Damage of RC Building Structures due to 2011 East Japan Earthquake

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ABSTRACT

This paper presented the investigation of reinforced concrete building structures by 2011 East Japan Earthquake. Generally, reinforced concrete structures in Miyagi region performed very well during the earthquake and effect of seismic retrofit was found in mitigation of damage, although severe damage to some seismically retrofitted buildings was noticed. A good correlation was observed between calculated seismic capacity *Is*-index and observed damage. Moreover, buildings designed according to the current seismic design code had minor damage in its structural members. However, major damage to non structural elements was commonly observed. Some typical damage observed by author’s field survey in Miyagi pref. which is conducted mainly as an activity of the AIJ committee is described. Damage to structural members was not found in most of RC buildings which suffered tsunami, although damage to non structural elements was generally severe. However, severe structural damage induced by devastating tsunami was observed in some buildings.

1 INTRODUCTION

This paper is to describe reconnaissance activities of AIJ, Architectural Institute of Japan, after the 2011 East Japan Earthquake. Typical damages to reinforced concrete school buildings are outlined, both by the ground motion and tsunami waves, based on the field observation data of about two hundred school buildings in Miyagi region.

The school building committee and the reinforced concrete steering committee of AIJ jointly organized a special task committee and working groups on the post-earthquake investigation and damage evaluation of school buildings and educational facilities. The activity was also supported by the facility division, the ministry of education, science, sport and technology (MEXT). The members conducted the field survey from the middle April to the late June based on the request of the local governments in charge of the facility administration.

First, characteristics of strong motions records observed are introduced and compared with previous earthquakes. Secondly, the damage level statistics of the observed buildings and its correlation with the Japanese seismic performance indices are presented. The damage was rated into five levels which are; collapse, severe, moderate, minor, slight and no damage, based on the “Post-earthquake damage evaluation standards of Japan” (JBDPA 2001a). The local government and MEXT judged restoration procedure of repair or reconstruction based on the evaluated damage levels. Finally, typical damage observed is presented. Comments, lessons and recommendations from the damage induced by the Great East Japan earthquake are discussed.

2 GROUND MOTION IN MIYAGI REGION

2.1 General Information of 2011 East Japan Earthquake

Figure 1 shows the location of Miyagi Pref. and epicenter of this earthquake. The 9.0-magnitude (M_W) undersea earthquake occurred on 11 March 2011 at 14:46 JST (Japanese Standard Time) in the western Pacific Ocean at a depth of about 24 km, with its epicenter about 72 km east of the Oshika Peninsula of Miyagi, Japan(AIJ 2011).

2.2 Observed Strong Motion Records

Figure 2 shows the locations of strong ground motion observation stations. Strong motion records at over 30 stations in Miyagi Pref. from this earthquake were obtained by various organizations, including the Japan Meteorological Agency (JMA), K-NET from National Research Institute for Earth Science and Disaster Prevention (NIED), and Building Research Institute (BRI).

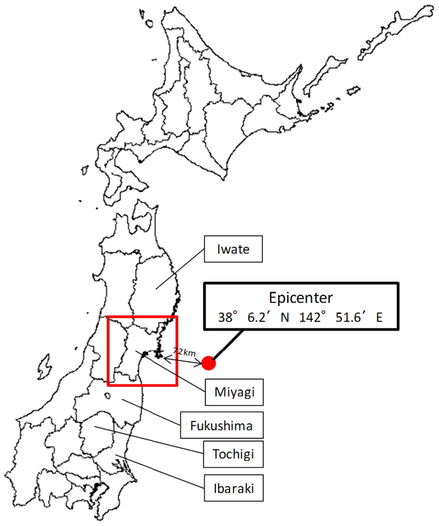


Figure 1. Location of Miyagi Pref. and epicenter of the earthquake

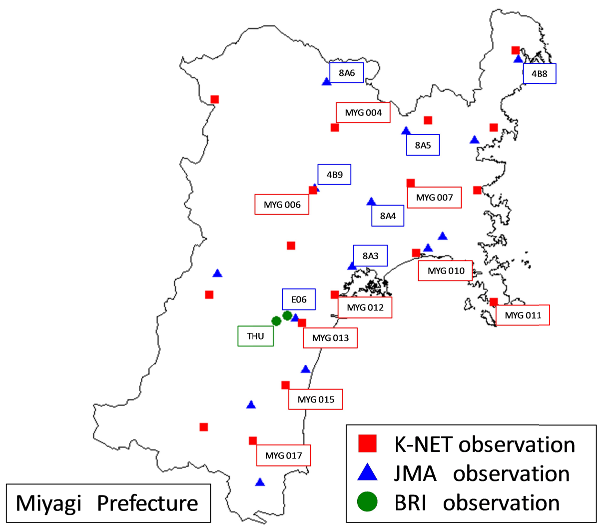


Figure 2. Locations of strong ground motion observation stations in Miyagi

Figure 3 shows acceleration time history at MYG004, MYG013 and 4B9 which recorded large ground acceleration. According to JMA, the earthquake may have ruptured the fault zone from Iwate to Ibaraki Pref. with a length of 500 km and a width of 200 km, therefore both acceleration time histories have plural peaks, and the duration of ground shaking is very long, about 180 sec. Due to long duration, soil liquefaction occurred at several locations from Tohoku district to Kanto district.

Table 1 shows the records of ground motion for intensities over 5.6 using JMA Seismic Intensity Scale observation stations in Miyagi pref. Several records exceed 1000 gal in their peak ground accelerations(PGA) and the maximum recorded acceleration was 2699 gal obtained at MYG004, N-S direction.

Figure 4 shows 5%-damped acceleration response spectrum and comparison with past major earthquakes.MYG004 has extremely high acceleration response, 11852gal, in the very short period(T＜0.5sec). MYG013 and 4B9 has a response spectrum peak around 1sec, also the peak value of their acceleration response is almost as same as JR Takatori at 1995 Kobe and COUNTRY HOSPITAL at 1994 Northridge, which had severe damage.

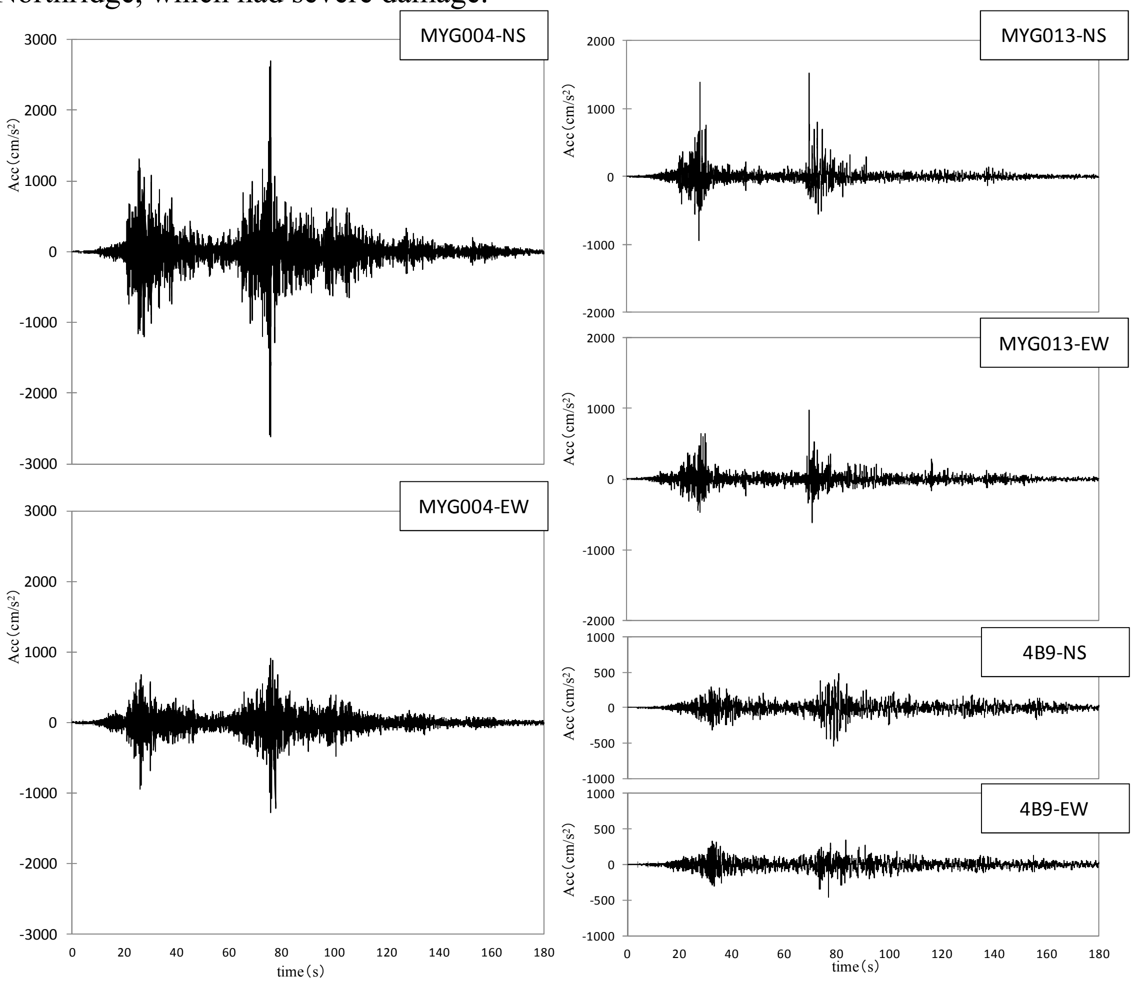


Figure 3. Observed acceleration time history

Table 1. Records of ground motion at each observation stations in Miyagi pref.

Name of station	direction	PGA (gal)	PGV (kine)	JMA Scale※	Name of station	direction	PGA (gal)	PGV (kine)	JMA Scale※
MYG004	NS	2699.1	117.6	6.67	8A3(Matsushima)	NS	359.5	54.6	5.74
	EW	1268.6	51.2			EW	336.9	70.1	
MYG006	NS	444.1	50.6	6.16	8A4(Wakuya)	NS	405.8	87.2	6.02
	EW	571.5	89.1			EW	438.7	80.7	
MYG007	NS	568.0	34.9	5.81	8A5(Tome)	NS	389.6	55.6	5.75
	EW	650.9	34.1			EW	433.9	52.7	
MYG010	NS	458.2	51.5	5.93	8A6(Kurihara)	NS	551.8	49.5	5.70
	EW	377.0	53.1			EW	710.7	35.9	
MYG011	NS	921.0	18.6	5.63	4B8(Kesennuma)	NS	379.1	28.0	5.80
	EW	688.2	35.5			EW	664.4	54.6	
MYG012	NS	758.5	31.6	6.02	4B9(Osaki)	NS	549.6	78.0	6.21
	EW	1969.1	61.8			EW	456.4	86.9	
MYG013	NS	1517.1	84.3	6.38	E06(Sendai)	NS	409.9	53.9	5.69
	EW	982.3	43.0			EW	317.9	54.2	
MYG015	NS	410.7	69.9	5.99	THU	NS	332.8	49.2	5.60
	EW	353.2	52.6			EW	329.8	61.1	
MYG017	NS	317.4	45.6	5.83					
	EW	349.3	49.2						

※JMA Scale＝Japan Meteorology Agency Secimic Intencity Scale

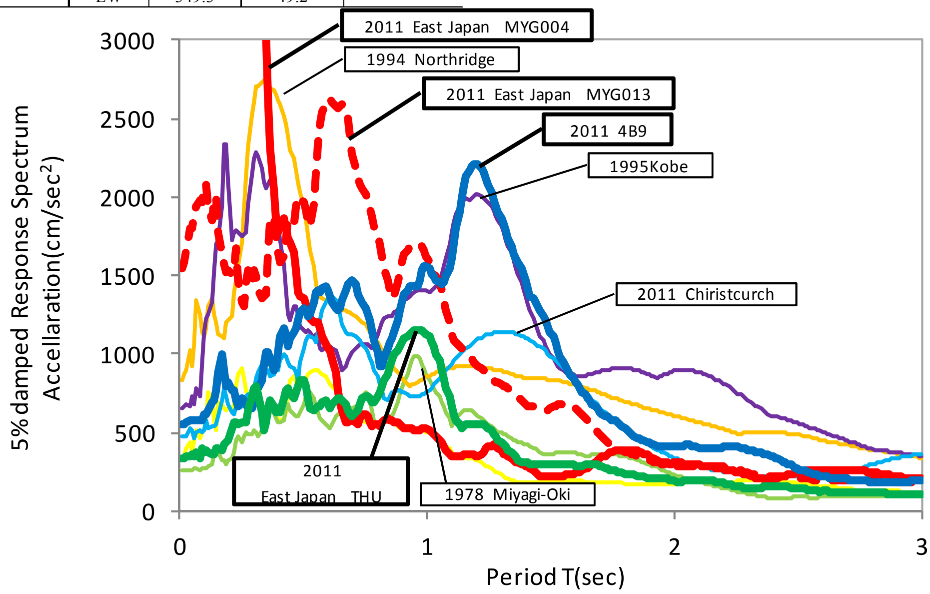


Figure 4. 5%-damped acceleration response spectrum and comparison with past major earthquakes

3 OUTLINE OF DAMAGE TO RC SCHOOL BUILDINGS IN MIYAGI

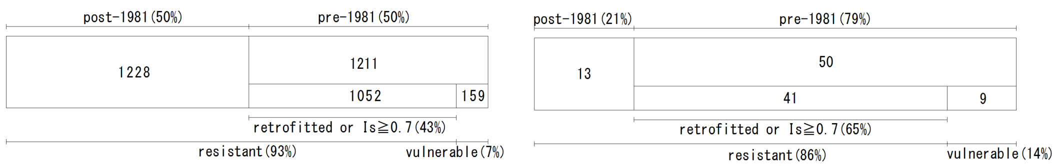
3.1 Damage Statistics

The Japanese seismic design codes for buildings were revised in 1971 and 1981. Specifications such as maximum spacing of hoops of reinforced concrete columns were revised to increase structural ductility in 1971, whereas the verification on the ultimate lateral load carrying capacity of designed structure by limit state or pushover analysis considering deformation capacity of members was required in 1981.In Japan, screening by seismic evaluation and retrofit of vulnerable buildings has been widely applied to existing buildings, especially after the 1995 Kobe Earthquake. As a result, more than 90 percent of school buildings in Miyagi prefecture are reported to be provided with required seismic capacity.

Figure 5 shows seismic capacity statistics classified according to the construction year and seismic capacity. There are 686 elementary and junior high schools which have 2371 school buildings in Miyagi Prefecture (2010, MEXT). Generally one gymnasium, usually steel structure, is located on the average in each school. So, there are about 1600 RC school buildings in Miyagi Pref. Figure 5(b) shows RC school buildings investigated by the AIJ committee after this earthquake. This figure excludes small building such as connecting passage ways and staircases. The percentage of school buildings designed by current seismic design code (post-1981) is 50% of the total number. However, the investigated buildings designed by current seismic design code are only 20% of the whole investigated number. On the other hand, rate of investigated vulnerable buildings is as twice as that of all vulnerable buildings.

Figure 6 shows damage statistics due to ground motion. This figure excludes buildings suffered from tsunami and damage of the foundation. Most of vulnerable buildings (post-1981, Is < 0.7) suffered from moderate to severe damage.

Figure 7(a) shows the damage ratio of 151 RC school buildings in Nada and Higashi-nada Ward, Kobe City suffered from the 1995 Kobe Earthquake. Most of the buildings, which suffered from serious damage, were designed and constructed before 1981, and especially those before 1971 had extensive damage. On the other hand, most new buildings designed according to the current seismic codes enforced in 1981 showed fairly good performance and prevented severe structural damage. As mentioned above, seismic capacity evaluation and strengthening have been applied to existing buildings especially after the 1995 Kobe Earthquake. All RC school buildings in Sendai City were satisfied with the criteria. Figure 7(b) shows the damage ratio of 386 RC school buildings in Sendai City suffered from the 2011 East Japan Earthquake. It is obvious that there is no buildings suffered from over severe damage. In addition , there are few buildings suffered from over moderate damage irrespective of age.



(a) All buildings in Miyagi pref. (b) Investigated RC buildings

Figure5. Seismic capacity statistics of school buildings

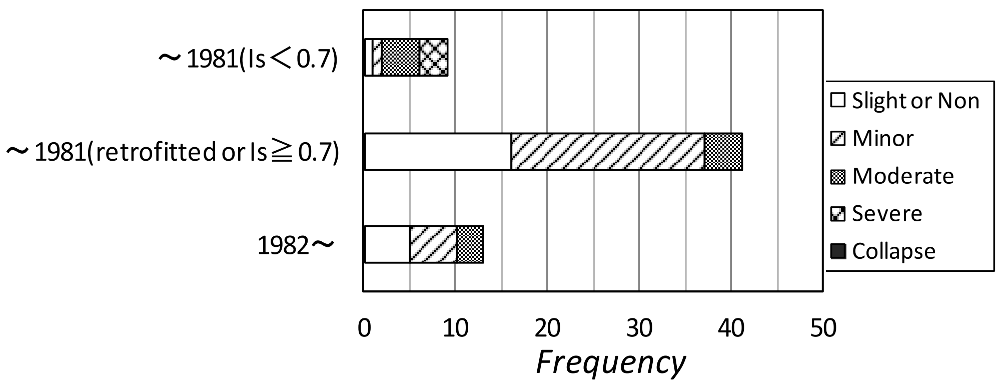
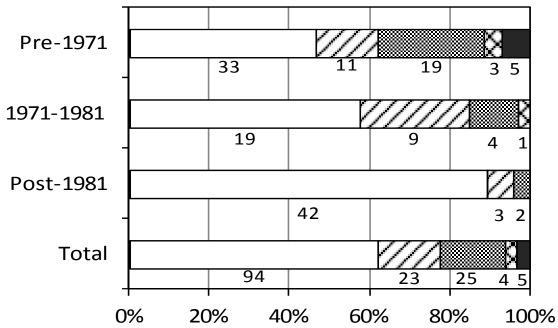
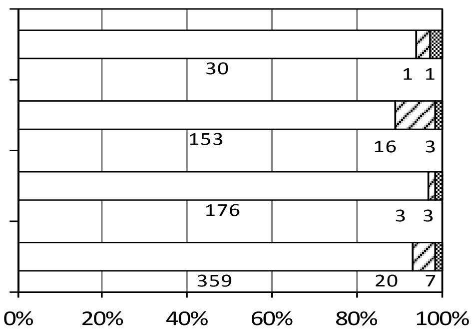


Figure6. Damage level of investigated school buildings in Miyagi Pref.



(a) 1995 Kobe EQ



(b) 2011 East Japan EQ

Figure 7. Damage ratio of RC school building

3.2 Relationship between Seismic Capacity and Damage

Figure 8 shows the relationship between the seismic capacity index (*Is*-Index) and construction age of 32 RC school buildings, where *Is*-Indices of each building are evaluated by the "Japanese Standard for Seismic Capacity Evaluation of Existing Reinforced Concrete Building"(JBDPA 2001b). *Is*-Index can be calculated by Eq.(1) at each story and each direction.

$$Is = E_0 \times S_D \times T \tag{1}$$

E_0 is a basic structural index calculated by Eq.(2).

$$E_0 = \phi \times C \times F \tag{2}$$

C-Index is strength index that denotes the lateral strength of the buildings in terms of shear force coefficient. *F-Index* denotes the ductility index of the building ranging from 0.8 (extremely brittle) to 3.2 (most ductile), depending on the sectional properties such as bar arrangement, member proportion, shear-to-flexural-strength ratio etc. ϕ is story index that is a modification factor to allow for the mode shape of the response along the building height. S_D and T are reduction factors to modify E_0 in consideration of structural irregularity and deterioration after construction, respectively.

The Seismic Evaluation Standard recommends as the demand criterion that *Is*-Index higher than 0.6 should be provided to prevent major structural damage or collapse. This criterion is based on the correlation study from the past earthquake damage and the calculated indices for the damaged buildings(Okada 1998). Past experiences of the big earthquakes reported that buildings with *Is*-Indices higher than 0.6 escaped severe damage or collapse. Is-Index of school buildings is demanded higher value (0.7) than normal buildings. It is because that school buildings require not only the security of safety but also the security of function to use buildings without repairing structural damage after big earthquake. As can be found in Figure 8, *Is*-Indices for most of the buildings were more than 0.7 and prevented severe structural damage even if they were old buildings. Figure 9 shows the relationship between *Is*-Index and damage level indices *R*-Index proposed in "Standard for Post-earthquake Damage Level Classification of Reinforced Concrete Building" (JBDPA 2001a). A good correlation was observed between calculated *Is*-index and observed damage. Most buildings with *Is*-values lower than 0.6 were vulnerable to moderate and severe damage. Most of the buildings with *Is*-values higher than 0.7

avoided severe damage and had minor and slight damage (R > 80). *Is*-Index of 0.7 is generally regarded as an effective demand criterion for screening seismically vulnerable buildings.

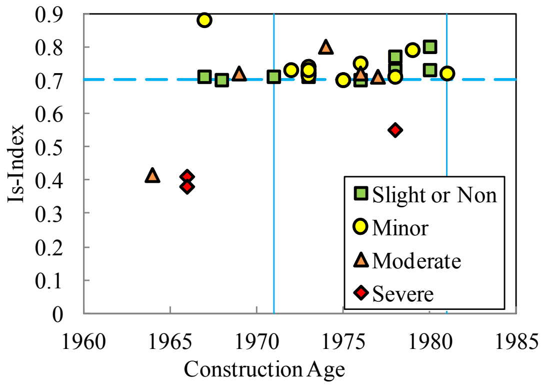


Figure 8. Construction age and *Is*-Indices of RC school buildings

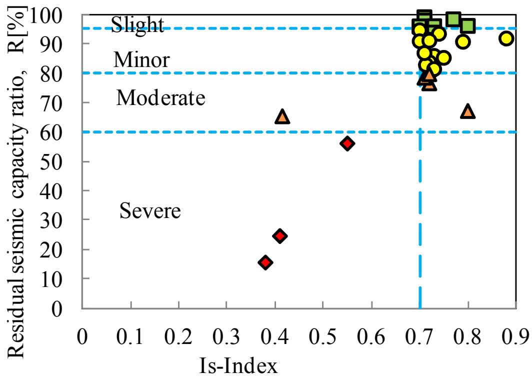


Figure 9. Is-Indices and damage indices

4 TYPICAL OBSERVED DAMAGE

In this chapter, some typical damage observed by author's field survey in Miyagi pref. which is conducted mainly as an activity of the AIJ committee is described. The damage is classified into 2 main classes; Damage by tsunami and damage by ground motion.

4.1 Damage by Ground motion

4.1.1 Severely damaged buildings

Comparatively, the percentage of severely damaged building of the observed buildings is not greater than previous damaging earthquakes. Some of the severely damaged buildings are mentioned below.

Figure 10 hows 3 storied RC school building in Shitigahama town built in 1966. Seismic capacity Is-index of the building was evaluated much lower than the criteria of 0.7, however, it was not retrofitted before the earthquake. Many of its columns and shear walls failed in shear as shown in figure 11and figure 12.

Figure 10. North view of school building

Figure 11. Shear failure in column

Figure 12. Shear failure in shear wall

Figure 13 hows 9-story steel reinforced concrete(SRC) building of Civil Engineering and Architecture building in Tohoku University constructed in 1969, which suffered from minor damage due to the 1978 Miyagi Oki earthquake. Small shear cracks and flexure cracks were observed in main shear walls, adjacent beams and few columns in the 3rd and 4th floor as shown in figure 15(a)(Shiga 1980). Acceleration records were obtained both in 1st and 9th floor.

Figure 13. North view of building in Tohoku Univ.

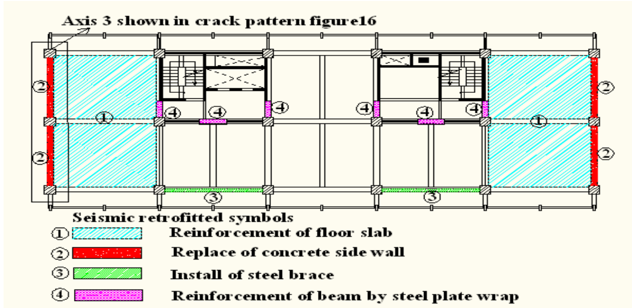
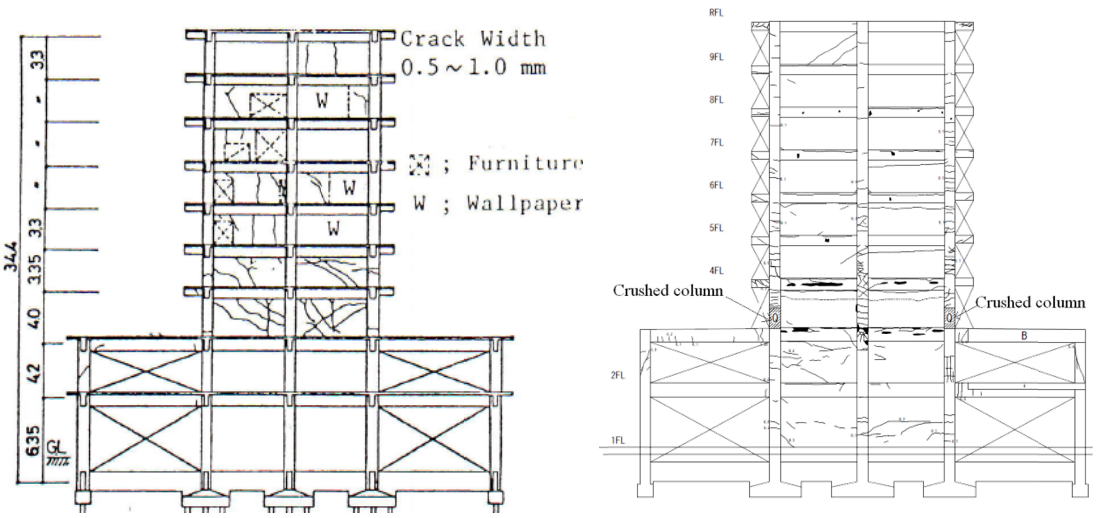


Figure 14. Typical floor plan

In 2001, it was seismically retrofitted by installing framed steel braces to the longitudinal direction, replacement of shear walls in transverse direction and jacketing of adjacent beams with steel plates(see Figure 14). Even though it was retrofitted, it was severely damaged by the 2011 earthquake as shown in figure 15(b). The damage was concentrated in the 3rd story. Boundary columns of shear wall in transverse direction were crushed with fracture and buckling of steel (see Figure 16). Damage to connection between installed shear wall and frame was observed (see Figure 17). One of the reasons for such a severe damage to a retrofitted building would be poor connection between new installed elements and existing structure. Another reason may be strong ground motion at the site especially for period of 1 sec. which is fundamental vibration period of this building as mentioned above in figure 4 as 2011 East Japan THU NS.



(a) 1978 Miyagi Oki Earthquake **(b) 2011 East Japan Earthquake**

Figure 15. Crack pattern of building in Tohoku University

Figure 16. Boundary column of shear wall at 3rd story

Figure 17. Damage to bottom of shear wall in the 3rd story

4.1.2 Seismically retrofitted buildings and seismically evaluated buildings;

Most of the existing buildings in Miyagi prefecture which were design according to the old seismic code were retrofitted. Although, a few retrofitted building suffered severe damage as mentioned in the previous examples, but in general, seismically retrofitted buildings performed well against this earthquake.

Figure 18 shows 3 storied RC building of an elementary school in Sendai city constructed in 1974. The building is divided by expansion joint into west side and east side. Seismic evaluation was carried out to both sides. According to the seismic evaluation, the East side building needed to be retrofitted and the West side was evaluated to have enough seismic capacity and no retrofitting was needed. The East side building was retrofitted by adding framed steel braces and shear walls. By this earthquake, the retrofitted building had only minor damage. On the other hand, the East side building had shear failure in its short columns as shown in figure 19. Shear failure of those short columns was allowed in the seismic evaluation because axial loads could be redistributed to other columns and the building didn't collapse. However, the school couldn't continue using the east side of the building. This issue of functionality is one of important problems. The response spectrum of this area is mentioned above in figure 4 as 2011 East Japan MYG013 NS.

Figure 18. North view of school building in Sendai city

Figure19. Shear Failure in short columns of East side building

4.1.3 Damage of Buildings designed according to the current seismic code

All the school facilities in Sendai city were either designed with the current seismic code or have been already seismically evaluated and retrofitted if necessary.

Severely damaged buildings which may be a threat to life safety were not observed in this survey. However, Moderate damage to some buildings designed according to the early versions (early 1980s) of the current seismic design code was observed. This damage caused the building to be non-functional after the earthquake. Figure 20 shows a typical example of a four storied elementary school building constructed in 1985. This building had a shear failure in one of its walls as shown in figure 21. Beams with shear failure were also noticed as shown in figure 22.

Figure20. North view.

Figure 21. Large shear cracks in wing wall.

Figure 22.Shear failure in beam

4.1.4 Damage to non structural elements:

Major damage to non structural elements was observed in buildings designed according to current seismic design code, although the damage in its structural members was commonly minor. This damage was likely to be observed in high-rise housing buildings.

Figure 23 shows an eleven storied SRC apartment building in Sendai city. It had a minor damage in its structural members. However, many of its non structural partition RC walls around doors and windows were severely damage as shown in Figure 23. Most of the residents of this building were concerned about safety and had to leave. Therefore, this building became unusable due to such damage. In figure 28, large parts of ceiling fell in a gym of a junior high school in Kurihara city fell down.

Figure23. Damage to non structural wall

Figure 24. Large parts of the false ceiling fell down

4.1.5 Damage to foundations;

Settlement and tilting of buildings as a result of liquefaction had occurred in some regions of Miyagi prefecture. Figure 25 shows a junior high school building in Osaki city. The right side of the building was constructed in 1978. The left side was added in 1991. This school rests on a soft ground with pile foundation of 20m in depth. Evidence of liquefaction was seen around the school as shown in figure 26. The right side part had a settlement of about 60 cm, the south part was inclined by angle of 1/25 rad. The newly added part had a settlement of about 10 cm and slightly inclined. The response spectrum of this area is mentioned above in figure 4 as 2011 East Japan 4B9 NS.

Figure 25. Difference in level of Expansion joint

Figure 26. Liquefaction evidence located 3 stair steps from the ground surface.

4.2 Damage by Tsunami;

The Northeast coastal areas have been heavily damaged by Tsunami. However, as for reinforced concrete structures, most of the damage due to tsunami were in its non structural elements such as false ceilings, window and doors.
Figure 27 shows a high school building in Kesennuma city. The flooding reached 3rd floor. Windows, doors ceiling were washed away and classrooms were full of debris.
Figure 28 shows a floor slab that was lifted up and damaged at connections with beams in Ishonamaki city.

Figure 27. Flood reached 3rd floor

Figure 28. Slab uplifted and dismantled from beam

Figure 29. Building overturned by tsunami

Figure 30. piles were pulled out and fractured

In addition, Onagawa town suffered a devastating tsunami, some RC building were overturned from its base as shown in figure 29. Piles were pulled out and buildings overturned as shown in figure 30. Design structures to resist such force were not considered since it the first time to experience such forces and behavior. Such phenomena needs further study.

5. CONCLUSION

This paper presented the investigation of reinforced concrete building structures. Overall, reinforced concrete structures in Miyagi region performed very well during the earthquake, although severe damage to some seismically retrofitted buildings was found. A good correlation was observed between calculated seismic capacity *Is*-index and observed damage. Most of the buildings with *Is*-values lower than 0.6 were vulnerable to moderate and severe damage. Most of the buildings with *Is*-values higher than 0.7 escaped severe damage. Moreover, buildings designed according to current seismic design code had minor damage in structural members. However, major damage to non structural elements was seen even in new buildings.

Damage to structural members was not found in most of RC buildings which suffered tsunami, although damage to non structural elements such as windows, partitions, ceiling boards and equipments was generally severe. However, severe structural damage induced by devastating tsunami was observed. Structural design against tsunami force, which is not taken into account in the current design code, needs to be studied.

REFERENCES

Architectural Institute of Japan (AIJ). (2011), *Preliminary Reconnaissance Report of the 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake* (in Japanese), Maruzen, Japan

BRI Strong Motion Observation, http://smo.kenken.go.jp/ja/smreport/201103111446/

Japan Building Disaster Prevention Association(JBDPA). (2001a). *Standard for Post-earthquake Damage Level Classification of Reinforced Concrete Building.*

Japan Building Disaster Prevention Association(JBDPA). (2001b). *Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings*.

JMA,http://www.seisvol.kishou.go.jp/eq/kyoshin/jishin/110311_tohokuchiho-taiheiyouoki/index.html

NIED K-NET, http://www.k-net.bosai.go.jp/k-net/

OKADA, T., KABEYASAWA T., NAKANO Y., MAEDA M., and NAKAMURA T.(2000). "Improvement of Seismic Performance of Reinforced Concrete School Buildings in Japan -Part 1 Damage Survey and Performance Evaluation after 1995 Hyogo-ken Nambu Earthquake-", *Proceedings of 12th World Conference on Earthquake Engineering*, paper No.2421 (CD-ROM).

Shiga T.,(1980)."performance of the building of faculty of engineering, Tohoku University, During the 1978 Miyagi-Ken-Oki Earthquake", *7th WCEE Instabul*.