukagawa (FKS017). The maximum acceleration response was close to 2.5G and the maximum velocity response was close to 160kine, which may be regarded as apparently exceeding the very rare level, the level 2 of BSL, in the wide area up to 2 seconds. The intensity might have been higher in the region than in north Fukushima or Koriyama, probably due to the soil amplification.

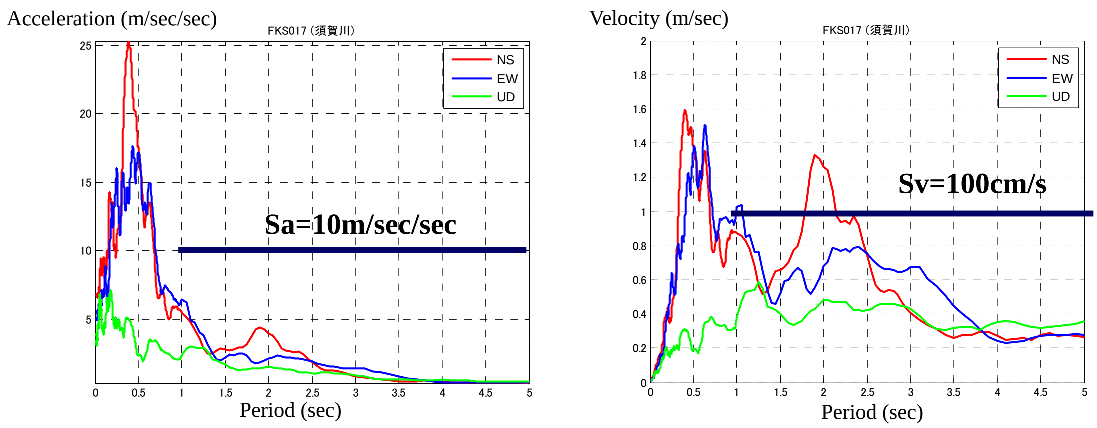

Fig. 5 K-net records at Sukagawa city

S-elementary school in Sukagawa city

The appearance and the site plan of S-elementary school are shown in Photo 5 and Fig. 6. The school consists of four RC buildings with three stories, all of which were built in 1965, which were connected or isolated structurally using expansion joints. Among them, A- and B-buildings were severely damaged. The JMA seismic intensity was VI+ at the station approximately 1 km east from the school. The K-net station shown above was also close to the school. The damage to A-building is described here as an example.

Photo 5 An overview

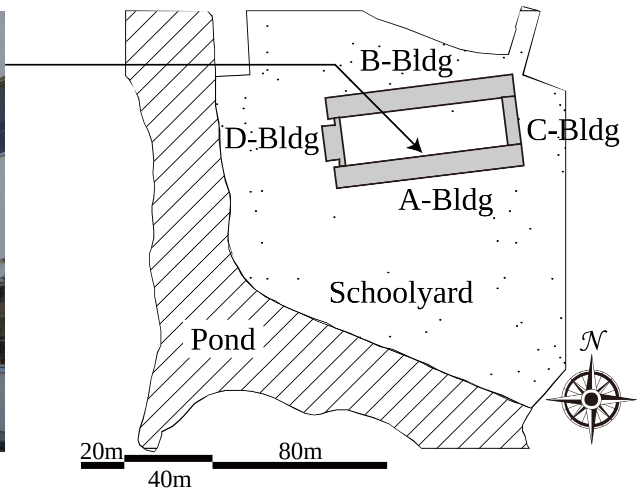

Fig. 6 Site plan

The damage of the building was mainly observed in the longitudinal direction. The I_s-values of the first and second stories in the longitudinal direction had been evaluated as 0.46 and 0.53, respectively. The ultimate base shear coefficient ($C_T S_D$) was 0.47.

In the first story of the building, the damages of the columns with wing-walls were serious as shown in Photo 6(a). These members failed in shear and vertically deformed, the damage rate of which was Grade 5. The space of hoop reinforcements was approximately 300mm. In addition, about 70 % of columns without wing-wall also failed in shear as shown in Photo 6(b). Damage levels of these columns were between Grade 2 and Grade 4. The residual seismic capacity ratio was estimated to be 39% of the original capacity and the damage was graded as severe.

(a) column with wing-wall (b) column without wing-wall

Photo 6 Damage to columns in the first story

SCHOOLS IN SOUTH-EAST FUKUSHIMA

K-net records at Nakoso of Iwaki city

The JMA intensity of the ground motion was defined as VI- at Nakoso of Iwaki city, while the response spectrum was calculated as shown in Fig. 7 from the record at K-net station of Nakoso (FKS012). The maximum acceleration response was close to 1.1G and the maximum velocity response was close to 140kine, which may be regarded as close to the very rare level, the level 2 of BSL, though in the wide frequency area up to 2.5 seconds. The spectral intensity in the region might have been not higher in the short period region but higher in the longer period than the other areas, probably due to the site amplification and also the directivity of waves to the site close to the source.

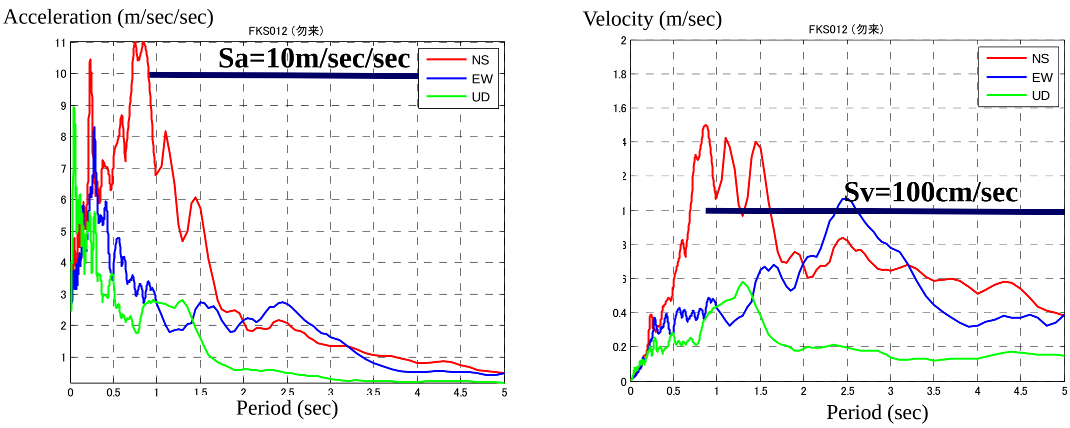

Fig. 7 K-net records at Nakoso city

S-elementary school in Iwaki city

S-elementary school locates in the southern coast of Iwaki City, and the site is on the high plateau locally. The place name of the site means tide watching hill. The investigated classroom building is a reinforced concrete building of the west side part of the buildings shown in photo 7. The building is connected to the east side building through an expansion joint. The investigated building with three stories and was constructed in 1974.

The first floor plan with the damage grade of structural members is shown in Figure 6.2.19. The longitudinal direction of the building is composed of moment resisting frames including secondary walls. In this direction, minor cracks of damage level I or II were observed in many columns and their wing walls. The transversal direction of the building is rigid-frame structure with seismic walls of 100-120 mm in thickness. Diagonal cracks whose maximum damage level was level III were observed in the seismic walls at the first floor.

(a) South side view of the building (b) Shear cracks of a wall in span direction

Photo 7 An overview and damage of S-elementary school

I-high school in Iwaki city

Layout plan of the buildings in I high school is shown in Fig. 8. Buildings for classroom (Building A and Building B) are located on the north and south. Two connecting corridor buildings (Building C and Building D) are connected to Buildings A and B with expansion joint. Building A is four-story reinforced concrete (RC) building, while Building B is three-story, and the Buildings C and D both two-story for connecting corridor and classrooms. These were constructed from 1973 to 1975, portion to portion over the years, as was typical process in the age.

The seismic intensity of JMA scale around the school was reportedly 5-. However, the school is on a small hill with height of 30-40m from the plain land around, and all four buildings suffered moderate or severe damages. The damage level is much higher than another school buildings located just at the foot of the hill. The amplification of the ground motions due to the hill zone effect is estimated from the damages though the quantity should be investigated further.

An overview of the Building A is shown in Photo 8. The north frame of the building was severely damaged, and the columns of the special classroom at the west end of the building in the first floor failed in shear up to the damage index of V. The vertical shortening of the columns was estimated obviously from the deformation of the window frames between them as shown in Photo 9. On the other hand, the shear wall at the west end of the building suffered no serious damages as shown in Photo 10. Some girders with standing wall in the north frame failed in shear. The floor level of Building A was 15cm lower than that of Building C. The residual seismic capacity index was calculated as R=33.3% for the longitudinal direction in the first story, by which the damage was classified into the severe damage.

Some of the columns in the Building B failed in shear, which were classified as the damage rate of IV as shown in Photo 11. The joint between Building B and D was damaged due to pounding. The floor level of Building B was lower than that of Building D by 12cm. The residual seismic capacity ratio was calculated as R=47% for the longitudinal direction of the first story. The damage was classified also into the severe damage.

Columns of the east frame in the first story of the Building C failed in shear evaluated as V with vertical shortening. The residual seismic capacity ratio R= 72% for the longitudinal direction of the first story, by which the damage was classified into the moderate damage. In Building D, shear cracks classified as III were observed in some columns, from which the residual seismic capacity ratio was 73% also classified into the moderate damage. The ground in front of the entrance subsided much.

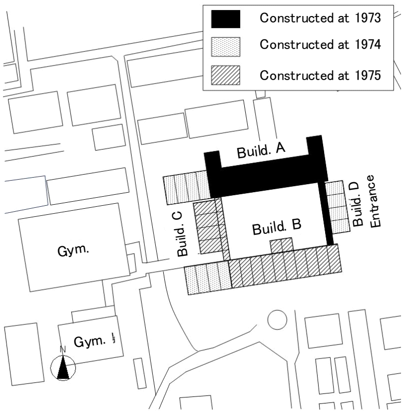

Fig. 8 Location of buildings

Photo 8 An overview of the building A

Photo 9 Shear failure of the first story column at north frame of the building A

Photo 10 West side view of the building A

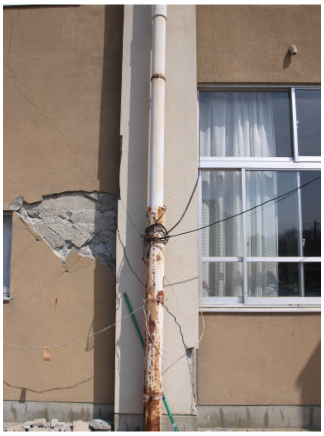

Photo 11 Shear failure of the column at the south frame of the building B

CONCLUSIONS

Typical structural damages to reinforced concrete school buildings observed in Fukushima prefecture after the 2011 East Japan Earthquake were reported with design details of the buildings and also ground motions recorded at K-net stations nearby. The survey was conducted as part of reconnaissance activity of AIJ, Architectural Institute of Japan. The causes of the damages are discussed with peculiar problems to the buildings.

ACKNOWLEDGMENTS

The field survey was conducted as the reconnaissance activity of Architectural Institute of Japan, from April to June 2011, which was requested from the local governments through MEXT, Ministry of Education as part of the rehabilitation procedure on the damaged school buildings. The clerical supports of the staffs in the local governments and MEXT and the technical support of practical engineers on the field survey are gratefully acknowledged. The strong motion data at K-net stations were downloaded from the web at NIED, National Research Institute for Earth Science and Disaster Prevention.

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