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

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SUMMARY:
Damage survey on reinforced concrete school buildings in Fukushima was outlined, which was conducted as part of reconnaissance activity of AIJ, Architectural Institute of Japan, after the East Japan Earthquake 2011 March 11. The surveyed buildings were school buildings and educational buildings, 778 in total, which were selected from quick inspection by local governments. The damage levels were classified with the evaluation of the damage rates based on the Japanese standard. The inventory damage rates were estimated partially for the high school buildings in Fukushima prefecture, where the whole list of parameter was available. The statistical damage rates were analysed in relations with structural indices such as the ages of buildings, the effects of retrofit or strengthening, the calculated indices by seismic performance evaluation and the intensity of ground motions recorded nearby.

Keywords: damage evaluation, damage rate, seismic evaluation, retrofit, The East-Japan Earthquake

1. INTRODUCTION

The Architectural Institute of Japan reconnaissance teams have conducted survey on building structures after the 2011 East Japan Earthquake, March 11, from which preliminary report has been published in Japanese (AIJ, 2011). Typical damages to buildings by ground motions with relatively heavy levels were included in the report basically by quick inspection, while the overall damage rates including minor or less could not be estimated. It was difficult to perform the inventory or detailed survey on damages to buildings systematically, because the damages area spread widely and the structural damages were regarded as relatively minor behind serious disasters caused by the Tsunami and the NPP. Moreover in recent days, the information tends to be controlled strictly by the administrators, not only on private buildings but also on public buildings. The damage survey only in academic viewpoints is becoming more difficult than in old days.

The Architectural Institute of Japan reconnaissance teams on the survey of reinforced concrete buildings were in the following four groups based on the intended use of buildings as: (1) school buildings and community centres, (2) public buildings (mostly government offices), (3) residential buildings, and (4) commercial buildings. The surveyed buildings were incomprehensive as a results, especially for the commercial buildings or private company offices and private collective houses due to above reasons. However, for school buildings and public halls could be surveyed rather systematically, as part of the rehabilitation process with detailed damage evaluation based on the request of the governments. Surveyed were 778 buildings in total, which were selected based on the preliminary list of the post-earthquake quick inspection by the local governments, including 400 RC buildings. As part of the results of survey, the damage rates of reinforced concrete school buildings in Fukushima are reported in the paper, focused on the inventory damage ratios in the region.

2. METHOD OF DAMAGE EVALUATION

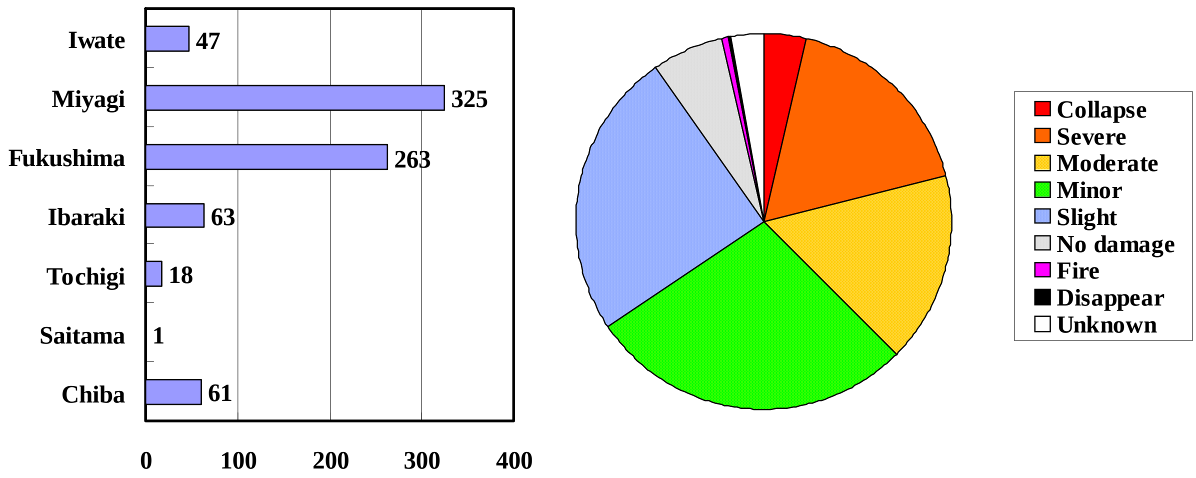
The evaluated damage rates were classified into five levels and no damage such as collapse, severe, moderate, minor, slight and no damage, based on the “Post-earthquake damage evaluation standards,” (JBDPA, 2001) as briefly described below. The rate of damage is calculated in term of the residual seismic capacity R, which expresses the estimated ratio of the post-earthquake residual capacity to the pre-earthquake original capacity from the observed damage grades of the surveyed vertical members. The vertical members are grouped into five types with estimated failure mode such as (1) shear column, (2) flexure column, (3) wall without boundary columns, (4) wall with a boundary column and (5) wall with boundary columns at both ends, among which the seismic capacity or strength ratios of the member types (1) through (5) are assumed to be 1:1:1:2:6, respectively, without calculation. The damage rate of each vertical member is classified into one of none [0] and the five levels from [I] to [V]. The ratios of the residual member capacity are assumed as 1:0.95:0.6:0:0 for the shear column and other wall members, and 1:0.95:0.75:0.5:0.1:0 for the flexural column, in accordance with the damage rates of [0] to [V], respectively, also without calculation.

Then the residual capacity ratio R for each story shear is estimated from the numbers of the vertical members classified into the types as above and the evaluated damage rate. If the evaluation is not available for some of the members, the residual capacity may be calculated only from the surveyed members. The residual capacity ratio R is calculated for each story and direction, from which the minimum value is adopted to rank the damage grade of the building, such as into the followings: (Grade 0) No damage, (Grade 1) slight, (Grade 2) minor, (Grade 3) moderate, (Grade 4) severe or heavy, or (Grade 5) collapse or near collapse, if the ratio R is (G0)100%, (G1)95<R<100, (G2)80<R<95, (G3)60<R<80, (G4)R<60, or (G5)R≒0, respectively.

3. SCHOOL BUILDINGS AND PUBLIC HALLS FOR DAMAGE SURVEY

The AIJ organized a special committee and working groups to investigate damages to school buildings and public halls, and also to evaluate the damage levels for the recovery process of the facilities, which were requested to AIJ officially from MEXT, Ministry of Education. The committee and WG members conducted the field survey based on the request of the local governments in charge of the facility administration. The number of the surveyed buildings was 778 in total, which were requested from the local governments, and additional more without request: (1) about 400 reinforced concrete (RC) buildings, (2) 250 steel or steel or steel composite buildings, (3) 130 others such as timber schools, community centres and public halls with various structural types. The regional distribution of the buildings for survey is shown Figure 1(a). However, the numbers do not necessary corresponds to the damage rates in the region, because these were not selected based on unified standard and so on. The result of damage evaluation or classified damage levels for all 778 buildings were also shown in Figure 2(b), however, which has no statistical meaning at this stage. Because the buildings for survey were selected through the request of the administrators, all the buildings with apparent serious damage should have been included for evaluation. However, a few of them were excluded due to the confusion of the procedure, while buildings with much less structural damages are included as a result. It should also be noted that most of the collapse buildings were timber structures or due to Tsunami. There were several collapsed RC buildings, schools and houses, although they are included in the list and figure.

For most of the public buildings, especially on schools, the seismic capacity indices “Is-values” had been evaluated by professional engineers based on the Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings (JBDPA, 2001 Japanese version and 2004 English version), requested from the administrative governments. In the process of the seismic evaluation, concrete strengths had been also tested with sample cylinders extracted from the existing buildings. Therefore, the calculated seismic performance indices or the concrete strengths could be reported with the results of the damage evaluation for most of buildings. The results of damage investigation above are to be compiled and will be published in the future from AIJ with the whole statistical analysis as well as detailed reports on selected buildings with the seismic performance evaluation.



(a) Regional distribution of buildings for survey (b) Classified damage levels as result of survey

Figure 1. Number of damaged buildings for survey and classified damage levels as result

4. GROUND MOTIONS AT K-NET STATIONS IN FUKUSHIMA

The strong motion network in Japan, called K-Net, had been installed and operated by NIED, National Research Institute for Earth Science and Disaster Prevention, from after the 1995 Hyogo-ken-Nambu Earthquake. The ground motions have been recorded at K-net stations also in the major cities in Fukushima region, by which the velocity response spectra were calculated, as shown in Figure 2, for the main shocks and for selected ten stations, such as in Yanagawa, Fukushima, Haramachi, Iwaki, Nakoso, Shirakawa, Sukagawa, Koriyama, Nihonmatsu, and Aizuwakamatsu. Although the magnitude was 9.0, while the epicentre distances were more than 200km－400km, the intensities were almost close to the design level of very rare earthquake(Level 2) in the building standard law. If these far field motions are compared with near field motions by recent earthquakes of magnitude around 7.0-7.4, such as 1995 Kobe, 2004 Niigata-Chuetsu, 2007 Niigata-Chuetsu-Oki, the far field motions have long duration, more than 120 seconds, and wide range of frequency components, while the near field motions have short duration, and with amplified components in the medium to longer period, so that the near field motions could be much more effective to the inelastic responses of medium-rise RC buildings and low-rise timber buildings. For example, the response spectra of 1995 JMA Kobe and Takatori motions were generally higher by two or three times around the fundamental periods of 1 to 2 seconds than those of the motions by the 2011 East Japan earthquake.

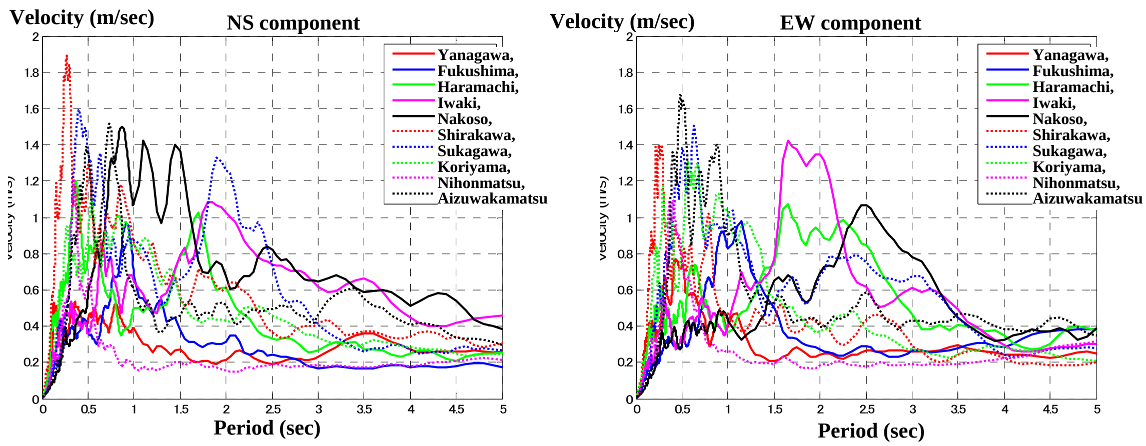


Figure 2. Velocity response spectra by the ground motions recorded in Fukushima

The responses of damaged buildings might be estimated approximately from these response spectra, while it should be noted that large errors could still occur in the estimation because of (1) micro-zone/local site effects, or soil amplifications, and (2) essential difference between the free-field recorded motions and the actual input motions to the structure including non-linear soil-structure interactions.

5. TYPICAL DAMAGES TO HIGH-SCHOOL BUILDINGS IN FUKUSHIMA

Relatively severe damage of near collapse were observed to the columns in I-high school buildings as shown in Photographs. 1(a) through (d). The school had two typical reinforced concrete buildings with 4-story in north and 3-story in south, the longitudinal direction of which was east to west. The two buildings were connected with two 2-story buildings, the longitudinal direction of which was north to south. These four buildings were isolated to each other with expansion joints. The buildings were constructed from 1973 to 1975, therefore the column hoops of 13mm or 10mm bars were placed at the spacing of 100mm. The seismic performance indices Is-values of the four buildings had been calculated as 0.59(4-story building), 0.64(3-story), 1.08 and 1.44(2-story). In Japanese practice, if the Is-value is higher than the standard required level Iso, it would be judged that the building satisfies the standard required seismic performance level. Iso is taken normally as 0.6 for general buildings and 0.7 for school buildings. Although the Is-values of I-high school were a little less than Iso for school buildings, the Is-values almost satisfy the requirement for general buildings. Therefore, it was expected from these values that the damages would not be minor or less under the main shock of the 2011 earthquake, the seismic intensity in JMA scale of which was 6+ around there. However, actually observed damages were relatively severe or moderate with the residual seismic capacity of R=33, 47, 73, 72%. One of the reasons for these heavy damages could be estimated that the high amplification of the ground motions might have been induced due to the hill site effect.

(a) Site of I-high school on the hill

(b) A west overview

(c) Damages to column in north frame

(d) Damages to column in south frame

Photograph 1. Site, buildings and damages of I-high school

6. AFTERSHOCK OBSERVATION

The author's laboratory have conducted series of aftershock observations after recent major earthquakes in Japan, such as 2004 Niigata-Chuetsu, 2007 Niigata-Oki, 2008 Iwate-Nairiku at various sites around buildings for damage survey. The objectives of the observations were to estimate or identify (1) the local site effects, (2) the input loss of the ground motions, and (3) the response characteristics of the damaged or undamaged buildings, which have brought successful data to verify these effects on site. A set of at least three points for observation at one site were ideal though the number of available seismographs were limited: (1) at free-field surface on site, (2) at the base of the building, and (3) at the roof of the building. If possible, it would be much more preferable idea that a temporary observation site could be added at deep underground and so on.

The aftershock observations were also spread out at various sites after the 2011 earthquake in parallel with the damage survey with the same objectives. The detailed results will be reported elsewhere, while an example of the results is shown here recorded at the site of I-high school described above, where the acceleration and velocity response spectrum of the aftershocks recorded at the top of the hill(Nogyo) and the bottom of the hill(Kogyo) on April 11 are compared in Figure 3. It was obvious that the response spectrum was much amplified at the hill top, especially in EW component by several times at around of the peak period of 0.6 second. Although the ratio of the main shock might have been smaller than in case of the aftershock for due to the non-linear soil responses, it would be necessary to take the local site amplification into account, such as at least by 1.5 or 2.0 times, if the new buildings are to be designed and constructed in the same site.

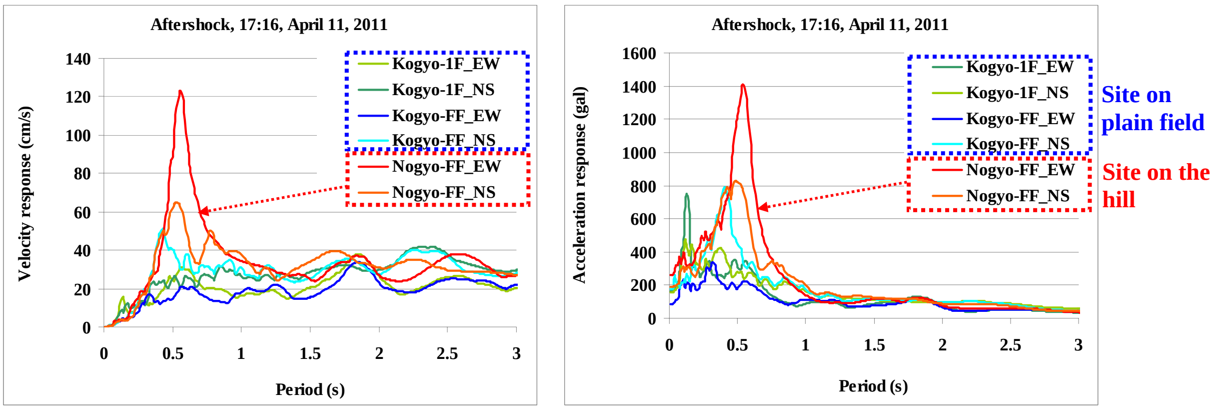


Figure 3. Response spectra of aftershocks at the sites at the top and the bottom of the hill

6. INVENTORY DAMAEGE RATES OF RC SCHOOL BUILDINGS

The total number of the school buildings and other educational facilities for the survey by the AIJ teams was 778 and more, which were widely distributed over nine prefectures in Tohoku and Kanto area of about 600km in NS direction. The list of the buildings for AIJ survey were based on the requests from the local governments, which were selected to determine the rehabilitation procedure, esp. for the damage level evaluation based on the post-earthquake quick inspection the government and engineers. The selected buildings had any damages, even slight or minor, structural or non-structural, though the damage levels of the buildings for survey were widely varied. Also some of the local governments could not respond to the call of MEXT in confusion, or some did not include minor or moderate damages into the list, though it was expected that most of relatively or apparently heavy/moderate damages have been included in the list. Therefore, we have to be careful to derive the damage statistics, especially the inventory damage rates in terms of the damage ratios to the whole existing buildings, whether the inventory damages have been identified and the whole buildings are selected appropriately as a parameter in the area.

At this stage, it is still difficult to drive meaningful damage rates for all the surveyed data, though the damage rates are summarized here tentatively and partially for school buildings under the administration of Fukushima prefecture, consisting of all public high-school buildings, including special school buildings for disabled students, 900 buildings in total. The other damage rates and statistical analysis on elementary/junior-high schools and public halls are to be published from AIJ in March 2012, though further detailed investigations need be continued for more years.

A set of parameter was as reinforced concrete buildings out of all prefecture school buildings: 440 buildings in total and 307 buildings built before 1982. Damage levels were evaluated for 62 buildings out of them, such as severe, moderate, minor, slight/no damage, tsunami, and out of survey. The damage rates in total are shown in Figure 4, while regional distributions are shown in Figures. 5 and 6. A set of parameter was taken as the RC buildings of 440 above, or the buildings of 307 built before 1982 out of them. Even minor damages were not reported on the RC buildings constructed after 1981, though some damages were reported on steel gymnasiums even constructed after 1981, which will be discussed in detail elsewhere. Although some damages might be overlooked, especially on new buildings, it was much reliable that the data on the school buildings under Fukushima prefecture than the other data.

It should be noted that the major structural damages were not reported to 88 RC high-school buildings in Aizu region, while 26 buildings have not been inspected nor evaluated in Soso region (Futaba, Namie, Tomioka, Iidate, Shinchi and Odaka of Minami-soma), evacuation area from the accident of TEPCO-NPP, where the entry has still been restricted for ten months after the accident.

The ratio of minor to severe damages in total, where the buildings were basically not functional in use, was about 6% to total and 8% to the buildings before 1982. Because these are is based with a parameter including Aizu and Soso, therefore if the two regions are excluded from the parameter, then the ratios are 8% and 12% respectively. As for the buildings classified into the grade of severe, which were to be demolished and rebuilt rather than repaired, the ratios were 1.1% to total, 1.6% to pre-1982, 1.5% to those without Aizu and Soso, 2.2% to pre-1982 without Aizu and Soso. Considering the intensities of the ground motions were close to the very rare level of BSL, level 2, in most regions, it may be concluded that these damage rates were satisfactorily low. This was partially owing to the seismic strengthening of school buildings, although it had been behind in Fukushima prefecture, which will be discussed later in this paper. Other reasons also lie in discrepancy with the standard requirement of seismic evaluation and the actual response behaviour.

As for the regional distributions, the damage rate was obviously small in Aizu region while relatively higher in Iwaki region. These are partially because of the earthquake intensity including the site effects and distance to the sources, especially to the Off-Iwaki source, though these were not much clear by K-net motions shown in Figure 2. It is also presumed for another reason of lower damages in Aizu region that the design seismic force is relatively higher including the permanent snow loads in the region.

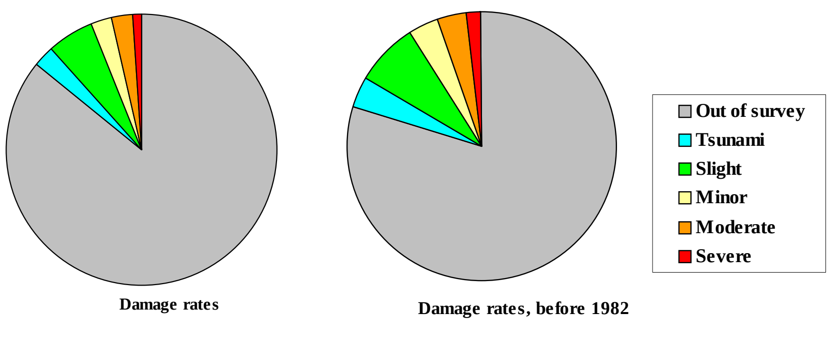


Figure 4. Inventory damage rates for all prefecture school buildings

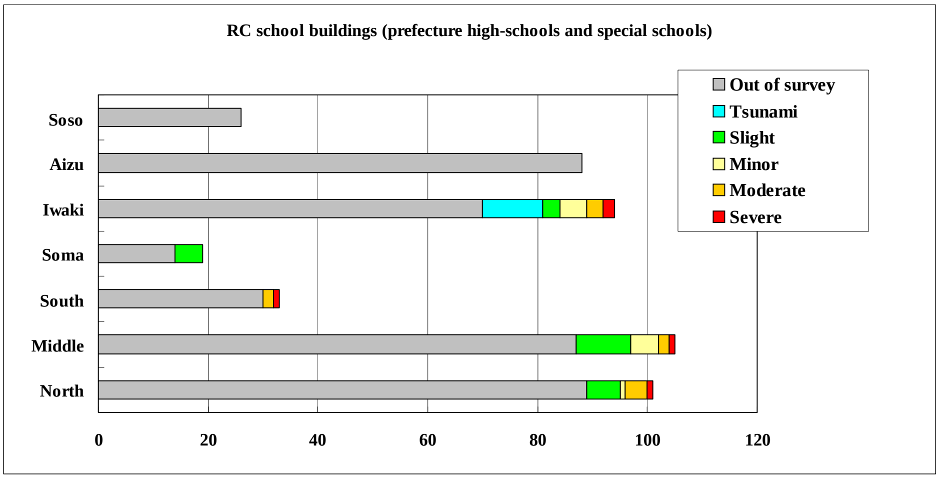


Figure 5. Regional distribution of inventory damage rates for all prefecture school buildings

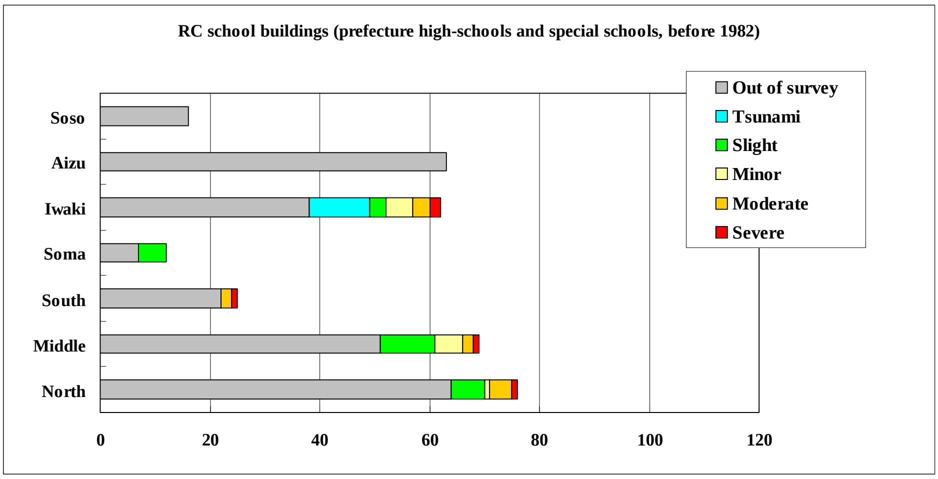


Figure 6. Regional distribution of inventory damage rates for prefecture school buildings before 1982

7. DAMAEGE RATES AND SEISMIC PERFORMANCE INDICES

Seismic performance evaluation of existing school buildings, as well as strengthening if required, have been implemented into practice, especially after 1995 Kobe earthquake, required by the law on "the promotion of seismic strengthening," which have been applied to public buildings and large commercial buildings open to public. If the seismic performance indices of old building constructed before 1982 are lower than the standard required level, they have to be strengthened up to the level or higher at the time of renovation or expansion. The seismic evaluation and the seismic strengthening of school buildings have been promoted by the local governments with the financial aid of MEXT, so that the ratios of the buildings exceeding the standard requirement to the whole existing buildings, hereafter called the seismic safety ratios, have been increasing about 5 percent per year, and the averaged ratios all over Japan have attained 80% for elementary/junior-high public schools, and 77% for high schools at the end of March 2011. The seismic safety ratios of school buildings at the time of the earthquake might have been close to these values averagely in Japan though the regional distributions are varying among prefectures.

As for the seismic performance indices Is of the RC buildings in high schools and special schools in Fukushima prefecture, they have been ranked into the grades of A to D, such as A(Is>0.7) requiring no retrofit, B(Is>0.7), B'(0.6<s<0.7), C(0.3<Is<0.6) and D(Is<0.3) requiring retrofit. The Is-values of the buildings have been ranked before and after the strengthening for retrofit with the buildings constructed after 1981, which had been regarded as to conform to the current code of practice, and classified as S. The seismic performance of the buildings constructed after 1981 have been regarded as to satisfy the Is>0.7 without evaluation procedure so far, although the detailed and rigorous evaluation might be necessary in the future.

If the seismic safety ratios of the RC school buildings were defined as the sum of the ranks S and A, then the ratio was around 50% before the strengthening started and had been upgraded up to 62% by the retrofit at the time of earthquake, as shown in Figure 7. The regional distributions of these seismic performance ranks are shown in Figures 8 after retrofit, namely at the Earthquake. It might be concluded that the safety ratios are relatively higher in Aizu, Soma and South regions with few rank D, where the damage ratios in Figures 8 and 9 were generally smaller.

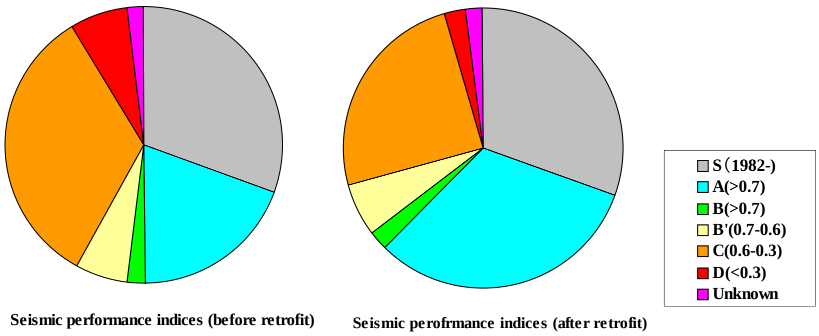


Figure 7. Seismic performance indices before and after retrofit

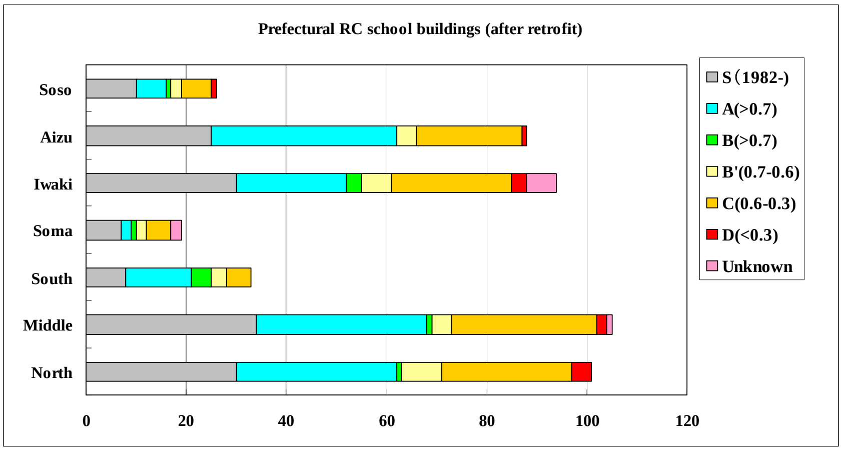


Figure 8. Regional distribution of seismic performance indices after retrofit

The relations between the observed damage level in terms of the residual capacity R and the calculated seismic performance level in terms of the structural seismic index Is-value are plotted directly in Figure 9. The unknown R is assumed as 99%, which might not be different much even if evaluated, except for Soso, where the surveyed has not been performed, while the unknown Is are assumed as zero, which is to be disregarded in the figure. Positive correlations are observed between Is and R generally.

It should be noted, however, in cases of the marks with dotted circles, that R is lower than 80% even if the Is-values are much higher or around 0.6. Four of these are the buildings of I-high school on the hill in Iwaki described above, and a building in S-special school in middle region, where the ground motions might have been higher there due to some local site effects and also have peculiar reason with columns in half-basement level. Detailed model and analysis are needed to simulate the damage level in relation with the estimated input motions.

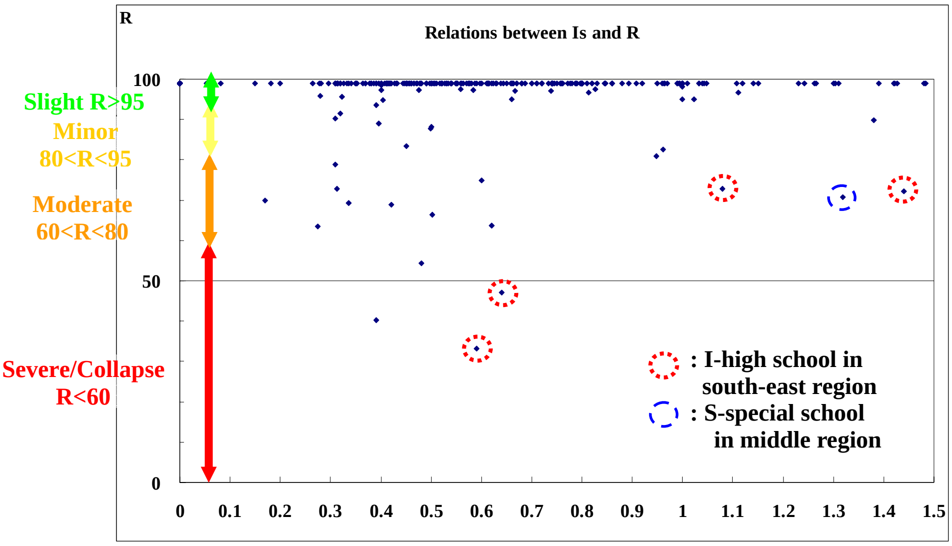


Figure 9. Relations between the seismic performance indices Is and the damage rates in terms of the residual capacity R (%)

8. TYPICAL DAMAGES AND DESIGN IMPLICATIONS

Typical damages to reinforced concrete school buildings by the 2011 Earthquake may be summarized as follows, including the observations reported elsewhere in detail (Kabeyasawa, 2012).

Several buildings suffered very serious damages, such as collapse or severe, which requires demolish and reconstruction for restoration, although the rate was very low. These damaged RC buildings of high schools were constructed before 1981 when the current code was put into practice. Shear failure of columns, especially of short columns, was observed probably due to insufficient rate of hoops, concentration of earthquake load or high varying axial load. Also, the damages might have been increased by the amplification of ground motions due to soils and hills, were observed and the effect was clearly verified through the aftershock observation. The ratio of collapse/severe damage was estimated as one percent for whole prefecture, two percent for the whole regions.

Numbers of buildings suffered moderate or minor damages, by which they were not functional in continual use and requires repair or strengthening. The damage ratio of minor or moderate and more was 6 to 8 percent for whole area and 10 to 12 percent for regions. Most of the new buildings designed by the current code or older buildings retrofitted to the current required level suffered relatively slight or minor damages, though some of them suffered

Relatively heavy damages are observed at the joint concrete with steel and/or timber members in concrete structures combined with steel or timber members, not only in the old buildings v. Non-structural walls and ceilings were severely damaged in many cases, not only with old but also with new buildings. Settlement of base foundation due to damages to piles or soils or liquefaction were observed, which could not be introduced in this paper. Not only non-structural but also structural failures due to the tsunami waves were observed in RC buildings, from which the rehabilitation seemed to be difficult in most cases.

Design implications and lessons from the damages may be summarized with the estimated reasons as follows:

Collapse and severe damages would be induced due to lack of the hoop ratio in the columns, load concentration, long span and high varying axial load by interrupted walls in the old buildings. The current seismic evaluation procedure would efficient to simulate these possible damages. Also engineers should ensure sufficient stiffness of steel members to preserve integral response behaviour.

Amplification of the ground motion peculiar to the site, especially on the hill, should be taken into account, in reconstruction and design of new buildings after demolish of the damaged buildings. Seismic micro zoning with soil condition and observation on site would be useful in design. Current seismic strengthening method was effective to improve the seismic performance of school buildings so that dissemination of seismic retrofit, esp. with economical methods, are essential to residential or commercial buildings also.

Design forces at the joints of concrete walls/columns and steel beams might be insufficient, even in the current design code. Further analytical and experimental studies are needed on the problem. Ceiling and non-structural walls need the sufficient specifications on detailing or structural calculation in new design to prevent damages and falling down. A transparent evaluation method for those in old buildings is also needed. Pile and foundation need ultimate state design to prevent damages to foundations with consideration of non-linear soil-structure interaction.

9. CONCLUSIONS

The results of AIJ damage survey on RC school buildings after the 2011 East Japan Earthquake are reported. The levels of damages to building structures are classified based on the field observation data on buildings in the affected regions. The damage rates in the selected area are analysed and discussed based on the statistical data of the inventory damage rates on high-school buildings as well as in relation with the calculated seismic performance indices. The lessons and design implications from the observed damages and analysis are also summarized.

ACKNOWLEDGMENTS

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