SEISMIC CAPACITY OF EXISTING RC SCHOOL BUILDINGS IN OTA CITY, TOKYO, JAPAN

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SUMMARY

The 1995 Hyogoken-nambu Earthquake which caused devastating damage to urban centers triggered a new direction in seismic evaluation and retrofit of existing vulnerable buildings in Japan. The widespread damage especially to older buildings designed to meet the code criteria of the time of their construction revealed the urgency of implementing seismically vulnerable buildings. Following the event, the Ministry of Construction promulgated a new law to promote seismic evaluation and retrofit, and the Ministry of Education launched a five-year project to financially support seismic retrofit of school buildings. Since then, extensive efforts have been directed toward seismic evaluation and retrofit of school buildings in Ota City, which is located in the south of the urban center of Tokyo, and all the school buildings in the City designed according to the dated codes were evaluated and some of them were retrofitted. In this paper, seismic capacities of existing RC school buildings in the City are statistically investigated and those before and after retrofit are mutually compared to discuss their structural performance.

INTRODUCTION

The 1995 Hyogoken-nambu (Kobe) Earthquake caused devastating damage to urban centers and triggered a new direction in seismic evaluation and retrofit of existing vulnerable buildings in Japan. The widespread damage to old buildings revealed the urgency of implementing retrofit of seismically vulnerable buildings.

Ota City, which is located in the south of urban center of Tokyo, had started a seismic retrofit program of school buildings before the Kobe Earthquake. However, since the damage observed in Kobe indicates that school buildings should be properly functional as refugee centers as well as structurally safe, all school buildings in the City are currently being reevaluated considering the required function as a temporary refugee center. To implement the lessons learned from the disaster, the Ministry of Construction enforced a new law to promote seismic evaluation and retrofit of existing vulnerable buildings, and the Ministry of Education launched a five-year national project to financially support seismic retrofit of school buildings throughout Japan. These nationwide actions have been significantly accelerating to promote the City's seismic retrofit program.

In this paper, seismic capacities of existing RC school buildings in the City are statistically investigated and those before and after retrofit are mutually compared to discuss their structural improvement.

OUTLINE OF RETROFIT PROGRAM AND INVESTIGATED RC SCHOOL BUILDINGS

All statistical data investigated in this paper are based on seismic capacities and other related data of RC school

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building in Ota City. As can be found in **Figure 1**, Ota City is located in the south of urban center of Tokyo. The City consists of residential areas in the north and industrial areas in the south, having a population of 650,000 and a population density of 10,800 per km^2. The City has 340 school buildings including both old and new constructions, and they consist of 91 primary and junior high schools.

As stated earlier, 1995 Kobe Earthquake caused serious damage to old building, especially to those constructed before 1981, and the Japanese Ministry of Education launched a five-year project in 1996 for the seismic retrofit of old school buildings. Since then, the City has directed significant efforts toward seismic evaluation of school buildings and other educational facilities, which were designed and constructed before 1981 when the current National Building Standard Law was enforced, and some of them have been retrofitted or demolished. Seismic evaluation and retrofit design of RC school buildings are based on the Guidelines for Seismic Evaluation and Retrofit [JBDPA, 1990a and b]. The basic concept of the Guidelines appears in **APPENDIX**.

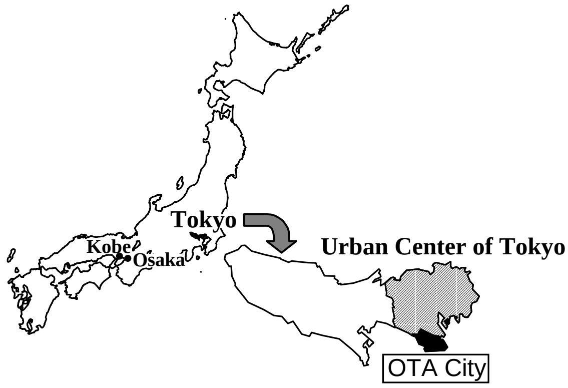
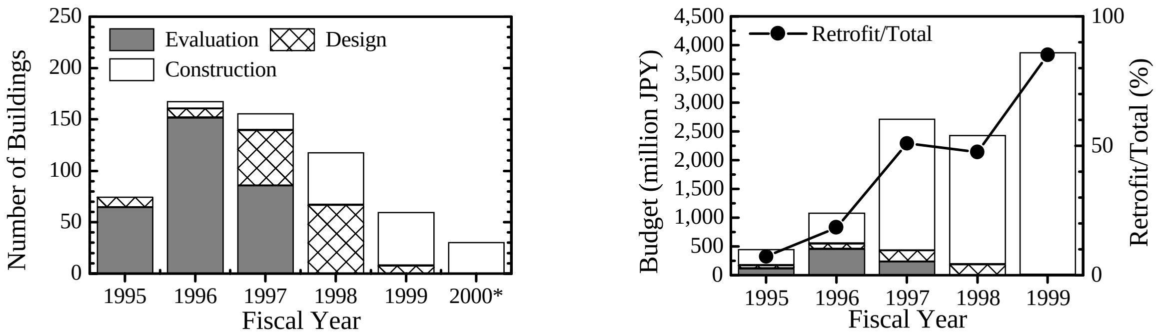


Figure 1: Location of Ota City, Tokyo



(a) Program schedule **(b) Budget details**

*** denotes planned schedule (as of April 1999)**

Figure 2: Outline of seismic retrofit program of school buildings constructed before 1981 in Ota City

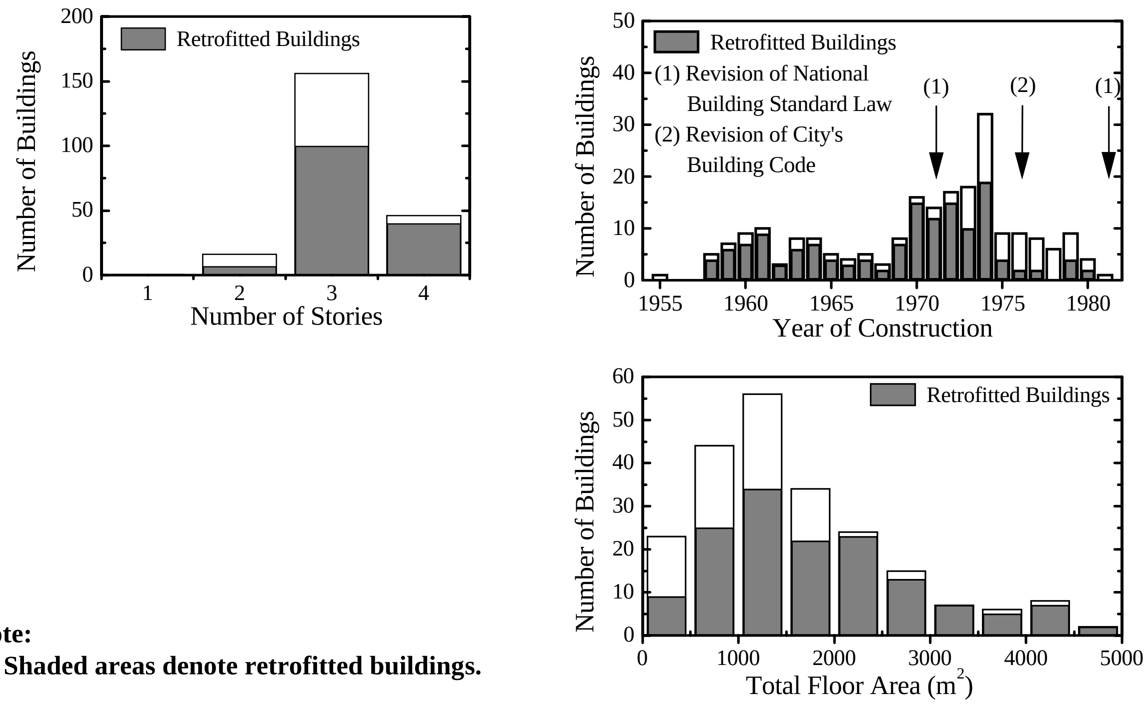
Figure 2(a) shows the retrofit program schedule of the City (as of April 1999). As can be seen in the figure, seismic evaluation of all schools constructed before 1981 is already completed in 1997 and their retrofit design and construction is currently of main concern. A review committee consisting of university professors, practitioners, and building officials is set up to lead the evaluation and retrofit proposals to favorable and fruitful results against an earthquake. In the committee, calculations and/or retrofit proposals are reviewed from the effective and economical engineering practice point of view based on sound engineering and scientific principles and knowledge. **Figure 2(b)** shows the budget details for the retrofit program in each year, together with the ratio of their sum to the total expense for new constructions, retrofit and maintenance of educational facilities. As can be seen in the figure, the expense for seismic retrofit significantly increases in the last three years and 85 % of the total expense is distributed to the program in 1999.

STATISTICAL INVESTIGATIONS OF EXISTING RC SCHOOL BUILDINGS IN OTA CITY

Seismic Capacity of Existing Buildings

Figure 3 shows the fundamental statistics of 219 RC buildings of 82 schools investigated herein. They are all constructed before 1981 and correspond to about 65 % of the total 340 school buildings in the City. The remaining 35 % are RC school buildings constructed after 1981, steel gymnasium facilities etc. The figure shows that the buildings investigated herein are mostly 3 storied and their total floor area is smaller than 2,500 m^2.

The first story of a multistory building generally has the lowest seismic capacity and often sustains most serious structural damage. Approximately 75 % of investigated buildings have the smallest *Is* index in the first story. A shaded area in **Figure 4(a)** shows the distribution of seismic capacity index *Is* in the first story of entire 219 school buildings, where *Is* indices in both principal directions of each building evaluated in accordance with the Guideline described in **APPENDIX** are plotted. As can be found in the figure, the distribution has two peaks, and a distribution containing a peak at smaller *Is* index corresponds to the longitudinal direction while the other to the transverse direction. This is generally because a school building has a few shear walls in the longitudinal direction but enough walls are provided in the transverse direction between classrooms.



Note:
Shaded areas denote retrofitted buildings.

Figure 3: Basic statistics of 219 buildings investigated

In Ota City, to facilitate identifying which school should be retrofitted with higher priority, each building is classified into five ranks shown in **Table 1** depending on the minimal value of *Is* index throughout the structure. The program gives higher priority to a school having a building classified into a lower rank. **Figure 5(a)** shows the distribution of seismic capacity rank of the investigated buildings with respect to their construction year. Although all of them are designed according to the dated code enforced before 1981, approximately half of them are classified into either rank A or B. Bearing in mind that buildings with *Is* index larger than 0.6 survived past major earthquakes in Japan [Nakano and Okada, 1988] and that the new law enforced in 1995 specifies *Is* larger than 0.6 for standard buildings to judge their structural safety, approximately half of the investigated buildings may perform well and avoid extensive structural damage during major earthquakes. **Figure 5(a)** also shows that the seismic capacity of older buildings is generally poor but it is improved in the 1970s, which is consistent with other investigations [Nakano and Okada, 1988]. This is mainly due that the Enforcement Order of Building Standard Law, which applies to buildings throughout Japan, was revised in 1971 and the minimum requirement for shear design was raised to improve ductility of members and overall structure. It should be also pointed out that the seismic capacity is significantly improved in the late 1970s because the City's building code was revised in 1976 to incorporate the importance factor of 1.25 for school buildings.

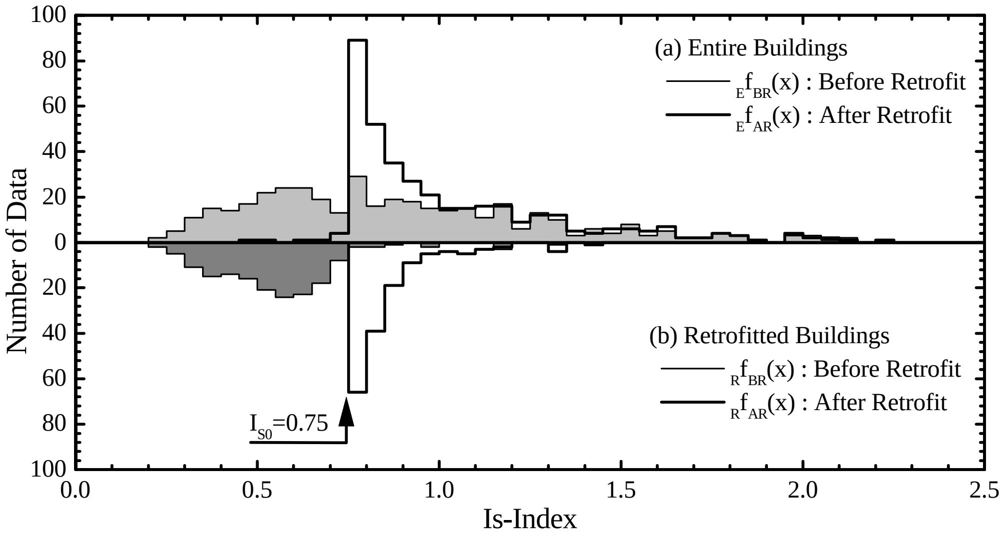
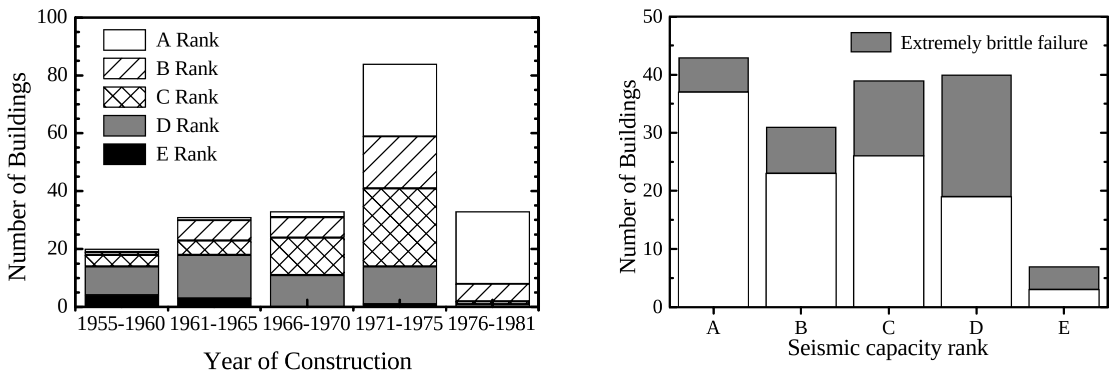


Figure 4: Distribution of *Is* index in the first story

Table 1: Classification of seismic capacity in Ota City

Rank	Definition of *Is*
A	$0.75 \leq Is$
B	$0.60 \leq Is < 0.75$
C	$0.45 \leq Is < 0.60$
D	$0.30 \leq Is < 0.45$
E	$Is < 0.30$



(a) Distribution of seismic capacity ranks (b) Ratio of buildings with brittle failure

Figure 5: Seismic capacity ranks and ratio of buildings with brittle failure

Seismic performance of a structure is often governed by the local but fatal failure of members due to such as extremely brittle failure in short columns. **Figure 5(b)** shows the ratio of buildings in which extremely brittle failure in short columns resulting in fatal damage of an entire structure may be expected during an earthquake. This failure pattern is generally found in the lower rank such as ranks C through E. The result suggests that the improvement of such columns is a key point to upgrade seismically vulnerable buildings.

Seismic Capacity of Retrofitted Buildings

Figure 4(b) shows the distribution of *Is* indices in the first story before and after retrofit of 143 buildings which are identified retrofit candidates. As briefly described in **APPENDIX**, the decision criteria *Iso* to screen sound buildings are set 0.75 in the City considering the basic required seismic capacity of 0.6 and the importance factor of 1.25. As can be seen in the figure, seismic capacities of buildings after retrofit have a significant peak just beyond *Is* = 0.75, and then sharply decrease.

Knowing the frequencies of existing and retrofitted buildings described above, a distribution of entire buildings EfAR (x) including retrofitted buildings can be given as **Eq. (1)** and is shown by a thick line in **Figure 4(a)**. The figure shows that the retrofit significantly improves seismic capacities of RC school buildings in Ota City.

$$EfAR(x) = EfBR(x) - RfBR(x) + RfAR(x) \quad (1)$$

where, EfAR (x), EfBR(x), RfBR(x) and RfAR(x) denote the frequency of following buildings, respectively:

EfAR (x) : entire buildings after retrofit
EfBR(x) : entire buildings before retrofit
RfBR(x) : retrofitted buildings before retrofit
RfAR(x) : retrofitted buildings after retrofit
x: Is index

Figure 4(a) and **(b)** shows that the distributions of existing buildings (EfBR(x)) with Is < 0.75 and retrofit candidates (RfBR(x)) are almost same but a few buildings with Is < 0.75 are not retrofitted as shown by EfAR(x). This is because (1) two demolished buildings are excluded from the retrofit candidates and (2) retrofit designs of other buildings are not completed yet because they are classified into Rank B in **Table 1** and identified to have lower priority for seismic retrofit. It is also interesting to note that some buildings with Is $\geq$ 0.75 are retrofitted. This is either because (1) they have bare columns in the first story that support shear walls in stories above and the columns may fail in a brittle manner when subjected to earthquake induced high axial forces resulting from walls above, or (2) they have Is indices lower than 0.75 in upper stories.

In **Figure 6** is shown the correlation of Is index in the first story of 143 retrofitted buildings before and after retrofit. The seismic capacity is improved especially in the weaker direction and the discrepancy between both principal directions decreases due to retrofit.

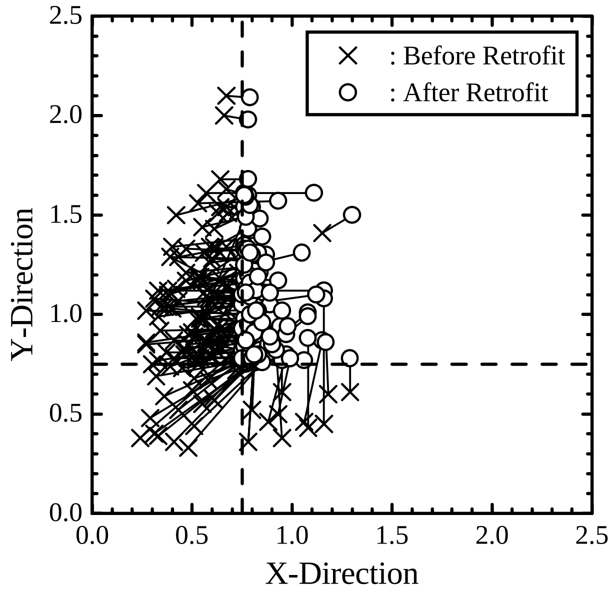
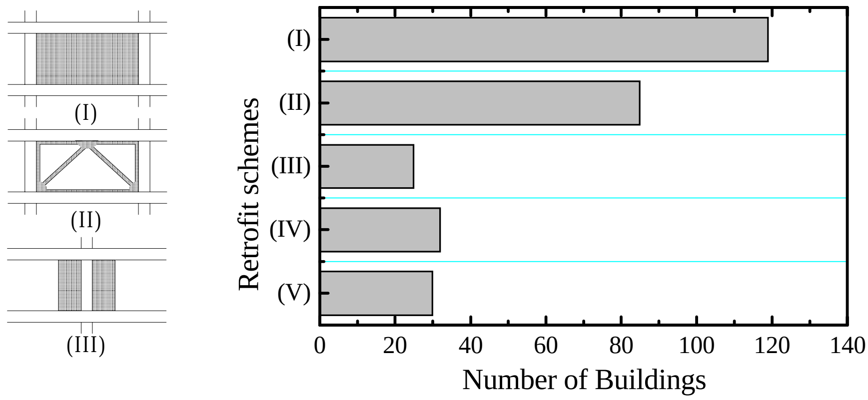


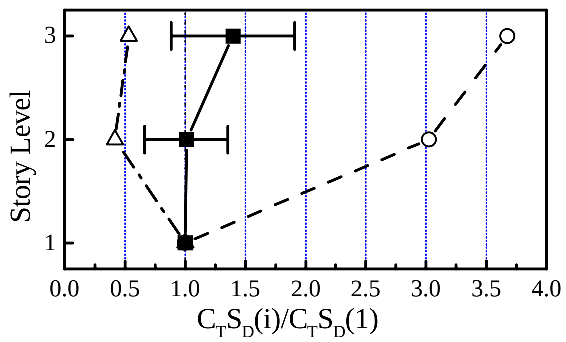
Figure 6: Correlation of *Is* index in the first story before and after retrofit

Figure 7 shows retrofit schemes employed in 143 retrofit candidates. It should be noted that some buildings employ not a single but several schemes together, and the total number in the figure is much larger than 143. In retrofitting an existing RC building, a scheme to infill new RC walls into existing bare frames had been most conventionally applied in Japan since numerous practical experiences as well as experimental and analytical researches were extensively made on this technique. Although it is one of the most reliable strategies to retrofit a seismically vulnerable RC building, infilling often causes less flexibility in architectural and environmental design and/or the increase in building weight sometimes leads to costly redesign of foundation. On the other hand, steel framed braces have been more widely applied in recent years, particularly following the 1995 Kobe Earthquake, to overcome such shortcomings resulting from the conventional RC walls mentioned above. As can be found in **Figure 7**, RC walls are most widely used but steel framed braces are applied to approximately 60 % of retrofit candidates in Ota City, which is same as the recent trends of seismic retrofit in Japan.

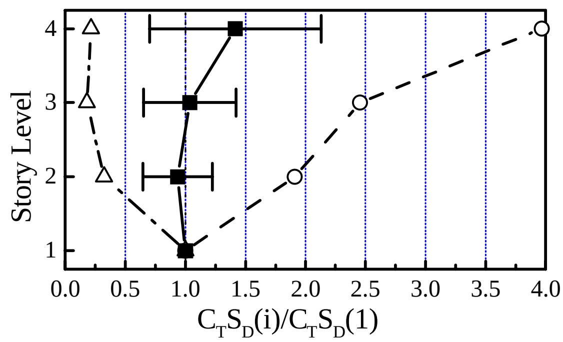


Note : (I) RC wall (II) steel framed brace (III) RC wing wall (IV) column jacketing (V) others

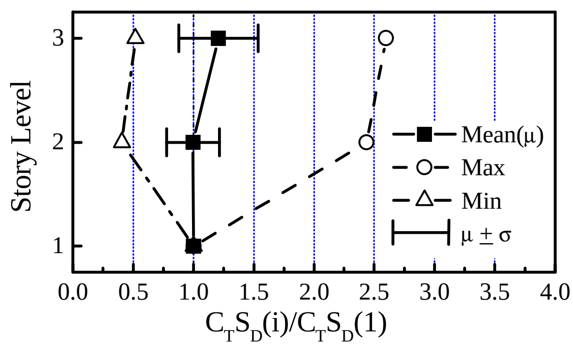
Figure 7: Employed retrofit schemes



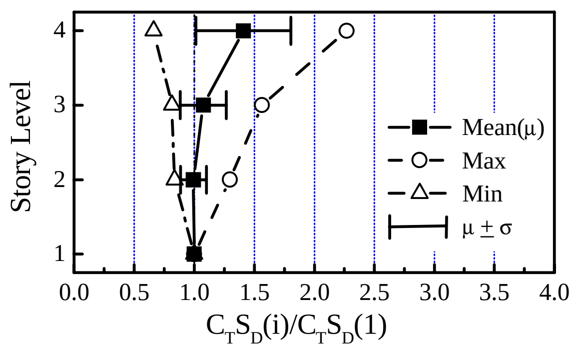
(a) 3 storied buildings before retrofit



(c) 4 storied buildings before retrofit



(b) 3 storied buildings after retrofit



(d) 4 storied buildings after retrofit

Figure 8: Distribution of lateral strength ratio *$R_S(i)$* (= *C_T* x *$S_D(i)$ / C_T* x *$S_D(1)$*) along stories

The distribution of lateral strength along stories is also identified an essential issue to ensure favorable seismic performance. As described in **APPENDIX**, *Is* index is basically calculated from the product of strength index *C* and ductility index *F*, and various combinations of *C* and *F* that can meet a certain value of required capacity index *Iso* therefore can be found numerically. However, if the strength along stories has wide variety rather than uniform distribution, damage may be concentrated in a story extremely weaker than others and the seismic performance may not be fully achieved as expected in the design stage. **Figure 8** shows the distribution of strength along stories for 3 and 4 storied buildings both before and after retrofit, where the strength ratio *Rs(i)* at *i*-th story plotted in the vertical axis is calculated from the ratio of C_T x S_D in each story to the first story as defined in **Eq. (2)**.

$$Rs(i) = C_T \times S_D(i) / C_T \times S_D(1) \qquad (2)$$

where C_T x $S_D(i)$: fundamental structural resistance index at *i*-th story considering structural irregularity as defined in **APPENDIX**

i : story level concerned

As can be seen from the figure, deviation of the lateral strength ratio *Rs(i)* along stories decreases and its mean value tends to converge on 1.0 after retrofit, which implies that the lateral strength distribution along stories is improved due to retrofit as expected. It should be noted that **Figure 8(b)** and **(d)** still include buildings with small value of *Rs(i)*, because they are ductile structures in upper stories and their strength index *C* is relatively low while ductility index *F* is high in upper stories. Although C_T x S_D values of buildings which have $Rs(i) <$ 0.70 in **Figure 8(b)** and **(d)** range from 0.43 to 0.51, their retrofit plans are judged appropriate considering the fact that buildings with Is > 0.75 and C_T x S_D > 0.40 generally performed successfully during the 1995 Kobe Earthquake [AIJ, 1997].

CONCLUDING REMARKS

Seismic capacities of existing RC school buildings in Ota City were statistically investigated, and their relationship before and after retrofit was discussed. Major findings in the investigations can be summarized as below.

1. Seismic capacities of existing RC school buildings in Ota City were widely distributed and significantly dependent on the direction of evaluation due to the presence/absence of shear walls. This result is consistent with other previous research results.
2. Their seismic capacities were also highly dependent on their construction year, and were typically classified into the following three groups: (a) pre-1971, (b) 1971-1975, (c) 1976-1981. This result indicated that revisions of the National Building Standard Law in 1971 and of the City's building code in 1976 significantly contributed to improving their seismic capacities.
3. Major retrofit schemes employed in Ota City were RC walls and steel framed braces, which was consistent with the recent trends of seismic retrofit in Japan.
4. The distribution of lateral strength along stories was improved as expected due to seismic retrofit.

APPENIDX

BASIC CONCEPT OF JAPANESE GUIDELINES FOR SEISMIC EVALUATION AND RETROFIT OF EXISTING RC BUILDINGS

The Guideline for Seismic Evaluation [JBDPA, 1990a] defines the following structural seismic capacity index *Is* at each story level in each principal direction of a building.

$$Is = Eo \times S_D \times T \qquad (3)$$

where, *Eo* : basic structural seismic capacity index, calculated by the products of Strength Index (*C*), Ductility Index (*F*), and Story Index (ϕ) at each story and each direction when a story or building reaches at the ultimate limit state due to lateral force. ($Eo = \phi \times C \times F$)

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

F : index of story ductility, calculated from the ultimate deformation capacity normalized by the story drift of 1/250 when a standard size column is assumed to fail in shear. *F* is dependent on the failure mode of structural members and their sectional properties such as bar arrangement, member's geometric size etc. F is assumed to be in the range of 1.27 to 3.2 for ductile columns, 1.0 for brittle columns and 0.8 for extremely brittle short columns.

ϕ : index of story shear distribution during earthquake, estimated by the inverse of design story shear coefficient distribution normalized by base shear coefficient. $\phi = (n+1)/(n+i)$ is basically employed for the i-th story of an n-storied building.

S_D : factor to modify E_o index due to stiffness discontinuity along stories, eccentric distribution of stiffness in plan, irregularity and/or complexity of structural configuration, basically ranging from 0.4 to 1.0.

T : reduction factor to allow for the grade of deterioration, ranging from 0.5 to 1.0.

Required seismic capacity index I_{so}, which evaluates structural safety against an earthquake, is defined as follows.

$$I_{so} = E_s \times Z \times G \times U \quad (4)$$

where, E_s : basic structural seismic capacity index required for the building concerned. Considering past structural damage due to severe earthquakes in Japan, standard value of E_s is set 0.6.

Z : factor allowing for the seismicity.

G : factor allowing for the soil condition.

U : usage factor or importance factor of a building.

Typical I_{so} index for school buildings in Ota City is 0.75 considering $E_s = 0.6$, $U = 1.25$ and other factors of 1.0. It should be noted that $C_T \times S_D$ defined in **Eq. (5)** is required to be larger than or equal to 0.3 in the Guideline for Seismic Evaluation [JBDPA, 1990a] to avoid fatal damage and/or unfavorable residual deformation due to large response of structures during major earthquakes.

$$C_T \times S_D = \phi \times C \times S_D \quad (5)$$

Seismic retrofit of buildings is basically carried out in the following procedure. [JBDPA, 1990b]

(1) Seismic evaluation of the structure concerned. : I_s and $C_T \times S_D$ are calculated.
(2) Determination of required seismic capacity : I_{so} is determined.
(3) Comparison of I_s with I_{so}.
(if $I_s < I_{so}$ or $C_T \times S_D < 0.3$ and retrofit is required, then following (4) through (6) are needed.)
(4) Selection of retrofitting scheme(s).
(5) Design of connection details.
(6) Reevaluation of the retrofitted structure. : I_s and $C_T \times S_D$ are checked.

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