Proceedings of the International Symposium on Engineering Lessons Learned from
the 2011 Great East Japan Earthquake, March 1-4, 2012, Tokyo, Japan

DAMAGE SURVEY ON BUILDINGS AND THE LESSONS FROM THE 2011 EAST JAPAN EARTHQUAKE

Toshimi KABEYASAWA

Professor, Earthquake Research Institute, University of Tokyo,
Tokyo, Japan, kabe@eri.u-tokyo.ac.jp

ABSTRACT: Damage survey on buildings is outlined, which was conducted as a part of reconnaissance activity of AIJ, Architectural Institute of Japan after the 2011 East Japan Earthquake. Typical types and levels of damages to building structures are classified, both by the ground motions and the tsunami waves, based on the field observation data on buildings in the affected regions. The damage rates in the selected area are analyzed and discussed based on the statistical data of the inventory damage rates, as well as in relation with calculated seismic performance indices.

Key Words: damage survey, reinforced concrete, school buildings, damage evaluation, seismic evaluation, strengthening

INTRODUCTION

Typical damages to buildings, especially to reinforced concrete buildings, both by the ground motions and the tsunami waves during the 2011 East Japan Earthquake, are outlined in the paper. The field survey was conducted in the first stage individually by research institutes or groups also as the members of AIJ, especially as the members of reinforced concrete steering committee, Architectural Institute of Japan. The report herein is mostly based on the individual survey by the author in Fukushima region but also partially referring to the manuscripts by the group members for the preliminary reconnaissance report of AIJ (AIJ, 2011).

Reinforced concrete buildings surveyed by AIJ teams were categorized into the following four groups based on the intended use as: (1) school buildings and community centers, (2) public buildings (mainly government offices), (3) residential buildings, and (4) commercial buildings. The surveyed buildings are not comprehensive especially for the commercial buildings or private company offices and private collective houses, while damaged school buildings and public halls are surveyed mostly based on the preliminary post-earthquake survey list.

The AIJ organized a special committee and working groups after the earthquake to investigate damages to school buildings and public halls, 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 members conducted the field survey based on the request of the local governments in charge of the facility ad-ministration. More than 700 buildings were surveyed in total: (1) about 400 rein-forced concrete (RC) school buildings, (2) 200 steel or steel concrete composed gymnasiums, (3) 100 others such as timber schools, community centers and public halls with various structural types.

The results of damage investigation above are to be compiled and published from AIJ with the whole statistical analysis on the surveyed buildings as well as detailed reports on selected buildings and seismic performance evaluation. In this paper, typical damages observed through the survey of AIJ and the derived lessons are reported with part of the statistical investigation from the survey.

GROUND MOTIONS AT K-NET STATIONS IN FUKUSHIMA

Ground motions at surface were observed at K-net stations in Fukushima region, which 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 acceleration response spectra and the velocity response spectra are calculated, as shown in Fig. 1 and Fig. 2, respectively, for the main shocks starting from 14:46, March 11, to estimate input ground shaking to the surveyed buildings below, most of which were close either of ten stations selected in Fukushima region, such as in Yanagawa, Fukushima, Haramachi, Iwaki, Nakoso, Shirakawa, Sukagawa, Koriyama, Nihonmatsu, and Aizuwakamatsu.

Far field motions by the 2011 earthquake of magnitude 9.0 are compared with near field motions by recent earthquakes of magnitude around 7.0, as shown in Fig. 3 and Fig. 4. The far field motions have long duration, more than 120 seconds, and wide range of frequency components, while near field motions have short duration, and with amplified components in the longer period, so that the near field motions are sometimes more effective to responses of medium RC buildings and low-rise timber buildings.

Although the magnitude 9.0, the epicenter distances were more than 200km－400km, so that the intensities were almost close to design level of very rare earthquake, Level 2. The ground motions recorded during the 2011 Earthquake were smaller less than the extreme motions recorded at recent near field earthquakes (1995 Kobe, 2004 Niigata, 2007 Niigata). The near field extreme motions (1995 Kobe and 1948 Fukui) might have been twice to three-times higher than the 2011 records, so that relatively small damages would not ensure the safety in the future. The near field earthquakes occur once or more every ten year somewhere in Japan, therefore the collapse or severe damages of buildings, which might cause the casualty, could still be the major problem in the future earthquakes more than in cases of the 2011 earthquake.

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

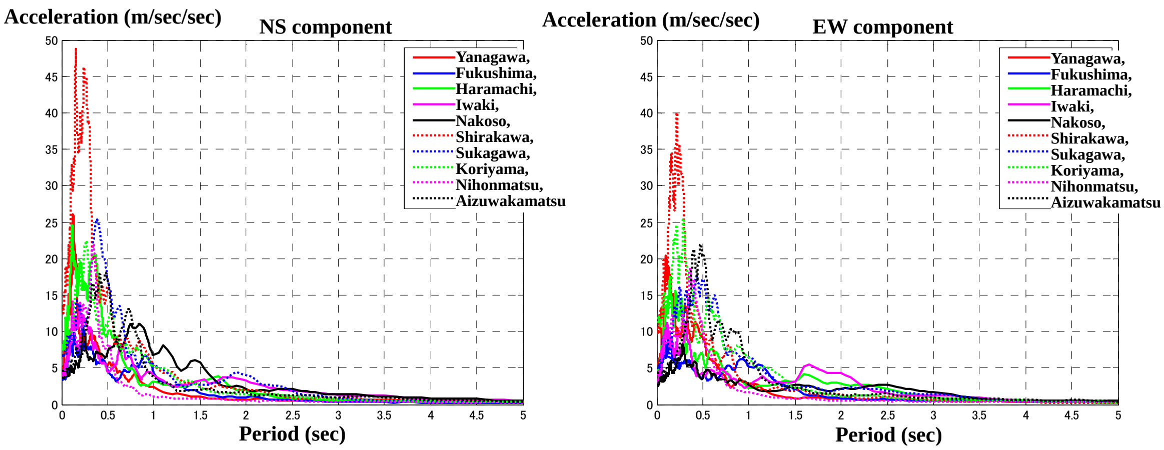

Fig. 1 Acceleration response spectra by the ground motions recorded in Fukushima

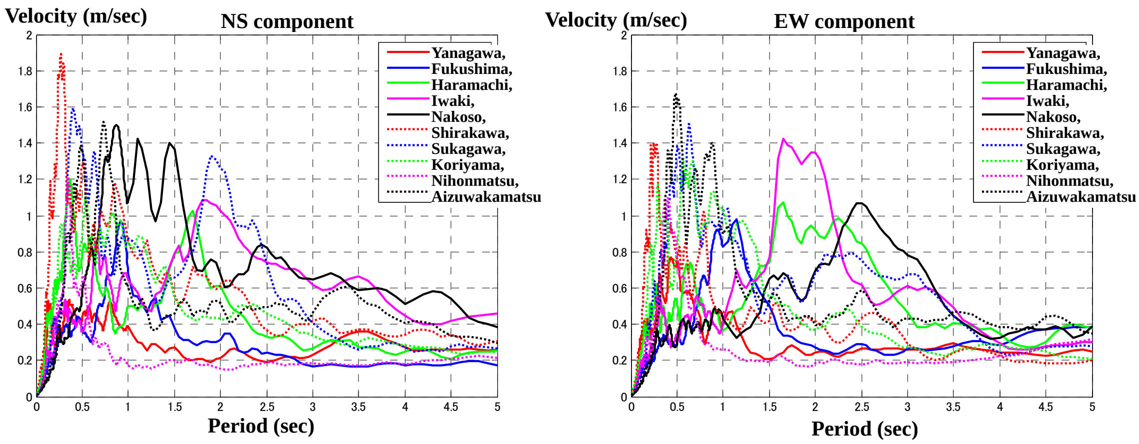

Fig. 2 Velocity response spectra by the ground motions recorded in Fukushima

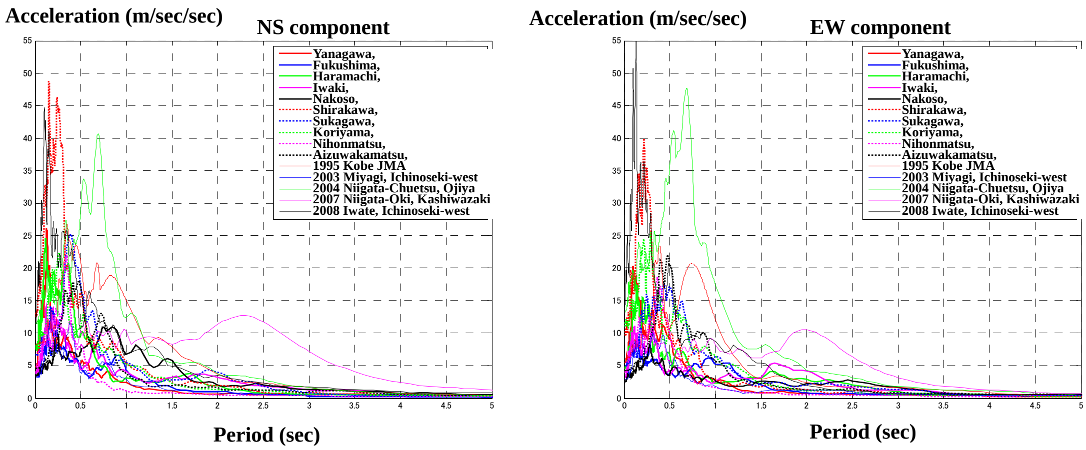

Fig. 3 Acceleration response spectra compared with those by recent near field motions

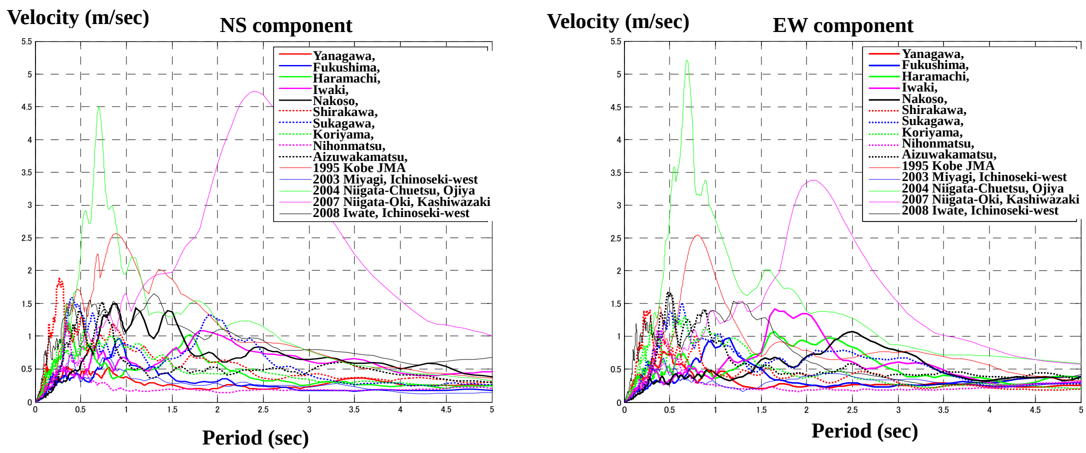

Fig. 4 Velocity response spectra compared with those by recent near field motions

METHOD OF EVALUATING DAMAGE LEVEL

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, 2001a) and described as below. Because the buildings for survey were selected through the request of the administrators, all the buildings with serious damage such as moderate or more should have been included for damage 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.

Detailed investigations on the design, construction, age and structural drawings were available for most of public buildings, while the investigations on private buildings are limited very much. Also for most of the public buildings, especially on schools, the seismic capacity indices “Is-values” had been evaluated based on the Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings (2001 Japanese version and 2004 English version) by professional engineers re-quested 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. Some of the seismic indices or the concrete strengths are referred with the damage evaluation below, though the detailed results and analyses with the seismic intensities will be reported elsewhere.

On the other hand, the ground motions have been recorded at K-net stations in the major cities and JMA intensity scales have been identified officially by Japan Meteorological Agency for more small zones of municipal area. The seismic intensity sensors are installed mostly in the free field nearby the city hall buildings. The JMA intensity scales at the site of the damaged buildings are referred in the report below from these identified values such as 5-, 5+, 6-, 6+ and 7(not recorded in the 2011 earthquake), which approximately correspond to 8-, 8+, 9, 10 and 11 by the Modified Mercalli intensity (MMI) scale.

The post-earthquake damage evaluation on the reinforced concrete buildings were conducted based on “the Japanese standard of damage evaluation in post-earthquake inspection[JBDPA, 2001]”, by which the damage grade were classified into one of the five grades and no damage estimating the residual seismic capacity ratio R. The rate of damage is calculated in term of the residual seismic capacity R, which expresses the ratio of the post-earthquake residual capacity to the pre-earthquake original capacity, estimated from the observed damage grades of surveyed vertical members.

The vertical members and estimated failure mode are grouped into five types 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. 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 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.

Then the residual capacity of each story is estimated from the numbers of the vertical members with the type classified 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 col-lapse, if the reduction ratio R is (0)100%, (1)95<R<100, (2)80<R<95, (3)60<R<80, (4)R<60, or (5)R seems to be close to zero, respectively.

TYPICAL DAMAGES TO BUILDINGS IN FUKUSHIMA

Damages to buildings in north Fukushima

F-college

Collapse of a building, so-called pancake crush, was observed, as shown in Photo 3, in F-college located north of Fukushima city, which was three-story reinforced concrete building for administration built in 1965. Although the JMA seismic intensity around the site was classified into V+, the site was close to the area of VI lower, and also it was indicated from aftershock observation that the ground motion might be higher in the site than the center of Fukushima city. The building had a Y-shaped plan with a stair hall in the center and three longitudinal blocks spread to north, east and west directions as equivalent triangular. It is estimated that the concentration or unequal distribution of the lateral earthquake loads might have occurred among the three blocks, due to the difference of the inner column heights, by which the severe collapse was induced peculiar to this building.

Photo 1 Damages to F-college building

N-elementary school

Severe brittle failure of a short column at the entrance hall was observed in N-elementary school 3-story RC building constructed in 1968, as shown in Photo 2. The seismic intensity at the site was estimated as V+ and the seismic performance index was calculated as Is=0.42, though the heavy damage was concentrated to the short column. Moderate damages to other columns were observed and the damage level was classified into severe, so that the building is to be demolished and replaced.

Photo 2 Damages to N-elementary school building

H-high school
Severe brittle failure of short columns in the north frame was observed in H-high school 4-story RC building constructed in 1970, as shown in Photo 3. The intensity of the motion around the sight was VI lower. The shear failure is mainly due to less hoop ratio based on the old code, 9 ϕ @250mm. The damage level was classified into severe and the building is to be demolished. Calculated Is was 0.39 in the second story and measured concrete strength was 16MPa. The damage level of the other 3-story building with Is=0.47 was moderate and is to be repaired and strengthened.

Photo 3 Damage to H-high school building

D-Gymnasium
Spalling off of concrete was observed at the base anchorage of roof truss fame in D-gymnasium in north Fukushima. The structure is reinforced concrete column-wall system with steel truss-frame roof. The administrator said that the damage of spalling off was induced by the aftershock of April 7, when refugees occupied the gymnasium to stay day and night. It was fortunate that the refugees barely escaped from injury during the aftershocks. Also the detailed post-earthquake inspection is necessary to avoid the secondary damages. Though it is not considered even in the current code, the author have suspected that much higher expanding forces might have acted to the joint than estimated from design calculation, not only in this case but also in many other cases, where the steel beams were connected or anchored to the cantilever columns or walls, which could be induced by the different phases of responses on the opposite sides, as like as shown in Fig. 5(a). The difference could not be estimated from elastic/symmetric modes but might be possible in inelastic/asymmetric modes with insufficient stiffness on the roof. The possible maximum forces should be investigated further through analytical and experimental studies.

Photo 4 Damage to D-Gymunasium

Fig. 5(a) Expanding force on the joint

Damages to buildings in middle Fukushima

M-junior high school

Near collapse failure was observed at M-junior high school building, 3-story built in 1966, as shown in Photo 5, where the JMA seismic intensity recorded as 5+. The shear walls from base to top are located as partitions between classrooms in the span direction except for two frames in the first story, as shown in Fig. 5(b), by which large varying axial loads were generated to the isolated columns during earthquakes and the near collapse failure was induced.

Photo 5 Damage to M-junior high school building

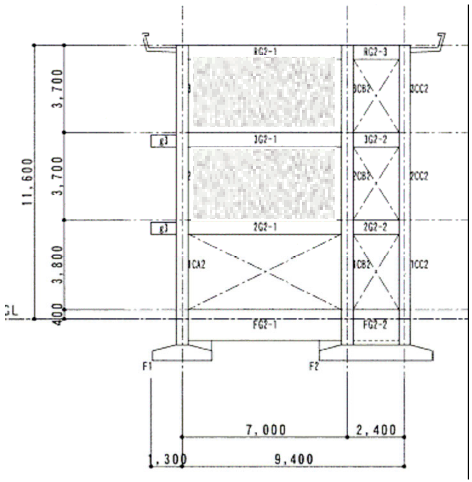

Fig. 5(b) Discontinuous walls

A-high school

Severe shear failure in short columns are observed in A-high school, 3-story RC building built in 1964. The structure was bare from original with very low seismic performance index (Is=0.17) and suffered the severe damage, as shown in Photo 6. The building is to be demolished. The damaged building was connected with expansion joint to the adjacent building in west, which had been retrofitted at the time of the earthquake. The building was originally built in 1966 and the seismic index before retrofit was evaluated as Is=0.25, which had been strengthened with steel braces exceeding the standard required level of Is=0.7. The retrofitted west building suffered no damage, as shown in Photo 7. The effect of retrofit on the actual seismic performance was indisputably evident in the case.

Photo 6 A-high school building (Bare east part, 1964)

Photo 7 A-high school building (Retrofitted west part, 1966)

K-elementary school

The effect of retrofit was also verified in K-elementary school, which was structurally continuous but had been partially retrofitted at the time of earthquake. The building was built in 1969, and the bare west part, waiting for retrofit in 2011, suffered severe damage, while the east part had been strengthened with steel braces and resulted in no damage, as shown in Photo 8 and Photo 9. In this case, the retrofit was found to be effective partially to the frame nearby the strengthening, but the rigid slab assumption was not much effective in case of the longer building the longer longitudinal size.

Photo 8 K-elementary school building (Bare west part, Severe)

Photo 9 K-elementary school building (Retrofitted east part, No damage)

S-elementary school
Severe damages to columns to north frame were observed in S-elementary school buildings, consisting of four three-story RC buildings built in 1965, as shown in Photo 10. The JMA seismic intensity was 6+ at the station 1 km east from the school. The I_s-value was 0.46 with the space of column hoops was 300mm.

Photo 10 Damages to K-elementary school buildings

S-junior high school
The gymnasium with RC walls and Steel keel beam and roof built in 1985 suffered moderate structural damage to the joint concrete on the roof, as shown in Photo 11. The joint behavior and the design should be investigated in detail further as indicated for the damage of D-gymnasium above.

Photo 11 Damages to S-junior high school gymnasium

I-training center
It was not functional in use long time after the earthquake due to damages to ceilings in a gymnasium of I-training center, which was in accordance with the current code and almost with no/slight structural damages, as shown in Photo 12.

Photo 12 Damages to I-training center gymnasium

T-public hall

Structural damages to the south façade in T-public hall were slight though serious damages were observed in the third-story conference room with the falling of ceilings, as shown in Photo 13. The building was built in 1967 up to the second story with RC frames, as a public hall of Tamura city, and the third story was added in 1980 with RC columns, steel beams and PC lightweight roof-slabs. The joint concrete at beam ends spalled off, probably due to the out-of-plane expanding behavior of cantilever columns, which might not had been taken into account in design analysis. The damage was evaluated as moderate, though the heavy repair construction would be required.

Photo 13 Damages to T-public hall building

Damages to buildings in south Fukushima

S-high school

Damage to a short column was observed in S-high school building, 2-story RC built in 1964, as shown in Photo 14. The intensity of the ground motions in the region was VI+ and relatively high. The acceleration response spectra recorded in Shirakawa exceeded 4G at around the period of 0.25 sec., which might be estimated not to be effective to the damages to the buildings.

Photo 14 Damages to S-high school building

Damages to buildings in east Fukushima (Minami soma)

S-elementary school

Damages by Tsunami wave were observed in S-elementary school building, 2-story RC built in 1975 and gymnasium, RC with steel roof, built in 1992. The height of the Tsunami wave was up to 1.6m at the site in Minami-soma, which was located about 3km west from the coast, as shown in Photo 15.

Photo 15 Damages to S-elementary school building and gymnasium

Damages to buildings in south-east Fukushima (Iwaki)

IK-high school

Damages by Tsunami wave was observed in IK-high school buildings, originally as fisheries high school, 3-story and 4-story RC main buildings built in 1979-80, as shown in Photo 16. The height of the Tsunami was up to the ceiling of the first story of 3.5m, where the site was located along the coast of south Iwaki. The structural damages were not observed in the RC buildings. Heavy damages to external walls were observed in other twenty buildings, one- or two-story, RC or steel structures, while structural members remained though residual deformations are observed in some steel members, as shown in Photo 17.

Photo 16 Damages to IK-high school RC buildings

Photo 17 Damages to IK-high school buildings

I-high school

Relatively severe damages of near collapse were observed to the columns in I-high school buildings as shown in Figs. 18 through 20. Four RC buildings with 4-/3-/2-/2-story were constructed from 1973 to 1975. The column hoops were 13mm bars at the spacing of 100mm. The seismic indices Is-values had been calculated as 0.59, 0.64, 1.08 and 1.44. It was expected from these values that the damages would not be so heavy under the main shock of the seismic intensity 5- around. However, it was also expected that the high amplification of the ground motions could be induced due to the hill site effect. Actually observed damages were relatively severe or moderate with the residual seismic capacity of R=33, 47, 73, 72%.

Photo 18 Site on the hill of I-high school buildings

Photo 19 Damages to I-high school buildings

Photo 20 Damaged columns in I-high school buildings

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) local site effects, (2) input loss of the ground motions, and (3) response characteristics of the buildings, which have brought quite successful data to verify these effects on site. Therefore, a set of three points for observation at one site will be ideal though the number of available seismographs is 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 in Fig. 6 for the site of I-high school described as 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 the figure. It was obvious that the response spectrum at around of the period of 0.6 second was much amplified at the hill top, especially in EW component by several times. Although the ratio of the main shock might have been smaller than in case of aftershock for due to the non-linear soil responses, it would be necessary to take the local site amplification into account, such as by 1.5 or 2.0 times, if the new buildings are to be designed and constructed in the rehabilitation procedure.

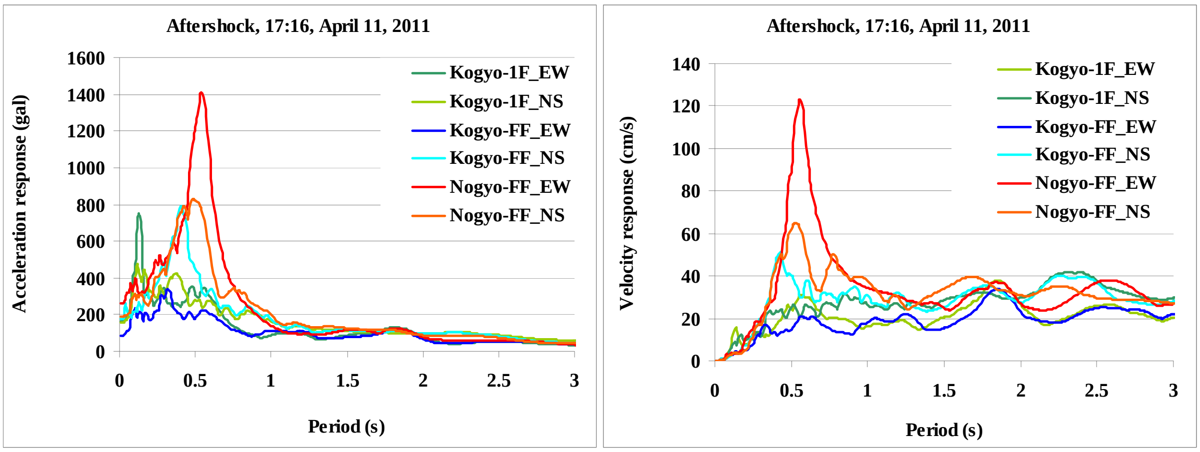

Fig. 6 Response spectra of aftershocks at the sites at the top and the bottom of the hill

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 about 700, which were widely distributed over nine prefectures in Tohoku and Kanto area. The list of the buildings for AIJ survey were based on the requests from the local governments through MEXT, 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 Fig. 7, while regional distributions are shown in Figs. 8 and 9. 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 behavior.

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 Figs 1 to 4. 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.

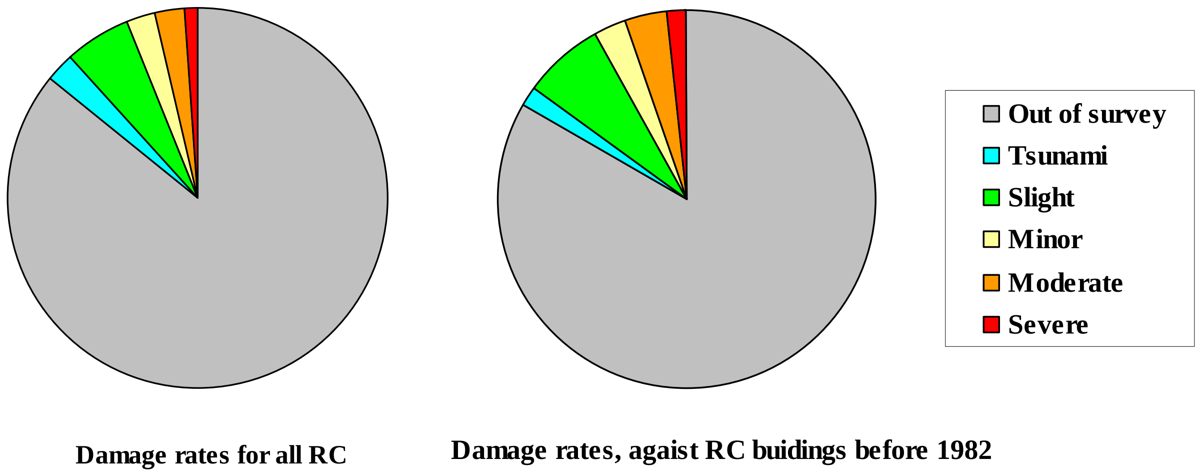

Fig. 7 Inventory damage rates for all prefecture school buildings

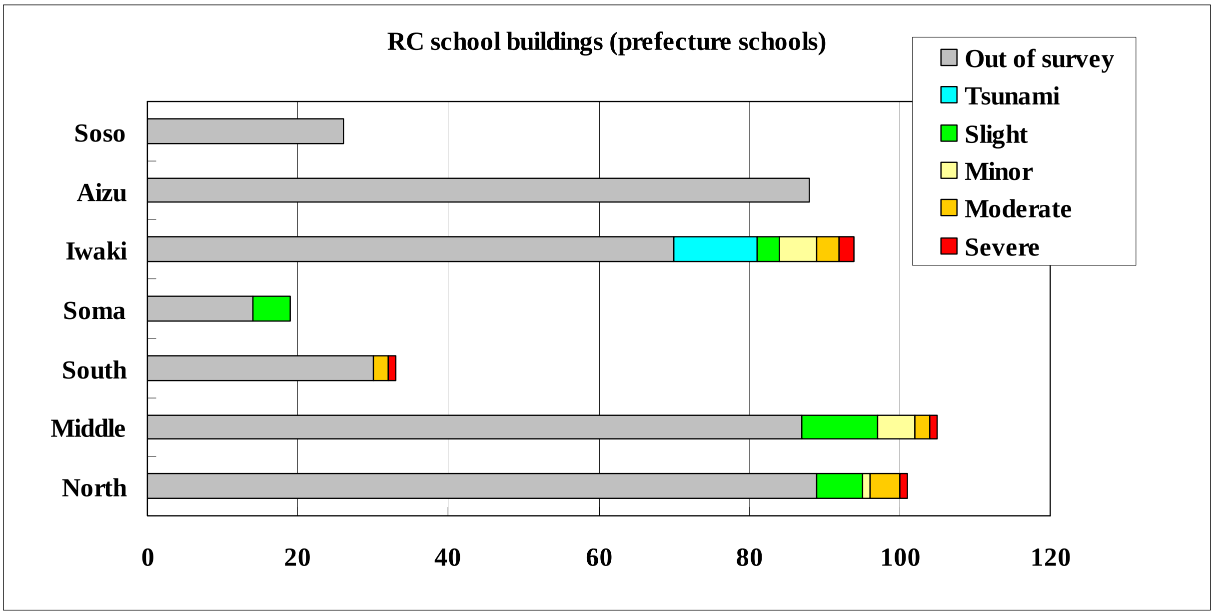

Fig. 8 Regional distribution of inventory damage rates for all prefecture school buildings

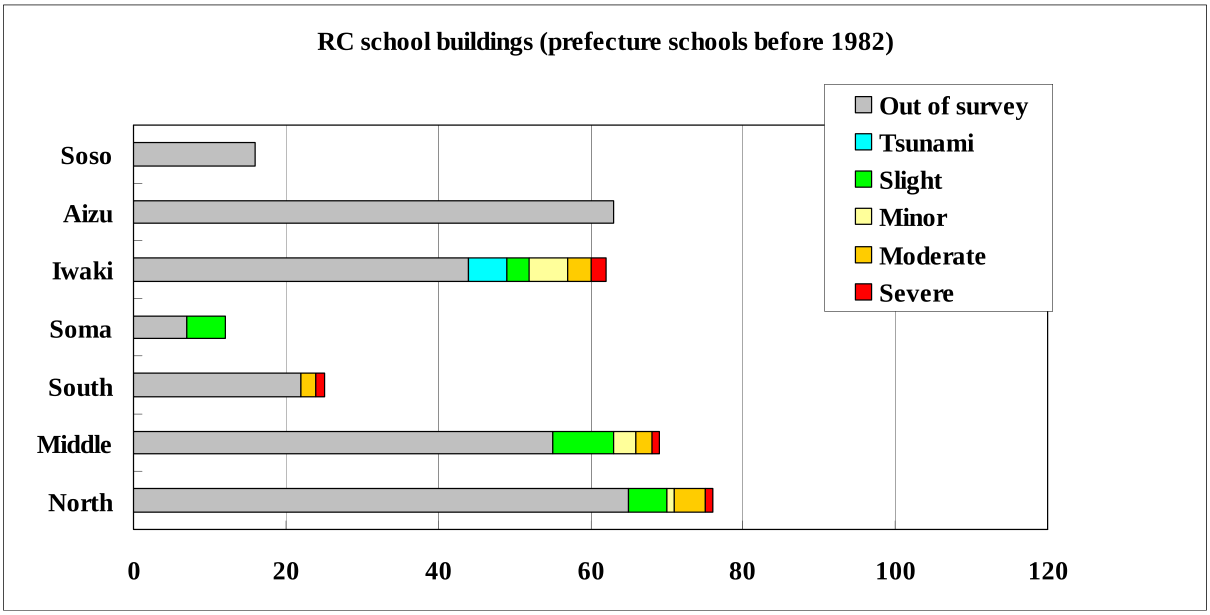

Fig. 9 Regional distribution of inventory damage rates for prefecture school buildings before 1982

RELATIONS BTW DAMAEGE RATE AND SEISMIC PERFORMANCE

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 after 1995. 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 after 1981 have been regarded as exceeding the safety requirements in the seismic performance evaluation standard without any evaluation procedure so far, however the detailed and rigorous evaluation might be necessary in the future, especially for buildings designed and constructed before 1995.

If the seismic safety ratio 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 Fig. 10. The regional distributions of these seismic performance ranks are shown in Figs. 11 and 12, also before and after retrofit. 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 Figs. 8 and 9 were generally smaller.

The direct relations are plotted in Fig. 12 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. The unknown R is assumed as 99%, which might not be different much, even if evaluated, while the unknown Is is assumed as zero, which is to be disregarded. 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 is 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. Detailed model and analysis are needed to simulate the damage level in relation with the estimated input motions.

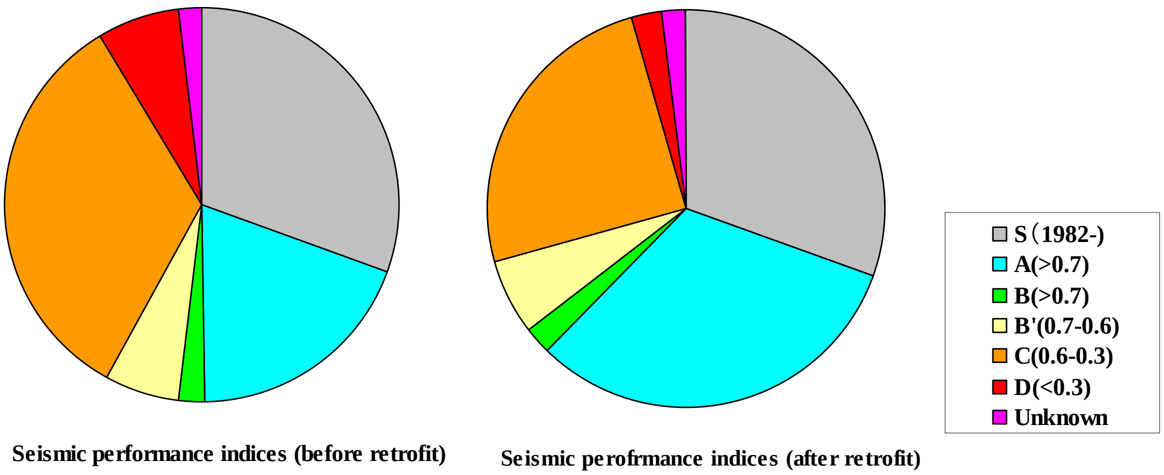

Fig. 10 Seismic performance indices before and after retrofit

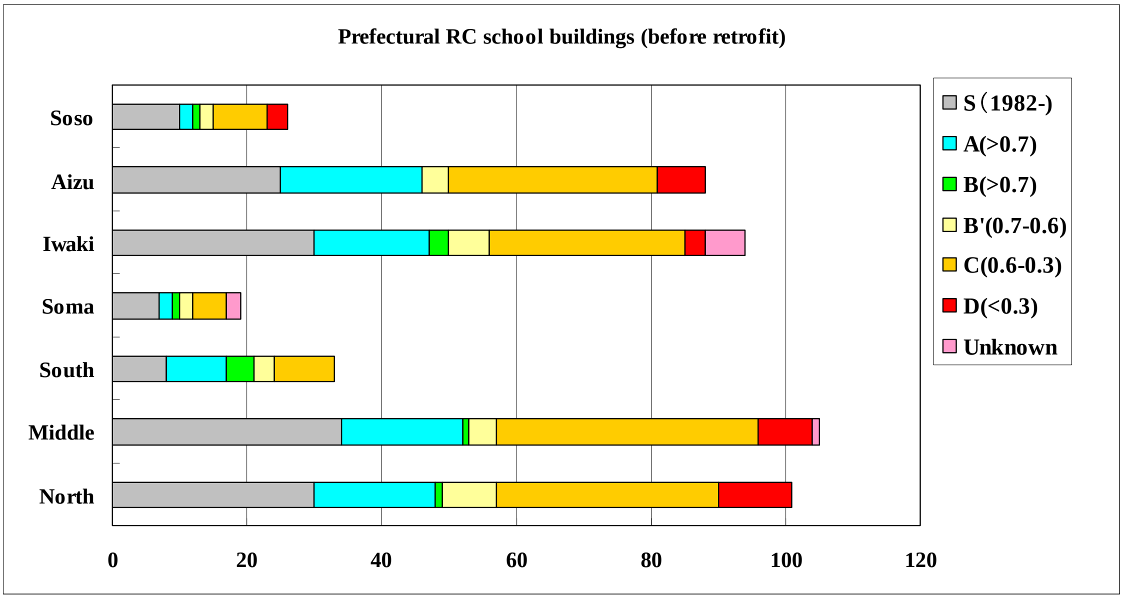

Fig. 11 Regional distribution of seismic performance indices before retrofit

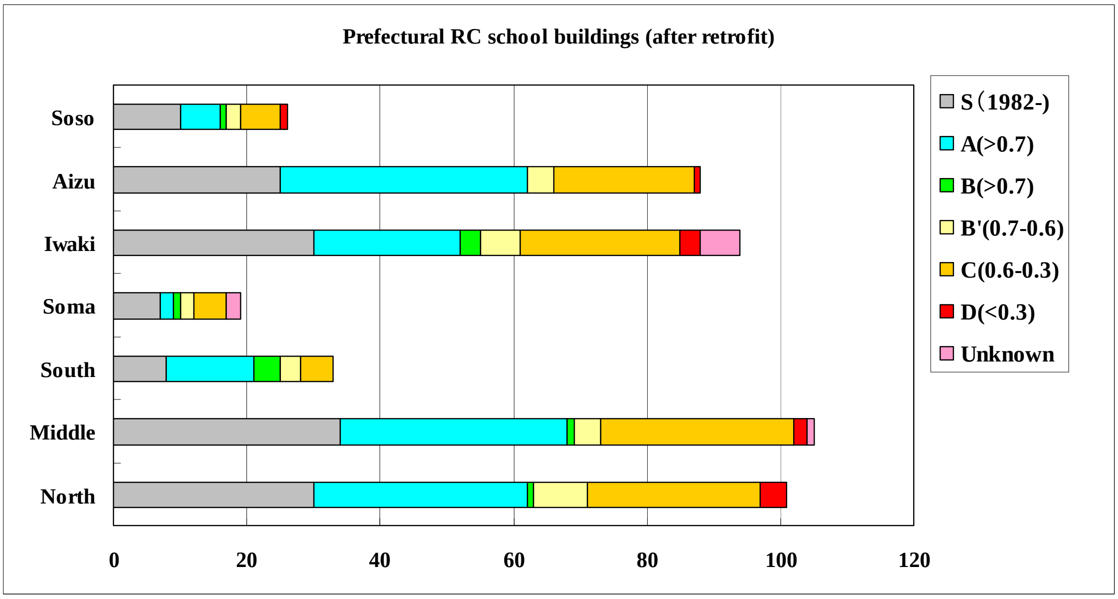

Fig. 12 Regional distribution of seismic performance indices after retrofit

LESSONS FROM THE DAMAGES AND DESIGN IMPLICATIONS

Summary of the observed damages and their reasons

As a result of survey, typical damages to reinforced concrete school buildings from the 2011 Earthquake may be summarized as follows with estimated reasons:

(1) Several buildings suffered very serious damages, such as collapse or severe, which requires demolish and reconstruction for restoration, although the rate was very low.

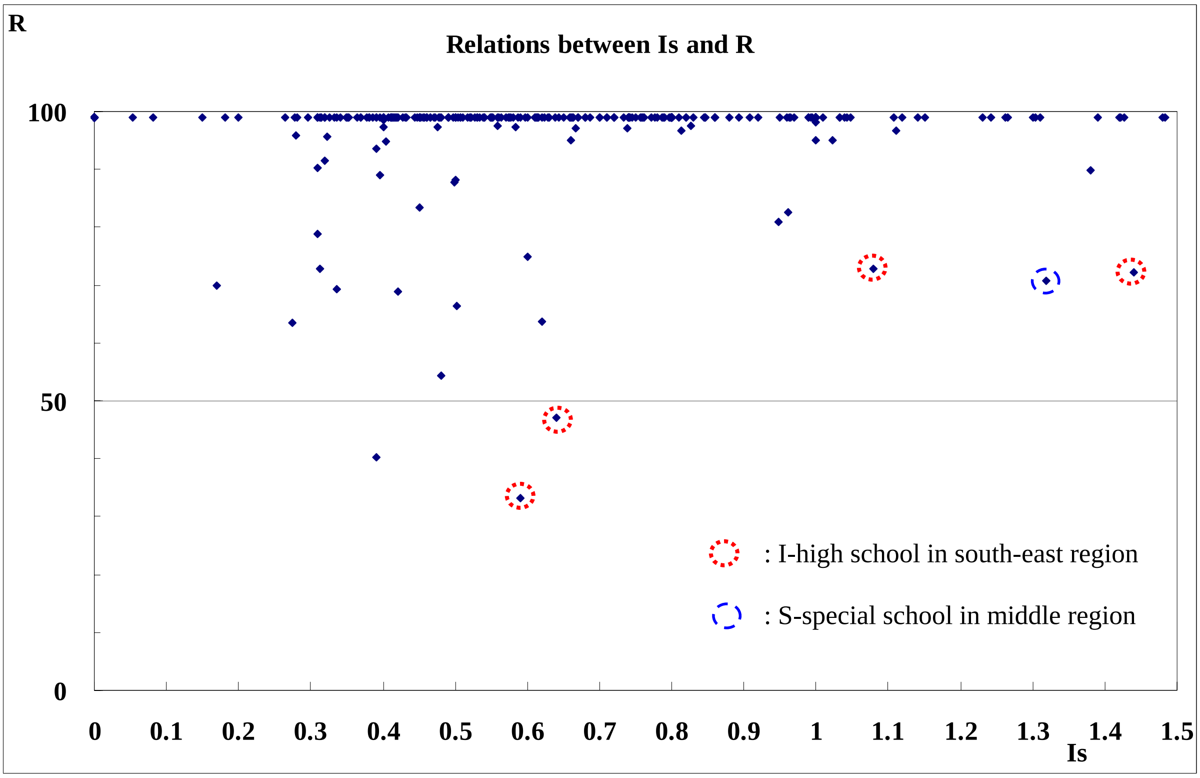

Fig. 13 Relations between the seismic performance indices **Is** and the damage rates in terms of the residual capacity **R** (%)

(2) Numbers of buildings suffered moderate or minor damages, by which they were not functional in continual use and requires repair or strengthening.
(3) The damaged RC buildings of high schools were constructed before 1981 when the current code was put into practice.
(4) 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.
(5) Relatively heavy damages are observed at the joint concrete with steel and/or timber members in concrete structures combined with steel or timber members.
(6) 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.
(7) Non-structural walls and ceilings were severely damaged in many cases, not only with old but also with new buildings.
(8) Damages seemed to be increased by the amplification of ground motions due to soils and hills, was observed and the effect was clearly verified through aftershock observation.
(9) Settlement of base foundation due to damages to piles or soils or liquefaction were observed, which could not be introduced in this paper.
(10) 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 further research needs

(1) 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.
(2) 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. Also engineers should ensure sufficient stiffness of steel members to preserve integral response behavior.

(3) Amplification of the ground motion peculiar to the site, especially by the hill, should be taken into account, in reconstruction and design of buildings after demolish of damaged buildings. Seismic micro zoning with soil condition and observation on site would be useful in design.
(4) Pile and foundation need ultimate state design to prevent damages to foundations with consideration of non-linear soil-structure interaction.
(5) Ceiling and non-structural walls need the sufficient specifications on detailing or structural calculation in new design to prevent damages and falling down. The transparent evaluation method for those in old buildings is also needed.
(6) Structural plan to add strength in longitudinal direction using walls and wing walls
(7) 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.
(8) Location plan and design against possible tsunami waves are required for the buildings in the tsunami-affected regions.
(9) Extreme motions from near sources should be considered not only to ensure safety but also functionality in use for school buildings, which would have much higher intensity than observed in the 2011 earthquake.

CONCLUSIONS

The results of AIJ damage survey on RC school buildings after the 2011 East Japan Earthquake are reported. Typical types and 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 analyzed and discussed based on the statistical data of the inventory damage rates as well as in relation with calculated seismic performance indices. The lessons and design implications from the observed damages and analysis are summarized.

ACKNOWLEDGMENTS

The field survey was conducted as the reconnaissance activity of Architectural Institute of Japan, from April to June 2011, which was requested from the local governments through MEXT, Ministry of Education as part of the rehabilitation procedure on the damaged school buildings. The voluntary activities of the committee members of AIJ, the clerical supports of the staffs in the local governments and MEXT and the technical support of practical engineers on the field survey are gratefully acknowledged. Some of the statistics, esp. on seismic evaluation of school buildings, are based on the closed data within Fukushima prefecture provided to the author in the process of damage evaluation. The efforts of the engineers and staffs involved in the seismic evaluation and strengthening practices are also gratefully acknowledged.

REFERENCES

JBDPA(2001a), "*Standard for Damage Level Evaluation and Guidelines for Recovery Technologies of Buildings Damaged by Earthquake (in Japanese),*" Japan Building Disaster Prevention Association, 360pp.

JBDPA(2001b), "*Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings (2001 Japanese version and 2004 English version),*" Japan Building Disaster Prevention Association.