Damage due to Earthquakes and Improvement of Seismic Performance Reinforced Concrete Buildings in Japan

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Abstract: Japan, which is one of the most earthquake prone countries in the world, has suffered from damaging earthquakes repeatedly and learned lessons from damages. First, history of damages to existing reinforced concrete (RC) buildings due to previous earthquakes and seismic code revision are summarized. Secondly, basic concept and procedure of Japanese seismic evaluation method were outlined and seismic capacity index, I_s, of buildings suffered Kobe Earthquake. Strong correlation between damage level and seismic capacity index, I_s, was found. After the 1995 Kobe Earthquake, the law for promotion of seismic evaluation and retrofit was enforced based on the lessons learnt from the damage and investigation. Seismic evaluation and retrofit were widely applied to existing RC buildings in all over Japan and contributed to improvement of seismic capacities of existing RC buildings designed by old seismic code. The improvement was proved by recent major earthquakes such as 2011 Tohoku Earthquake and 2016 Kumamoto Earthquake. Typical damage pattern, failure modes and tendency in each earthquake were introduced and effectiveness of seismic evaluation and retrofit was discussed.

Keywords: RC existing building, seismic evaluation, seismic retrofit, earthquake damage

1. Introduction

Japan, which is one of the most earthquake prone countries in the world, has suffered from damaging earthquakes repeatedly and learned lessons from damages. First, history of damages to existing reinforced concrete (RC) buildings due to previous earthquakes and seismic code revision are summarized. Secondly, basic concept and procedure of Japanese seismic evaluation method were outline and seismic capacity index, $I_{s,}$ of buildings suffered Kobe Earthquake. Strong correlation between damage level and seismic capacity index, I_s, was found. After the 1995 Kobe Earthquake, the law for promotion of seismic evaluation and retrofit was enforced based on the lessons learnt from the damage and investigation. Seismic evaluation and retrofit were widely applied to existing RC buildings in all over Japan and contributed to improvement of seismic capacities of existing RC buildings designed by old seismic code.. As a result of upgrade of seismic capacity for old buildings, damage to structural elements was remarkably decreased. Typical damage pattern, failure modes and tendency in each earthquake were introduced and effectiveness of seismic evaluation and retrofit was discussed.

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.

2. History of damaging earthquake and seismic code revision in Japan

Japan has suffered from earthquakes repeatedly and seismic code was revised based on the lessons. Table 1 shows history of damaging earthquakes and seismic code revision. The 1923

Great Kanto Earthquake induced catastrophic damage to buildings in Tokyo area and casualties of over 140,000. It resulted in introduction of seismic design to building design code in 1924. Japanese Building Standard Law was enacted in 1950, five years after the end of the World War II. Working stress design was the basic concept of seismic design with seismic force of 20 percent of building weight. Allowable stresses were nominal yield strength of rebar and two third of concrete compressive strength.

The 1968 Tokachi-oki earthquake induced heavy damage and collapse of many reinforced concrete (RC) buildings as shown Figure 1. Brittle shear failure in columns were most typical damage and considered the main reason of collapse. Therefore, requirement of hoop spacing in columns were upgraded from 30cm to 10cm in order to prevent shear failure in 1971. At the same time, Japanese government established a national project for improvement of seismic capacity and seismic design including universities, national research institutes and construction companies. As a result of ten years project, ultimate state design was introduced to seismic code in 1981 revision. In addition, Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings (Seismic Evaluation Standard) was published by Japan Building Disaster Prevention Association (JBDPA) in 1977.

After code revision in 1981, number of casualty by earthquake disaster was remarkably reduced, except by tsunami, as shown in Table.1. However, the 1995 Great Hansin Earthquake (Kobe Earthquake) revealed vulnerability of existing buildings designed by old seismic code. Figure 2 shows damage statistics for RC school buildings in affected area (Okada et al. 2000). Significant difference in damage ratio was found between construction ages. Forty percent of the buildings before 1971 suffered moderate or severer damage. On the other hand, damage to the building after 1982 was limited and ninety percent remained slight or less damage. It is obvious evidence of a success of improvement of seismic capacity of buildings in japan by the seismic code revision in 1971 and 1981. Moreover, importance of seismic evaluation and retrofit was widely recognized. Law for Promotion of seismic Evaluation and Retrofit was enacted at the end of 1995, and it was a start point of general application of seismic evaluation and retrofit for existing buildings.

Table 1 History of damaging earthquakes and seismic code revision in Japan

year	Name earthquake / **seismic code revision	Magnitude (M)	casualty
1891	Nohbi EQ	8.0	7273
1923	Kanto EQ	7.9	140,000
1924	** Building code revision (introduction of seismic design)		
1948	Fukui EQ	7.3	3895
1950	** Building Standard Law (working stress design)		
1964	Niigata EQ	7.5	26
1968	Tokachi-oki EQ	7.9	52
1971	** Seismic code revision		
1975	Ohita Chubu EQ	6.4	0
1977	Seismic Evaluation Standard		
1978	Miyagi-ken-oki EQ	7.4	28
1981	** Revision of seismic code (ultimate strength design)		
1983	Nihon-kai Chubu EQ	7.7	104 ***
1993	Kushiro-oki EQ	7.8	2
	Hokkaido-nansei-oki EQ	7.8	230 ***
1994	Hokkaido-toho-oki EQ	8.1	0
1995	Sanriku Far-off EQ	7.5	3
	Kobe EQ	7.2	6434
1995	** Law for Promotion of Seismic Evaluation and Retrofit		
2000	** Revision of seismic code (Performance based design)		
2004	Niigata Chuetsu EQ	6.8	68
2008	Iwate Miyagi EQ	7.2	17
2011	Great East Japan EQ	9.0	18446 (incl. missing)
2016	Kumamoto EQ	7.3	88

Fig. 1 - Collapse of RC buildings in 1968 Tokachi-oki Earthquake

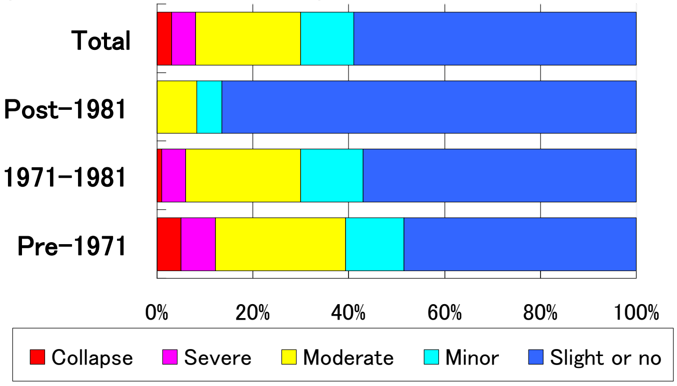


Fig. 2 - Damage statistics of RC school buildings (1995 Kobe Earthquake)

3. Seismic evaluation and retrofit for existing RC buildings

The Japanese Seismic Evaluation Standard (JBDPA, 1977) consists of three procedures of different levels, i.e., first, second and third level procedures. The first level procedure is the simplest but most conservative since only the sectional areas of columns and walls and concrete strength are considered to calculate the strength, and the inelastic deformability is neglected. In the second and third level procedures, the ultimate lateral load carrying capacity of vertical members or frames is evaluated using material and sectional properties together with reinforcing details based on field inspections and structural drawings.

In the Standard, the seismic performance index of a building is expressed by the I_s index for each story and each direction, as shown in Eq. (1)

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

where, E_0 : basic structural seismic capacity index calculated from the product of strength index (C), ductility index (F), and story index (I_s) at each story and each direction when a story or building reaches the ultimate limit state due to lateral force, i.e., .

Strength index C: index of story lateral strength, calculated from the ultimate story shear in terms of story shear coefficient.

Ductility index F: index of ductility, calculated from the ultimate deformation capacity normalized by the story drift of 1/250 when a standard size column is assumed to fail in shear. F depend on the failure mode of the structural members and their sectional properties such as bar arrangement, shear-span-to-depth ratio, shear-to-flexural-strength ratio, etc. In the standard, F is assumed to vary from 1.27 to 3.2 for ductile columns, 1.0 for brittle columns and 0.8 for extremely brittle short columns (shear-span-to-depth ratio less than 2).

ϕ: index of story shear distribution during earthquake, estimated by the inverse of design story shear coefficient distribution normalized by base shear coefficient. A simple formula of is basically employed for the i-th story level of an n-storied building by assuming inverted triangular shaped deformation distribution and uniform mass distribution.

S_D: factor to modify E_0-Index due to stiffness discontinuity along stories, eccentric distribution of stiffness in plan, irregularity and/or complexity of structural configuration, basically ranging from 0.4 to1.0

T: reduction factor to allow for the deterioration due to age after construction, fire and/or uneven settlement of foundation, ranging from 0.5 to 1.0.

Figure 3 shows the relationship between the second level seismic performance indices I_{s2} of RC school buildings suffered from Kobe Earthquake and construction age. The Seismic Evaluation Standard recommends as the demand criterion of the second level procedure that I_{s2} Index higher than 0.6 should be provided with buildings 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. Past experiences of 1968 Tokachi-Oki, 1978 Miyagi-ken-Oki and other earthquakes reported that buildings with I_{s2} indices higher than 0.6 suffered from moderate or less damage. As can be found in Figure 2, I_{s2} indices for most of the buildings constructed before 1971 were less than 0.6, whereas they were more than 0.6 for those constructed after 1981. As mentioned earlier, the Japanese seismic design codes for buildings were revised in 1971 and 1981. The results shown in Figure. 3 indicated that seismic capacities of reinforced concrete school buildings in Japan were successfully improved due to the revisions of seismic design codes.

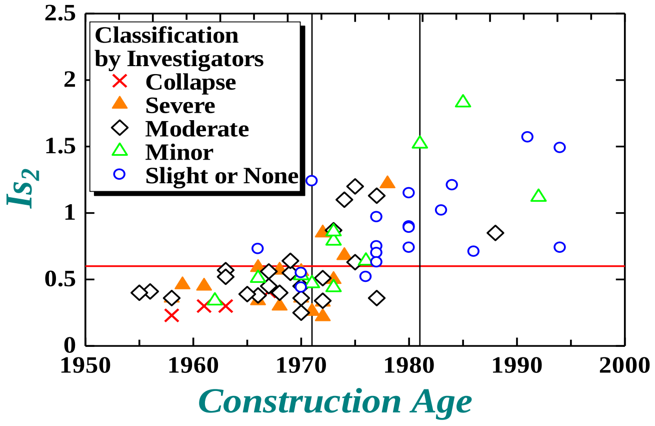


Fig. 3 - I_s-index and construction age of RC school buildings (1995 Kobe Earthquake)

4. Damage to RC building due to recent major earthquakes

4.1. Damage due to 2011 Great East Japan Earthquake

The Great East Japan Earthquake struck Tohoku region on March 11, 2011. Huge tsunami attacked coastal area and more than 20,000 people were killed. On the other hand, damage to building structure was relatively limited. That is attributed to seismic evaluation and retrofit of vulnerable buildings that has been widely applied to existing buildings, as mentioned in chapter 2, after the 1995 Kobe Earthquake. As a result, more than 90 percent of school buildings in Miyagi prefecture, which are located in the centre of Tohoku region and nearest prefecture from epi-center, are reported to satisfy the criteria of the seismic evaluation standard (Maeda et al, 2012a).

Figure. 4 shows the damage ratio of 520 RC school buildings in Miyagi Prefecture suffered from the 2011 East Japan Earthquake. In the figure, first generation (pre-1971) and second generation (1972 to1981) buildings are classified into two groups; a) un-retrofitted and b) retrofitted or evaluated safe. Tendency of damage ratio of un-retrofitted is similar with those found in the 1995 (Fig. 1), although damage ratio of severer damage is fewer. 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. Most of the buildings before 1981, if retrofitted or evaluated safe, escaped damage as ca be found in the Figure 4. It is an evidence of effectiveness of seismic evaluation and retrofit.

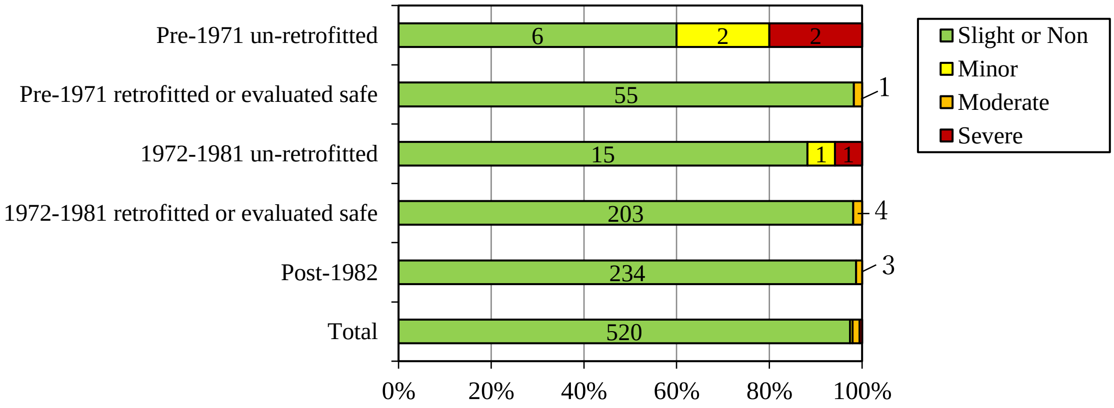


Fig. 4 - Damage statistics of RC school buildings in Miyagi prefecture

The Seismic Evaluation Standard recommends as the demand criterion that I_s-Index higher than 0.6 should be provided to prevent major structural damage or collapse. I_s-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 5, I_s-Indices for most of the buildings were more than 0.7 and prevented severe structural damage even if they were old buildings. Figure 6 shows the relationship between I_s-Index and damage level indices *R*-Index proposed in “Standard for Post-earthquake Damage Level Classification of Reinforced Concrete Building” (JBDPA 1990). A good correlation was observed between calculated I_s-index and observed damage. Most buildings with I_s-values lower than 0.6 were vulnerable to moderate and severe damage. Most of the buildings with I_s-values higher than 0.7 avoided severe damage and had minor and slight damage (R > 80). I_s-Index of 0.7 is generally regarded as an effective demand criterion for screening seismically vulnerable buildings.

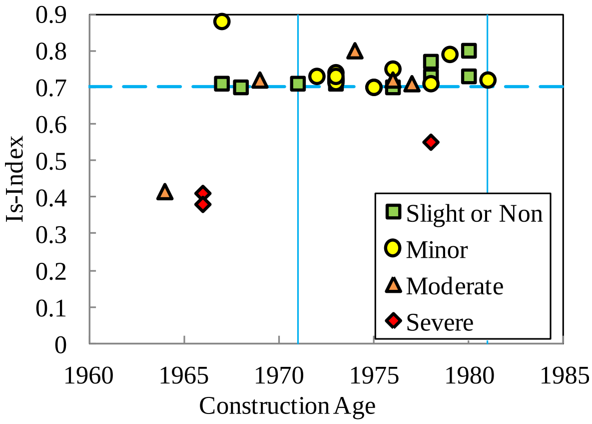


Fig. 5 - *Is*-index and construction age of RC school buildings (2011 East Japan Earthquake)

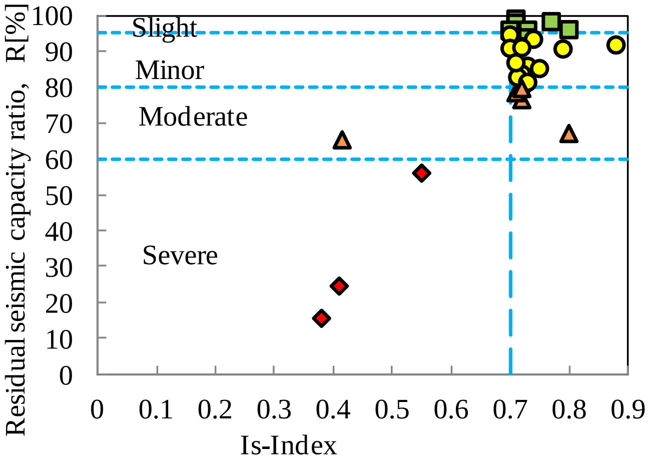


Fig. 6 - *Is*-index and damage level of RC school buildings (2011 East Japan Earthquake)

As mentioned above, most of seismically retrofitted RC buildings performed well against the 2011 East Japan earthquake. However, few retrofitted building suffered moderate damage. Figure 7 shows three 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 west side building had shear failure in its short columns as shown in Figure 7b). 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.

a) General view of the building

b) Shear failure of short columns

Fig.7 - Damage to RC school buildings in 2011 East Japan Earthquake

Another issue was damage to non-structural elements. Figure 8(a) shows an overview of an eleven storied SRC residential building which was evaluated as I_s-index of larger than requirement (0.6). However, shear failure of non-structural concrete wall were observed in lower stories as shown in Figure 8(b). These damage induce problems in functions of the building. Although damage to structural elements were quite limited, inhabitants evacuated from this building because of interruption of service and the building was finally demolished. It suggest functionality is getting more important for performance of buildings structure from the resilience point of view.

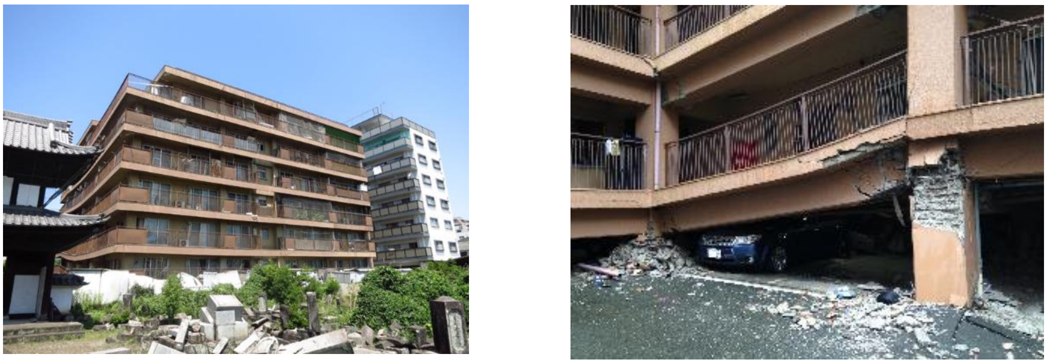
a) General view of the building b) Damage to non-structural RC walls

Fig.8 - Damage to a residential building in 2011 East Japan Earthquake

4.2. Damage due to 2016 Kumamoto Earthquake

The Kumamoto earthquake on 16th of April 2016 Magnitude of 7.3 is the most recent major earthquake in Japan. Human causalities were 88 death and 2137 injured. In general, damage to buildings that satisfied the seismic evaluation code where limited. Most of the damage observed was similar to those of observed in the past earthquakes.

Figure 9 shows the damage of 7-story residential RC building design by old seismic code and having soft first story (piloti) used as parking lot. Such damage was commonly observed in previous earthquake in Kobe earthquake 1995.



a) General view of the building b) Collapse of first story

Fig.9 - Damage to a residential building in 2016 Kumamoto Earthquake

Figure 10 shows 5-story RC building used as city hall. The story collapse occurred at the 4th story. This building was also designed by the old seismic code (before 1981) and was evaluated to have low seismic capacity I_s index. Future plans of either retrofit or rebuild was under consideration before the earthquake.

Fig.10 Damage to City Hall building in 2016 Kumamoto Earthquake

Figure 11 shows the damage of another RC building where the damage to its structure elements was slight. However, the non-structural secondary walls where greatly damaged. This repeated damage, rise the importance of revaluating serviceability limits due to non-structural elements.

a) General view of the building b) Collapse of non structural RC walls

Fig.11 - Damage to a residential building in 2016 Kumamoto Earthquake

5. Conclusions

In this paper, overview of damaging earthquakes, seismic code and evaluation standard in Japan was presented. Lessons learned and findings are summarized:

(1) There is great improvement of safety of both existing and new buildings and success in limiting earthquake damage.

(2) Heavy damage to public school buildings in recent earthquakes were limited because almost all buildings satisfied the current design code owing to wide application of seismic evaluation and retrofit.

(3) In recent earthquakes, damage was concentrated to un-retrofitted buildings designed based on old seismic code. This emphasize the necessity of speeding up the process of assessment and retrofit of buildings.

(4) Many buildings lost immediate occupancy because of damage to non-structural components even though they escape structural damage. The functionality is getting more important for performance of buildings structure from the resilience point of view.

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