

EFFECT OF SEISMIC RETROFIT ON SEISMIC RISK MITIGATION FOR REINFORCED CONCRETE BUILDINGS

Masaki Maeda¹

¹ Dept. of Architecture and Building Science, Tohoku University, Japan
Email: maeda@archi.tohoku.ac.jp

ABSTRACT:

It is of great importance to assess the seismic risk of existing buildings located in a high seismic region to avoid destructive damage due to severe earthquakes. In Japan, seismic capacity evaluation and strengthening have been applied to existing buildings especially after the 1995 Hyogoken-Nambu Earthquake. Judging criteria in seismic capacity for screening candidates to strengthening and required capacity level is generally set to harmonize with current seismic code. However, there has been few study that tried to prove the effect of seismic retrofit on mitigation of seismic risk such as damage ratio, repair cost, and number of injuries and death induced by severe earthquake.

In this paper, therefore, the effect by seismic retrofit is investigated. First, the relationship between seismic capacity and damage ratio of reinforced concrete buildings suffered 1995 Hyogoken-Nambu Earthquake is discussed.

Secondly, seismic capacity of public buildings in Sendai City before and after seismic retrofit is statistically examined and distribution of seismic capacity of R/C public buildings is calculated. Damage ratio due to earthquakes, which are expected to attack Sendai City in the near future, is estimated by probabilistic approach for both before and after retrofit. The cost for repair and reconstruction of damaged buildings based on the estimated damage ratio and the effect of seismic retrofit on mitigation of seismic risk is examined.

Finally, parametric study with different target seismic capacity for retrofit is carried out and the relationship between the target seismic capacity and predicted seismic risk was discussed from a cost point of view.

KEYWORDS: Seismic retrofit, Risk mitigation, RC building, Damage prediction,
Seismic capacity evaluation, Repair cost

1. INTRODUCTION

Seismic evaluation and/or retrofit of existing buildings located in a high seismic region is important to avoid destructive damage due to severe earthquakes. It is of great importance to assess the seismic risk of buildings and to decide a demand criterion for screening vulnerable buildings. In Japan, seismic capacity evaluation and strengthening have been applied to existing buildings especially after the 1995 Hyogoken-Nambu Earthquake. Judging criteria for screening retrofit candidates and required capacity level is generally set to harmonize with the current seismic code. However, there has been few study that tried to prove the effect of seismic retrofit on mitigation of seismic risk such as damage ratio, repair cost, and number of injuries and death induced by severe earthquakes.

In this paper, therefore, the effect of seismic retrofit is investigated. First, the relationship between seismic capacity I_s -Index and damage of reinforced concrete buildings suffered 1995 Hyogoken-Nambu Earthquake is discussed. Secondly, seismic capacity of R/C school buildings in Sendai City is statistically examined and distribution of seismic capacity I_s -Index of total R/C school buildings is estimated. Then, Damage ratio due to simulated earthquakes, which are expected to attack Sendai City in the near future, is predicted by probabilistic approach for both with and without seismic retrofit. The repair cost of damaged buildings are also predicted based on the evaluated damage ratio. Finally, the effect of seismic retrofit on seismic risk mitigation is discussed from a cost-effectiveness point of view.

2. DAMAGE TO REINFORCED CONCRETE BUILDINGS DUE TO THE 1995 HYGOKEN-NAMBU EARTHQUAKE

2.1 Damage Statistics

Damage survey and seismic capacity evaluation of reinforced concrete school buildings were carried out after the 1995 Hyogoken-nambu Earthquake by the Committee for School Buildings in the Architectural Institute of Japan (AIJ 1997, Okada 2000). The working group for R/C structures investigated structural damage to a total of 631 reinforced concrete school buildings in Kobe City and other neighboring cities subjected to a strong ground shaking. Damage statistics was shown in **Figure 1**. Note that 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 analysis or pushover analysis considering deformation capacity of members was required in 1981. 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 even under such strong ground motion, and the ratio of moderately or more damaged school buildings was only 8%. These results reveal that the seismic capacity of existing R/C buildings in Japan has been improved significantly due to revisions of the seismic design codes. However, it is necessary, as had been often pointed out before the earthquake, to identify seismically vulnerable buildings designed based on old seismic codes and to upgrade their seismic capacity.

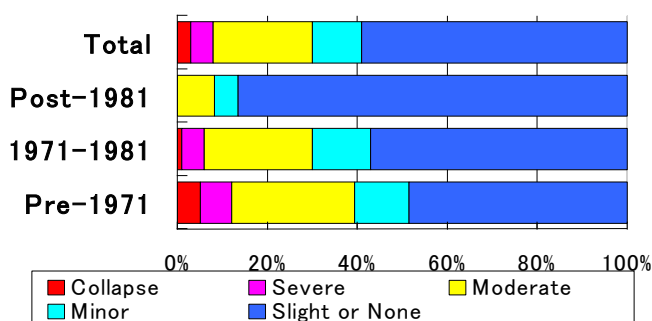


Figure 1 Damage ratio of R/C school buildings due to 1995 Hyogoken-nambu Earthquake (Okada 2000)

2.2 Relationship between Seismic Capacity and Damage

Figure 2 shows the relationship between the seismic capacity index (I_s -Index) and construction age of 82 R/C school buildings, where I_s -Indices of each building are evaluated by the “Japanese Standard for Seismic Capacity Evaluation of Existing Reinforced Concrete Building”(JBDPA 1990). I_s -Index can be calculated by Eq.(1) at each story and each direction.

$$I_s = E_0 \times S_D \times T \quad (1)$$

E_0 is a basic structural index calculated from the product of strength index (C), ductility index (F), and story index (ϕ), i.e., $E_0 = \phi \times C \times F$. C -Index 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 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 I_s -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. Past experiences of the 1968 Tokachi-Oki, 1978 Miyagi-ken-Oki and other earthquakes reported that buildings with I_s -Indices higher than 0.6 escaped severe damage or collapse. As can be found in **Figure 2**, I_s -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 2** indicated that seismic capacity of reinforced concrete school buildings in Japan were successfully improved due to the revisions of seismic design codes.

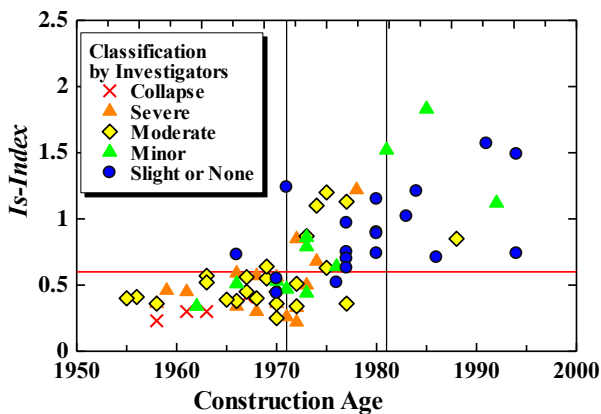


Figure 2 Construction age vs. seismic capacity I_s -Indices of R/C school buildings

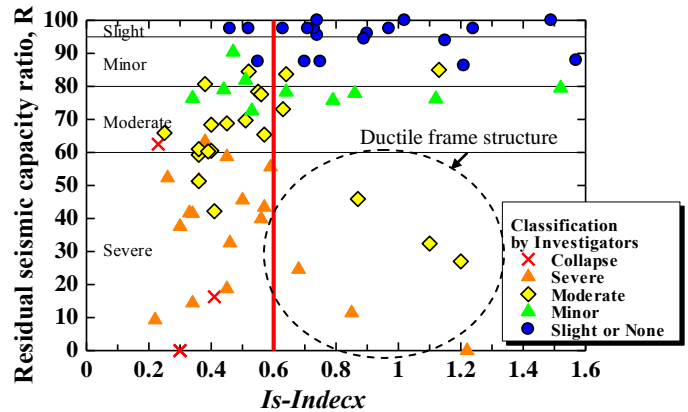
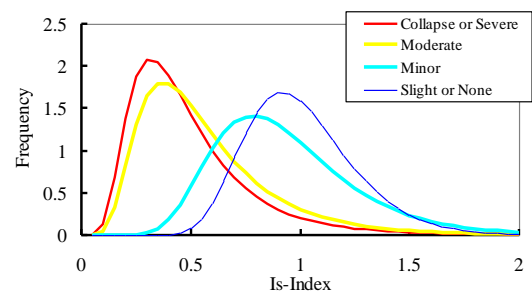


Figure 3 The second seismic performance indices and damage indices

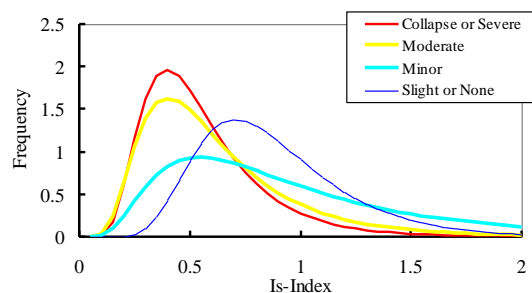
Figure 3 shows the relationship between I_s -Index and damage level indices R -Index proposed in “Japanese Standard for Damage Level Classification of Reinforced Concrete Building” (JBDPA 2001). A fair correlation was observed between calculated I_s -index and observed damage. Most of the buildings with I_s values lower than 0.4 had major damage. Most buildings with I_s -values lower than 0.3 were severely damaged or collapsed ($R < 60$). Those with I_s values of 0.4 through 0.6 were moderately damaged or more. Many buildings with I_s values higher than 0.6 avoided severe damage and had minor damage or less ($R > 80$). However, it should be noted that serious damage ($R < 60$) was observed in six buildings although their I_s values were higher than 0.6, which was different from the past experiences. One of the possible reasons for such serious damage may be their failure modes different from other buildings with serious damage. These buildings were ductile frame structures with relatively lower lateral strength (C -Index) but large deformation capacity (F -Index). In these buildings, relatively ductile failure modes such as flexural failure, bond splitting failure etc., which might have more deformability than other buildings with brittle failure, were found. I_s -Index of 0.6 is generally regarded as an effective demand criterion for screening seismically vulnerable buildings even though the exceptions mentioned above were found.

2.3 Evaluation of Relationship between Seismic Capacity I_s -Index and Damage Provability

Figure 3 suggests damage to buildings is not deterministic but probabilistic, and uncertainty should be taken into account to assess seismic damage. Therefore, the relationship between I_s -Index and damage probability was derived from the statistical data. **Figure 4** shows the distribution of I_s -Indices of R/C school buildings with different damage levels, which was approximated by a log-normal probability density function. Seismic intensity VI and VII on JMA scale were observed in the affected area. The distributions of I_s -Indices were estimated for each seismic intensity. **Table 2** shows damage ratio for seismic intensity VI and VII in Nishinomiya City and eastern part of Kobe City, where damage level of all the R/C school buildings was investigated by the AIJ’s committee. The relationship between I_s -Indices and damage probability can be obtained as shown in **Figure 5**, by summation of I_s -Index distributions (**Figure 4**) for each damage level multiplied by the damage ratio (**Table 2**). The figure indicates that damage probability decrease with increase of I_s -Indices. Estimated provability for moderate or more damage at $I_s=0.7$ is 4% and 16% for seismic intensity of VI and VII, respectively.



(a) Seismic intensity VII



(b) Seismic intensity VI

Figure 4 I_s -Index distribution of buildings with different damage level

Japanese seismic intensity scale was revised in 1996 and Intensity V and VI were divided into “upper” and “lower”. The revised seismic intensity is measured automatically with seismic intensity meters and announced rapidly to the public and officials (JMA). JMA seismic intensity I is calculated by Eq.(2)

$$I = 2 \log A + 0.94 \quad (2)$$

Where, A: acceleration value, of which exceeding time is equal to 0.3 sec during an earthquake.

Fragility curves for the new JMA seismic intensity were derived from the relationship between damage ratio and I_s -Indices (figure 5). Damage provability for seismic intensity VI and VII were employed in the estimation and accumulated log-normal function was employed to approximate the fragility curve for each I_s vakue. Obtained fragility curves are shown in Figure 6.

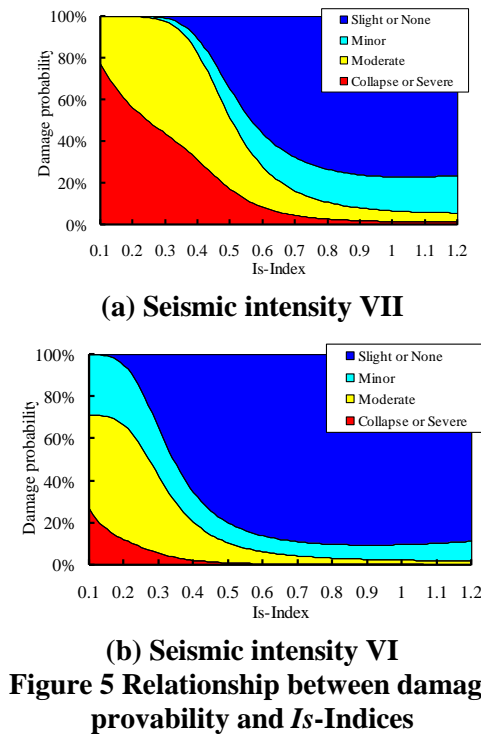


Figure 5 Relationship between damage provability and I_s -Indices

Table 2 Damage ratio in the area of seismic intensity of VI and VII

| Seismic Intensity | Slight or None | Minor | Moderate | Severe or Collapse | Total |
|-------------------|----------------|-------------|-------------|--------------------|-------------|
| VII | 99 60.0% | 25 15.1% | 26 15.8% | 15 9.1% | 165 100% |
| VI | 202 83.5% | 24 9.9% | 14 5.8% | 2 0.8% | 242 100% |

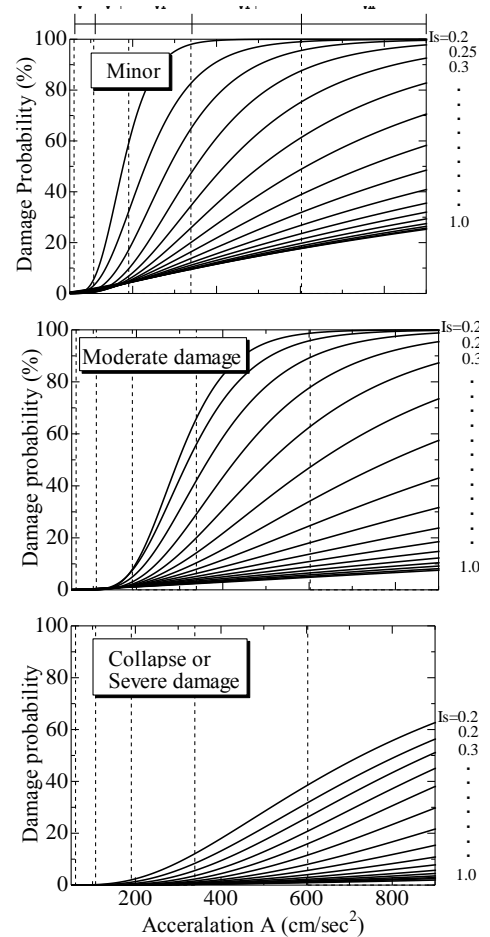


Figure 6 Fragility curve

3. SEISMIC CAPACITY OF R/C SCHOOL BUILDINGS IN SENDAI CITY

3.1 Progress of Seismic Evaluation and Retrofit of School Buildings in Sendai City

After the “Law for promotion for seismic retrofit” was enforced in 1995, the Ministry of Education has been promoting seismic retrofit of school buildings throughout Japan. In the screening of retrofit candidates, $I_s = 0.7$ is recommended as a demand criterion for school buildings, considering importance factor. The authors investigated the state of practice on seismic evaluation and retrofit of R/C school buildings in Sendai City. Result is shown in Table 3. In Sendai City, approximately 40% of 440 R/C school buildings, which are constructed after 1982 according to the current seismic codes, are considered to be provided with sufficient seismic capacity, whereas candidates for seismic evaluation and retrofit are as many as 60% (256 buildings). Sendai City began seismic evaluation and retrofit of the 256 buildings in 1996 and 234 have been already evaluated until 2003. As a result of the evaluation, a quarter of the evaluated buildings were provided with I_s -Index of larger than required

Table 3 Comparison of progress on seismic retrofit between in Sendai City and Japan

| Number of Buildings | Sendai City | Japan |
|--|-------------|---------|
| Total | 440 | 151,624 |
| Higher seismic capacity (retrofitted or post-1982) | 349 | 69,588 |
| Ratio | 79.3% | 45.9% |
| Constructed before 1981 | 256 | 100,243 |
| Higher seismic capacity (retrofitted or post-1982) | 165 | 18,207 |
| Ratio | 64.5% | 18.2% |

capacity of 0.7, whereas the rest (171 buildings) were judged as vulnerable and necessary to be retrofitted. Five buildings of the 171 candidates have been reconstructed and 97 buildings have been retrofitted until the end of 2005. Assuming that the building constructed after 1982 and already retrofitted are provided with sufficient seismic capacity, approximately 80% of R/C school buildings in Sendai City are seismic resistant. This ratio indicates seismic retrofit in Sendai City is making rapid progress comparing with school buildings throughout Japan as shown in **Table 3**.

3.2 Estimation of I_s -Index Distribution

Histogram of I_s -Index of the 243 evaluated buildings is shown in **Figure 7**. As can be seen from the figure, I_s -Indices of most of “pre-1971” buildings are lower than 0.7, whereas the distribution of I_s -Index shifts larger as the generation of the building becomes younger. Most of I_s -Indices after retrofit of 97 buildings were concentrated around 0.75 (0.75 in an average with standard deviation of 0.11), because target capacity for retrofit I_{so} -Index of 0.7 is employed in Sendai City.

Distribution of I_s -Index of total school buildings in Sendai City was estimated based on the distributions obtained here. In the estimation following states were considered:

- (a) *Without retrofit*: seismic upgrade of vulnerable buildings is not carried out at all. This state corresponds to the situation before 1995.
- (b) *Present state*: 97 buildings of the 171 vulnerable buildings have been upgraded and 5 buildings have been reconstructed (**Figure 7**). As a result, approximately 80% of total buildings are provided with 0.7 or larger I_s -Index.
- (c) *Retrofit completed*: all the existing vulnerable building have been retrofitted so that I_s -Index exceeds required seismic capacity, I_{so} -Index.

First, the buildings are categorized into 4 groups;

- (a) Vulnerable buildings not yet retrofitted
- (b) Retrofitted buildings
- (c) Buildings needless to be retrofitted ($I_s > I_{so}$)
- (d) Buildings constructed after 1982

Then, histograms of each category multiplied in accordance with the number of the buildings were added up, assuming that distribution shape of each category is maintained if the number of building increased or decreased. Obtained histograms are shown in **Figure 8** together with type II asymptotic extreme-value distribution function.

4. SEISMIC RISK ASSESSMENT FOR R/C SCHOOL BUILDINGS IN SENDAI CITY

4.1 Procedure of Seismic Risk Assessment

Seismic risk assessment of R/C school buildings in Sendai City was carried out using I_s -Indices distribution and damage provability estimated above. Miyagiken-oki earthquake and Nagamachi-Rifu Fault earthquake were employed in the

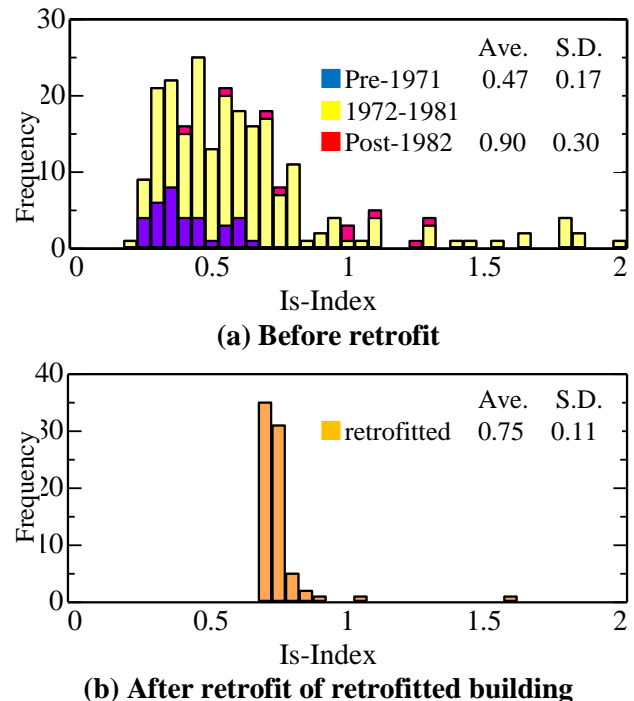


Figure 7 Histogram of I_s -Index of evaluated school buildings in Sendai City

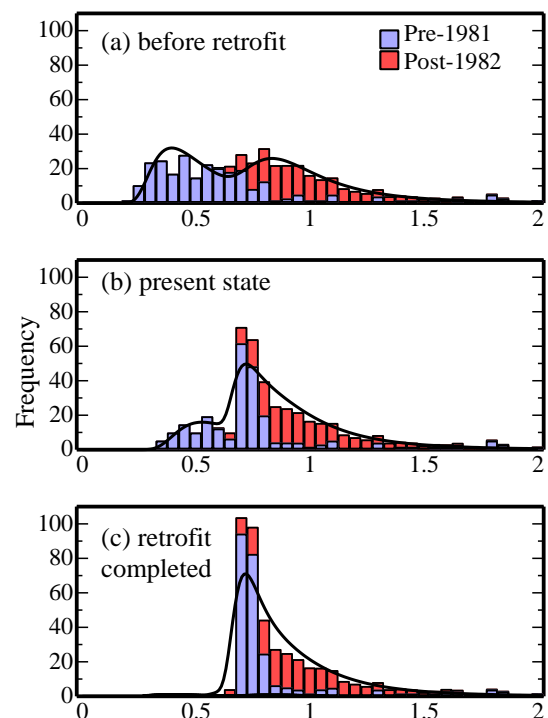


Figure 8 Estimated distribution of I_s -Index for total school buildings in Sendai City

assessment considering past damaging earthquakes and affecting active faults. Miyagiken-oki earthquake, of which average return period is 37 years, is most hazardous earthquake in the region. The probability of occurrence in 20 years is approximately 90% according to the investigation by the Japanese Headquarters for Earthquake Research Promotions. The epicentre is located on off-coastal of Miyagi Prefecture. The 1978 Miyagiken-oki Earthquake induced severe damage in Miyagi Prefecture [6]. Nagamachi-Rifu Fault is an active fault located beneath Sendai City downtown in the north-south direction. Return period of Nagamachi-Rifu Fault earthquake is considered longer than thousand years, therefore provability of occurrence is smaller than that of Miyagiken-oki earthquake. However, the damage may be expected larger if it occurred. Regional distribution of predicted seismic intensity in JAM scale due to the two earthquakes is shown in **Figure 9** (Sendai City 2002). Human activity is concentrated in the eastern part of the city, where larger intensity is predicted as shown in **Figure 9**. 88% of schools is located in the region of intensity “VI-“ for Miyagiken-oki earthquake, whereas 92% are in the region of intensity “VI+“ for Nagamachi-Rifu earthquake.

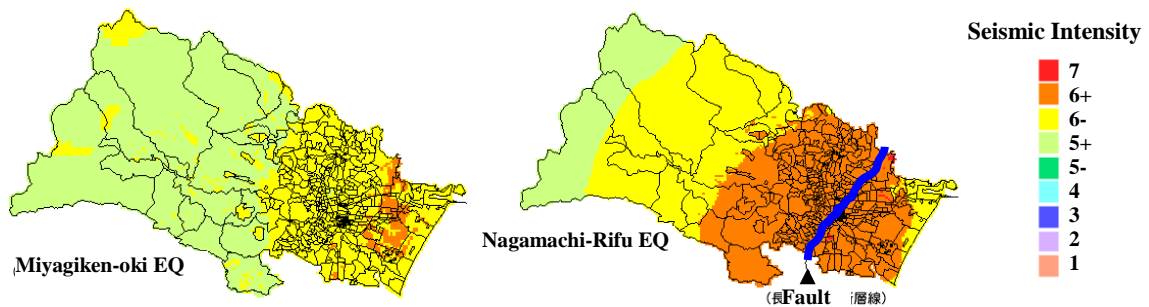


Figure 9 Distribution of predicted seismic intensity in Sendai City

Seismic risk assessment of R/C school buildings against the two hazardous earthquakes was carried out. *Is*-Index distributions in case of (a) “without retrofit”, (b) “present state” and (c) “retrofit completed” were employed in the damage assessment in order to discuss the effect of retrofit on mitigation of damage. In addition, *Iso*-Index distributions in case that required seismic capacity *Iso*-Index was reduced from 0.7 to 0.4, 0.5 and 0.6 were considered. Procedure of assessment is as follows:

- (1) Damage ratio of R/C school buildings was calculated based on the predicted seismic intensity at the site of each building and fragility-curve shown in **Figure 6**.
- (2) Economical and human damage was estimated using calculated damage ratio. Repair costs for damaged buildings was evaluated and compared with the costs for strengthening of the vulnerable buildings before earthquake. The number of killed or injured was also estimated based the damage ratio.

4.2 Damage Ratio Estimation of R/C School Buildings

Figure 10 shows predicted damage ratio due to the two earthquakes. Damage ratio was calculated using the damage probability corresponding to the median of acceleration *A* in each seismic intensity range in **Figure 6**. In **Figure 10**, “without retrofit” and “present state” indicate damage ratio before seismic strengthening began and in the present state (102 buildings of 173 vulnerable ones have been retrofitted), respectively. *Iso*=0.4, 0.5, 0.6 and 0.7 indicate the results assuming seismic retrofit of all the buildings with *Is*-index of lower than *Iso*-Index have been completed. Note that *Iso* of 0.7 is, as mentioned earlier, recommended generally as required *Is*-Index for school buildings in Japan. Cases with *Iso* of 0.4, 0.5 and 0.6 were considered in order to discuss the effect of seismic retrofit.

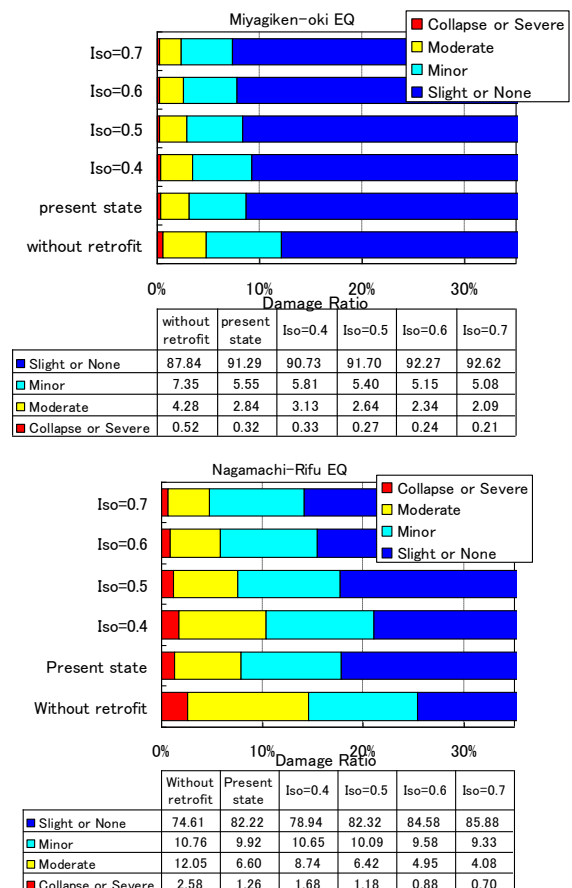


Figure 10 Predicted damage ratio

The ratio of severe, moderate and minor damage to school buildings due to the 1978 Miyagiken-oki Earthquake is reported to be 1.2%, 3.7% and 7.3%, respectively. Predicted damage ratio without retrofit for Miyagiken-oki earthquake agrees well with these damage experiences. Damage ratio of heavy damage due to Nagamati-Rifu earthquake, which is an inland earthquake, is predicted much larger than that due to Miyagiken-oki earthquake. Comparing before and after retrofit, the effect on mitigation of potential risk can be found. Predicted ratio for moderate or more damage in present state was reduced to 50-60% of those before retrofit by the seismic strengthening of the 102 vulnerable buildings.

4.3 Assessment of Repair Cost

The cost for retrofitting the vulnerable buildings before the earthquake and repair cost of the damaged buildings were evaluated using the predicted damage ratio. Evaluation procedure is as follows;

(1) Cost for retrofit, C_{Rt} , of each building can be calculated by Eq.(3)

$$C_{Rt} = U_{Rt} \times A_f \times 10\Delta Is \quad (3)$$

$$\Delta Is = {}_R Is - Is \quad (4)$$

Where, U_{Rt} : unit cost for retrofit per floor area required to increase 0.1 in Is -Index, A_f : total floor area of the building, ${}_R Is$: Is -Index after retrofit, ΔIs : increase in Is -Index

Table 4 shows costs for retrofit of the 97 school buildings in Sendai City. The average Is -Index after strengthening, ${}_R Is$, was 0.75 and total expense was 5,020 million yen. These give a unit retrofit cost U_{Rt} 5,400(yen/ $m^2\Delta Is0.1$), which is retrofit cost per floor area required for increase 0.1 in Is -Index.

(2) Repair cost, C_{Rp} , can be be calculated by Eq.(5).

$$C_{Rp} = \sum A_f \times (U_1 \times D_1 + U_2 \times D_2 + U_3 \times D_3) \quad (5)$$

Where, $\sum A_f$: total floor area of all the school buildings in Sendai City (=1,019,827 m^2),

U_1, U_2, U_3 : unit repair costs for collapsed or severely damaged, moderately damaged, and minor damaged buildings, respectively,

D_1, D_2, D_3 : damage ratio of collapsed or severely damaged, moderately damaged, and minor damaged buildings, respectively.

Table 5 shows statistical data of repair costs per floor area derived from investigation of school buildings damaged due to the 1995 Hyogoken-nambu Earthquake (Maeda 2002). Note that costs for reconstruction is shown in collapsed or severely damaged buildings, because almost of severely damaged buildings were demolished and reconstructed after the earthquake.

Evaluated costs for retrofit and repair are shown in **Figure 11**. In the figure, upper and lower limit of repair costs, corresponding to maximum and minimum damage provability in each range of seismic intensity in Figure 6, are also shown. The costs for retrofit spent until 2003 exceeds predicted repair costs without retrofit for Myagiken-oki earthquake, though the repair costs are reduced by strengthening of 97 buildings. The median of summation of retrofit and repair costs for every case is larger than predicted repair cost without retrofit. The upper limit of the summation is lowest for Iso=0.4, and the costs

Table 4 Cost for retrofit of R/C school buildings in Sendai

| | Total floor area $\sum Af$ | Average ΔIs | Total retrofit cost | Unit retrofit cost |
|--------------------------|-------------------------------|------------------------|---------------------|-----------------------------------|
| Retrofitted 97 buildings | 265,472 (m^2) | 0.35 | 5,020 (million yen) | 5,400 (yen/ $m^2 \square Is0.1$) |

Table 5 Repair cost of school buildings suffered the 1995 Hyogoken-nambu Earthquake (Yen/ m^2)

| Damage level | Collapse or Severe | Moderate | Minor | Slight or None |
|------------------|--------------------------|----------|-------|----------------|
| Unit repair cost | 213,000 (reconstruction) | 17,200 | 3,100 | 0 |

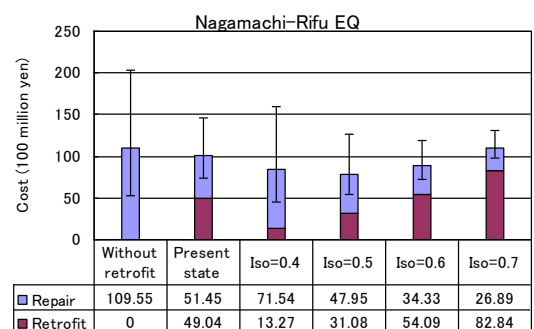
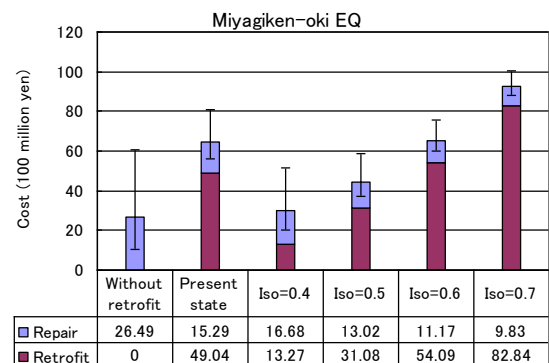


Figure 11 Predicted repair and retrofit costs

for $I_{so}=0.5$ is lower than the costs without retrofit. These results suggest $I_{so}=0.4$ or 0.5 may be enough for the required seismic capacity from cost effectiveness point of view, even if considering uncertainty of repair costs. On the other hand, the effect of seismic retrofit on mitigate of the repair costs can be found clearly for Nagamachi-Rifu earthquake. Predicted repair cost in the present state is reduced to approximately 50% and the summation of costs for retrofit and repair is smaller than repair cost without retrofit. The upper limit of the summation decreases as increase of I_{so} -Index, although apparent differences can not be found in the median of the summation. These results, suggest $I_{so}=0.6$ or 0.7 may be appropriate as a demand criterion against Nagamachi-Rifu earthquake.

5. CONCLUDING REMARKS

In this paper, a methodology to estimate potential seismic risk of R/C buildings was presented. The methodology was applied to school buildings in Sendai City, and the effect of seismic retrofit on the damage mitigation was discussed. Results can be summarized as follows.

- (1) Relationship between seismic capacity I_{so} -Index and damage probability was estimated from the statistical data of buildings damaged due to the 1995 Hyogoken-nambu Earthquake, and its applicability was examined. The damage ratio predicted agreed well with damage experience in the 1978 Miyagiken-oki Earthquake.
- (2) Economical and human damage for R/C school buildings were evaluated for two hazardous simulated earthquakes in Sendai City, and the damage mitigation by seismic retrofit was found. Moreover, reasonable level of required seismic capacity was discussed from cost effectiveness point of view. Required seismic capacity I_{so} may be reduced to 0.4 or 0.5 against a predicted off-coastal earthquake, of which probability of occurrence is extremely high, whereas I_{so} of 0.6 or 0.7 is recommended considering an inland earthquake with lower probability of occurrence but severer shaking.

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