Damage Survey on Reinforced Concrete School Buildings in Miyagi after the 2011 East Japan Earthquake

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SUMMARY:
This paper is to describe reconnaissance activities of AIJ, Architectural Institute of Japan, after the 2011 East Japan Earthquake. First, observed typical damages to reinforced concrete school buildings are introduced. Secondly, the damage level statistics of the observed buildings and its correlation with the Japanese seismic performance indices are presented. A good correlation was observed between calculated seismic capacity Is-index and observed damage. Generally, reinforced concrete structures performed well and effect of seismic retrofit was found in mitigation of damage, although severe damage to some seismically retrofitted buildings was noticed. Some buildings are selected for detailed investigation. Finally, comments, lessons and recommendations from the damage induced by the Great East Japan earthquake are discussed.

Keywords: Great East Japan earthquake, RC school buildings, damage survey, seismic evaluation

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 five 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 investigated buildings in Miyagi prefecture 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 (MW) 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

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). 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.

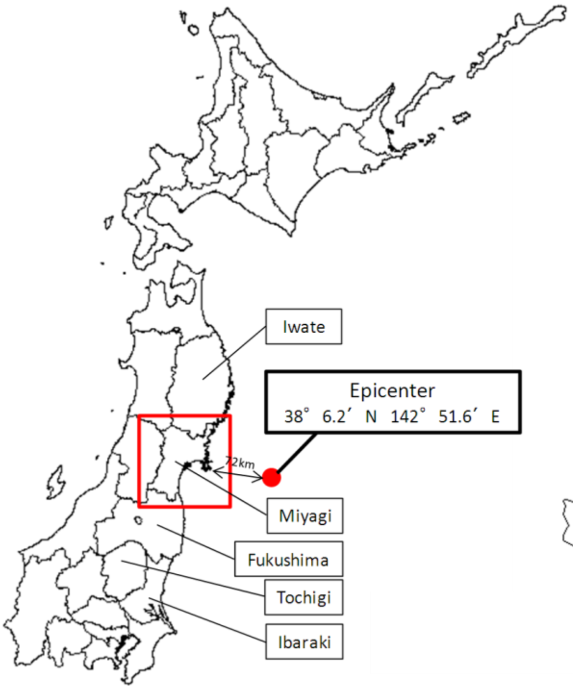


Figure 1. Location of Miyagi Pref. and epicenter of the earthquake

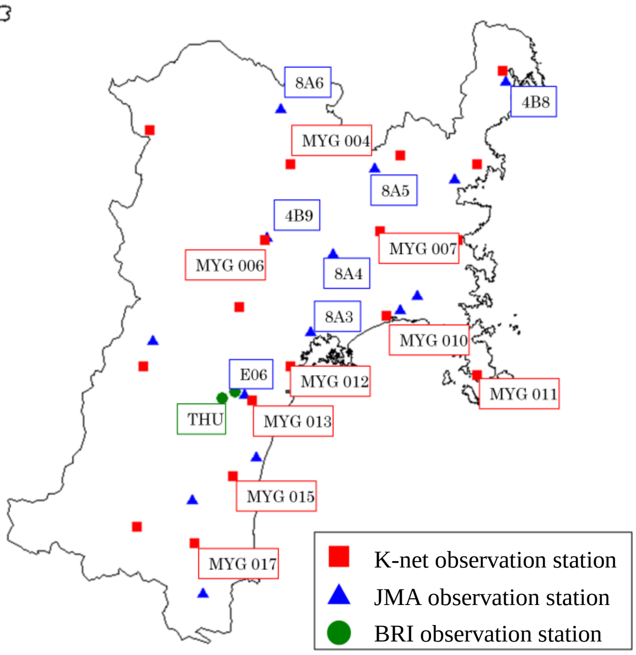


Figure 2. Locations of strong ground motion observation stations in Miyagi Pref.

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 3 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.

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

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

※JMA Scale＝Japan Meteorology Agency Secimic Intencity Scale

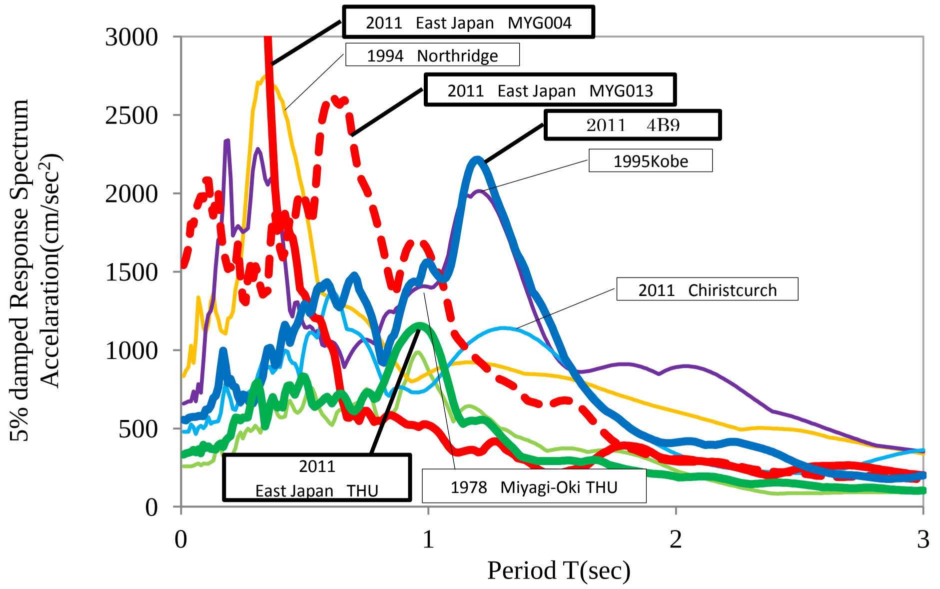


Figure 3. 5%-damped acceleration response spectrum and comparison with past major earthquakes

3. OUTLINE OF DAMAGE TO RC SCHOOL BUILDINGS IN MIYAGI

3.1 Damage Statistics

The Japanese seismic design codes for reinforced concrete 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, seismic capacity evaluation and strengthening have been widely applied to existing buildings especially after the 1995 Kobe Earthquake. By the 2011 East Japan earthquake, all school buildings in main cities of Miyagi Prefecture were seismically evaluated and most of vulnerable buildings were retrofitted (see Figure.4).

Figure.5 shows the damage ratio of 151 reinforced concrete school buildings located in Kobe city in 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. Figure.6 shows the damage ratio of 538 RC school buildings in main cities of Miyagi Prefecture suffered from the 2011 East Japan Earthquake. The buildings suffered from tsunami and damage of the foundation were excluded in the Figure. There were no collapses. Although there are few buildings suffered from over moderate damage, the effect of seismic retrofit can be obviously found in comparing with seismically retrofitted and un-retrofitted buildings. In addition, the ratio of serious damage for post-1981 or retrofitted is much smaller than that in 1995 Kobe Earthquake, it suggest that ground motion in 2011 East Japan Earthquake was not severe as 1995 Kobe Earthquake.

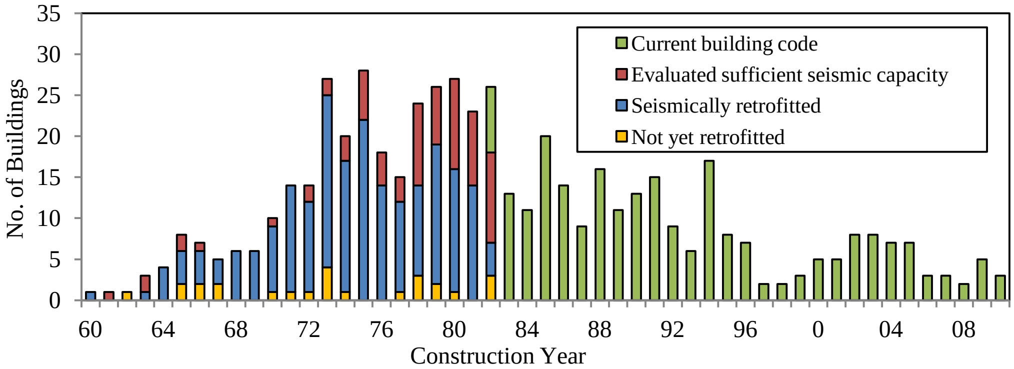


Figure 4. Construction year and progress of seismic retrofit of investigated RC school building in main cities in Miyagi Prefecture

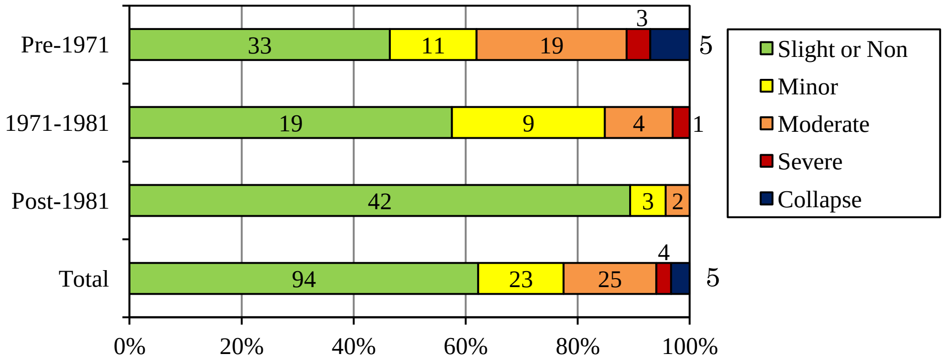


Figure 5. Damage ratio of RC school building in 1995 Kobe earthquake

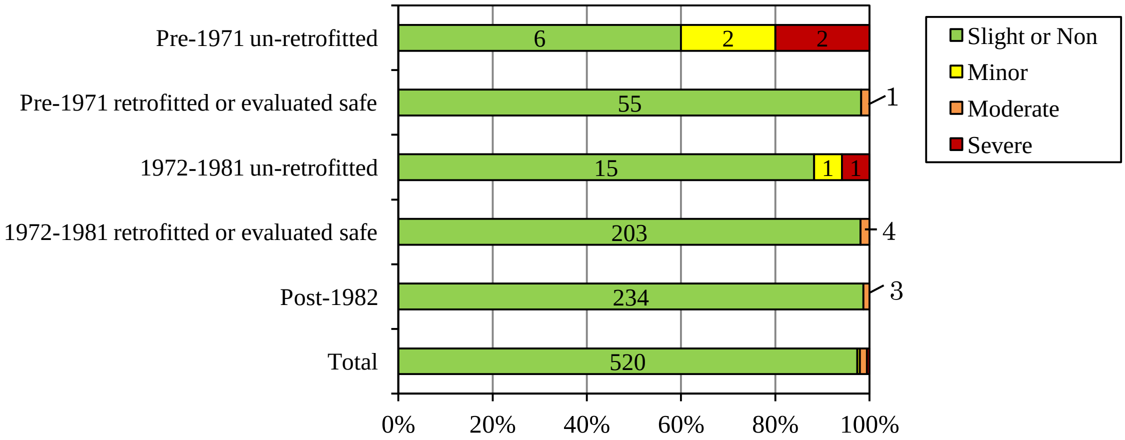


Figure 6. Damage ratio of RC school buildings of main cities of Miyagi Pref. 2011

3.2 Correlation between Seismic Capacity and Damage

Figure.7 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 according to the “Japanese Standard for Seismic Capacity Evaluation of Existing Reinforced Concrete Building”(JBDPA 2001b). *Is*-Index can be calculated by Eqn.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 Eqn.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. Ø 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 damaging 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. Figures 7 and 8 show all the buildings with Is-index lower than the criteria suffered from severe damage. As mentioned earlier, over 90% of RC school buildings have been already seismically retrofitted, *Is*-Indices for most of the buildings were more than 0.7 and prevented severe structural damage even if they were old buildings. Figure.8 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 or slight damage (residual seismic capacity ratio *R*> 80). *Is*-Index of 0.7 is generally regarded as an effective demand criterion for screening seismically vulnerable buildings.

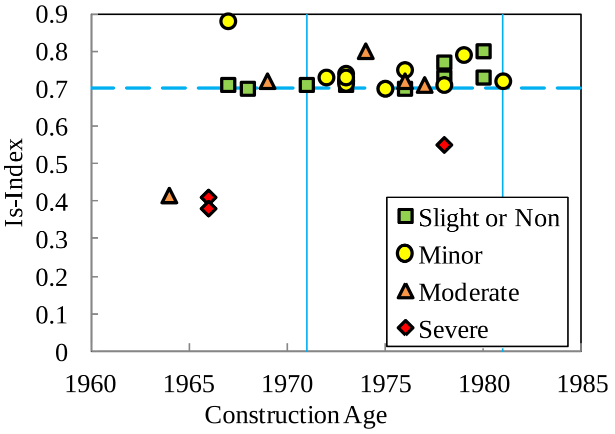


Figure 7. Construction age and *Is*-Indices of RC school buildings

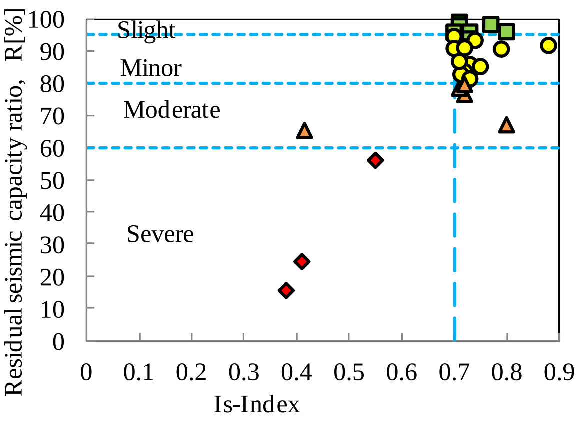


Figure 8. Is-Indices and damage indices

4. TYPICAL OBSERVED DAMAGE

4.1 Severely Damaged Buildings Due To Ground Motion

Comparatively, the percentage of severely damaged building of the investigated school buildings is not greater than previous damaging earthquakes such as 1995 Kobe Earthquake. Some of the severely damaged buildings are mentioned below.

Figure 9 shows 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. Seismic retrofit was planned for the buildings, however, it was not yet conducted before the earthquake. Many of columns and shear walls failed in shear as shown in Figure 10 and Figure 11.

Figure 9. Overall view of damaged school building

Figure10. Shear failure in column

Figure11. Shear failure in shear wall

4.2 Seismically retrofitted buildings and seismically evaluated buildings

Most of the existing buildings in Miyagi prefecture which were designed according to the old seismic code were retrofitted. In general, seismically retrofitted buildings performed well against this earthquake. However, few buildings had moderate or severe damage. Some cases were chosen for detailed investigation.

Figure 12 shows 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 flexural cracks were observed in exterior 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 by BRI both in 1st and 9th floor of the building. The response acceleration of 1st floor in the NS direction is shown in figure 3 and marked as 2011 East Japan THU. Response acceleration of 1st floor in the NS direction of 1978 Miyagi Oki earthquake is also shown in figure 3.

Figure 12. Civil Engineering Building in Tohoku Univ.

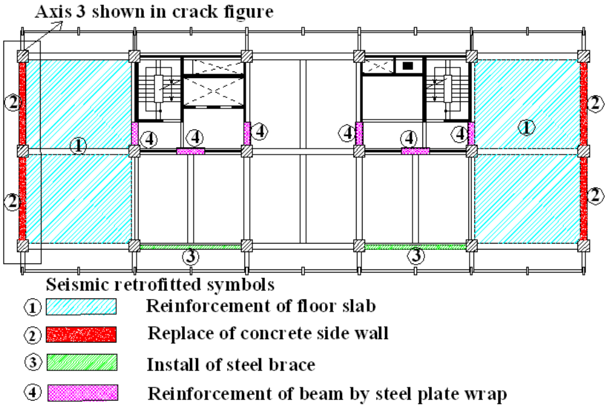
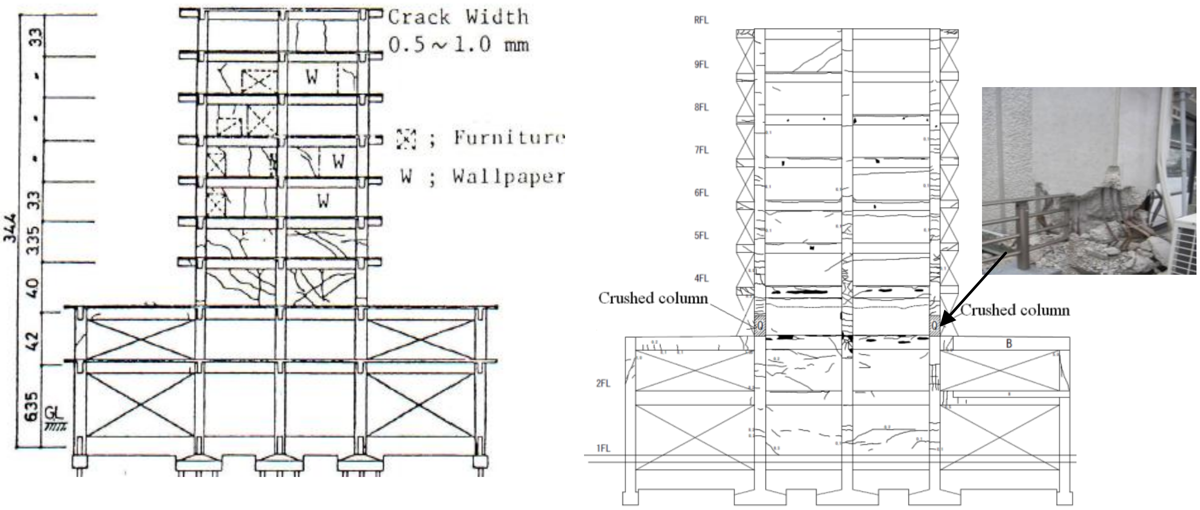


Figure 13. Typical floor plan and outline of retrofit

Originally, seismic capacities *Is*-indices were insufficient for the criteria of Is =0.7 as shown in Table 2. Table 2 shows *Is*-indices in transverse direction (Y-direction) in lower stories. There exist many residual cracks induced by previous earthquakes such as 1978 Miyagi Oki earthquake so that quite low age factor T=0.85 was employed in the evaluation. As can shown in Table 2, *C*-index, which is lateral strength of the building in terms of story shear coefficient, is relatively low but large ductility was estimated. In 2001, the building was seismically retrofitted by installing framed steel braces in the longitudinal direction, replacement of RC shear walls in transverse direction and jacketing of adjacent beams with steel plates (see Figure13). The main scheme of the seismic retrofit was mainly to increase lateral strength and ductility of the structure. The building was estimated as a relatively ductile structure, so that ductile members were selected for new installing elements in seismic retrofit. Although seismic capacities *Is*-indices after retrofit exceeded the criteria of Is=0.7, as shown in Table 3, *C*-indices for most ductile member group were about 0.3, which in minimum requirement of base shear coefficient for RC ductile moment frame structures.

Even though it was retrofitted, it was severely damaged by the 2011 earthquake as shown in Figure14(b). There was strong ground motion at the site at periods close to 1 sec, which is the fundamental vibration period measured for this building during the earthquake. Boundary columns failed in compression and the connection of walls to beam also failed indicating that the ductility of the shear walls was not increased as expected in the seismic retrofit. This may have been caused by poor connections between the wall webs (which were replaced during the retrofit) and the surrounding beams and columns.



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

Figure14. Crack pattern of building in Tohoku University

Table 2. Seismic evaluation before retrofit for the Y-direction (short direction)

Floor No.	**C (groups)**	**F (groups)**	**E_0**	**S_D**	**T**	**Is**
1	0.17	1.27	0.69	0.9	0.85	**0.53**
	0.19	3.26				
2	0.35	1.27	0.71	1	0.85	**0.60**
	0.18	3.50				
3	0.01	1.27	0.67	1	0.85	**0.57**
	0.16	2.00				
	0.21	3.50				
4	0.14	2.00	0.69	1	0.85	**0.59**
	0.24	3.50				

Table 3. Seismic evaluation after retrofit for the Y-direction (short direction)

Floor No.	**C (groups)**	**F (groups)**	**E_0**	**S_D**	**$C_T.S_D$**	**T**	**Is**
1	0.2	1.27	0.81	0.9	0.2	1	**0.730**
	0.03	2.00					
	0.01	3.34					
	0.22	3.50					
2	0.21	1.27	1.06	1	0.32	1	**1.06**
	0.09	2.00					
	0.32	3.50					
3	0.20	1.27	0.82	1	0.27	1	**0.82**
	0.03	2.00					
	0.27	3.50					
4	0.13	1.27	0.86	1	0.29	1	**0.86**
	0.29	3.50					

Figure 15 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 (see Figure 18) and the West side was evaluated to have enough seismic capacity and no retrofitting was needed. The Is-index for West side building depends on ductility (F=1.75) to reach the of Is> 0.7 which is the criteria in Japan (see Figure. 17). 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 West side building had shear failure in its short columns as shown in Figure 16. 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. This building wasn't retrofitted since it's judged that there is no threat to life safety. However, the school could not use this building after the earthquake and repairing expenses would be relatively high if compared to the retrofitting expenses for a better performance. This issue of functionality is one of important issues that require more attention. The response spectrum of this area is mentioned above in Figure 3 as 2011 East Japan MYG013 NS.

Figure 15. North view of school building

Figure 16. Shear failure in column

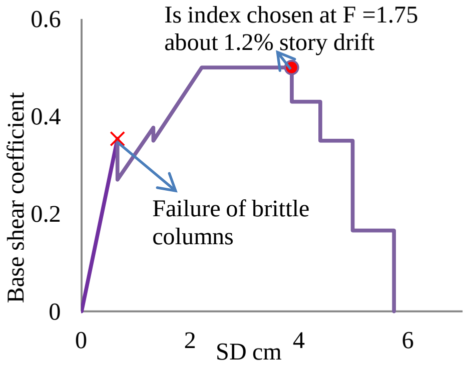


Figure 17. 1st story seismic evaluation results of West side Building

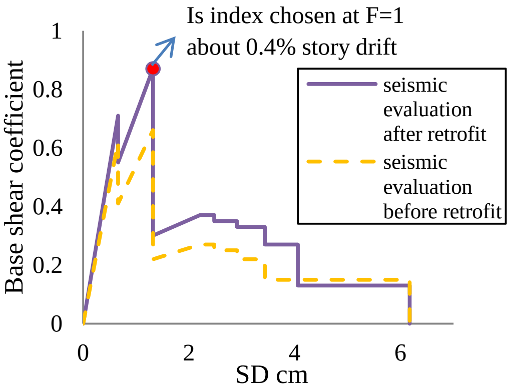


Figure 18. 1st story seismic evaluation results of East side Building

4.3 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. Figure 19 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 20. Beams with shear failure were also noticed as shown in Figure 21.

Figure 19. North view of building

Figure 20. Shear failure in wing wall

Figure 21. Shear failure in beam

4.4 Damage to non structural elements

Major damage to non structural elements was observed even 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.

In Figure 22, large parts of ceiling fell in a gym of a junior high school in Kurihara city fell down. Figure 23 shows a damaged masonry wall of which some concrete blocks fell down. Such damage could be a life threat.

Figure 22. False ceiling fell down

Figure 23. Partial collapse of concrete blocks partition wall

4.5 Damage to foundations

Settlement and tilting of buildings as a result of liquefaction had occurred in some regions of Miyagi prefecture. Figure 24 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. 25. 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 3 as 2011 East Japan 4B9 NS.

Figure 24. Settlement of school building in Osaki City

Figure 25. Liquefaction evidence located 3 stair steps from the ground surface.

4.6 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 was in non structural elements such as false ceilings, window and doors. Figure 26 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 27 shows a floor slab that was lifted up and disconnected from beams in Ishonamaki city.

Figure 26. Flood reached 3rd floor

Figure 27. Slab uplifted and dismantled from beam

5. CONCLUSION

This paper presented the investigation of reinforced concrete building structures. Japanese RC building showed good performance for saving lives on Great Japan EQ. However, a number of retrofitted buildings and buildings that had been evaluated to be safe had to be evacuated after the earthquake. Some of these buildings are going to be demolished because the repairs are too costly. This issue is one that requires attention.

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.

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