IMPROVEMENT OF SEISMIC PERFORMANCE OF REINFORCED CONCRETE SCHOOL BUILDINGS IN JAPAN- PART 1 DAMAGE SURVEY AND PERFORMANCE EVALUATION AFTER 1995 HYOGO-KEN NAMBU EARTHQUAKE

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SUMMARY

Seismic evaluations of reinforced concrete school buildings damaged due to the 1995 Hyogo-ken Nambu Earthquake are performed based on the Japanese Standard for Seismic Evaluation, and the correlation between observed damage and their seismic capacities are investigated. In the investigation, the first level seismic performance indices (Is_1) for 106 buildings and the second level performance indices (Is_2) for 74 buildings are calculated. Most of the buildings with Is_2 values lower than 0.4 are nearly collapsed or severely damaged and those with Is_2 of 0.4 through 0.6 are moderately damaged or more. However, those with Is_2 higher than 0.6 suffered from minor or less damages, except for several buildings which were likely to have sufficient deformation capacity but had relatively large residual deformations due to their low lateral resistance. From these results, a fairly good correlation can be fond between the calculated performance indices and the damage observed.

1. INTRODUCTION

This paper describes the activities of the Committee for School Buildings in the Architectural Institute of Japan (AIJ) on the damage survey and seismic performance evaluation of reinforced concrete school buildings carried out after the 1995 Hyogo-ken Nambu Earthquake, Japan.

Just after the earthquake, the AIJ established a task committee chaired by the first author consisting of about 40 members. The task committee and working groups investigated the damage of approximately 800 school buildings and other educational facilities, and their damage was identified based on the Standard for Damage Level Classification [JBDPA, 1991]. Seismic performance indices for approximately 100 buildings were also calculated, and the correlation between the calculated performance indices and the damage level was studied.

2. DAMAGES TO REINFORCED CONCRETE SCHOOL BUILDINGS

To identify damage to buildings, "Standard for Damage Level Classification of Reinforced Concrete Buildings [JBPDA, 1991]" was applied. In the Standard, damage level of an entire building was categorized according to *D*-Index as follows:

[Slight] $D < 5$
[Minor] $5 < D < 10$
[Moderate] $10 < D < 50$
[Severe] $50 < D$

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[Collapse] $D_5 = 50$

where, $D = \sum D_i$ (1)

$$D_1 = \begin{cases} 10\,B_1/A & (B_1/A < 0.5) \\ 5 & (B_1/A \geq 0.5) \end{cases} \tag{2}$$

$$D_2 = \begin{cases} 26\,B_2/A & (B_2/A < 0.5) \\ 13 & (B_2/A \geq 0.5) \end{cases} \tag{3}$$

$$D_3 = \begin{cases} 60\,B_3/A & (B_3/A < 0.5) \\ 30 & (B_3/A \geq 0.5) \end{cases} \tag{4}$$

$$D_4 = \begin{cases} 100\,B_4/A & (B_4/A < 0.5) \\ 50 & (B_4/A \geq 0.5) \end{cases} \tag{5}$$

$$D_5 = \begin{cases} 1000\,B_4/7A & (B_5/A < 0.35) \\ 50 & (B_5/A \geq 0.35) \end{cases} \tag{6}$$

A is the total number of columns in the most severely damaged story. B_i is the number of columns categorized into the "Damage Class *i*" according to **Table 1**.

Table 1: Damage classification of structural members

Damage Class	Observed Damage to Structural Members
1	Some cracks are found. Crack width is smaller than 0.2 mm.
2	Cracks of 0.2 - 1 mm wide are found.
3	Heavy cracks of 1 - 2 mm wide are found. Some spalling of concrete is observed.
4	Many heavy cracks are found. Crack width is larger than 2 mm. Reinforcing bars are exposed due to spalling of covering concrete.
5	Buckling of reinforcement, crushing of concrete and vertical deformation of columns and/or shear walls are found. Side-sway, subsidence of upper floors, and/or fracture of reinforcing bars are observed in some cases.

The working group for RC structures investigated structural damage to a total of 631 reinforced concrete school buildings in Kobe City, Nishinomiya City, Awaji Island, and other neighboring cities subjected to a strong ground shaking. Damage statistics was shown in **Table 2** [AIJ, 1997]. 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 present 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 damaged school buildings was only 8%. These results reveal that the seismic capacity of existing RC 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.

Table 2 : Damage statistics of reinforced concrete school buildings [AIJ 1997]

	Pre-1971	1971-1981	Post-1981	Total
Collapse	18 (5%)	2 (1%)	*0*	20 (3%)
Severe Damage	24 (7%)	9 (5%)	*0*	33 (5%)
Moderate Damage	90 (27%)	39 (24%)	11 (8%)	140 (22%)
Minor Damage	41 (12%)	21 (13%)	7 (5%)	69 (11%)
Slight or no Damage	159 (48%)	95 (57%)	115 (87%)	369 (59%)
Total	332 (100%)	166 (100%)	133 (100%)	631 (100%)

3. METHOD OF SEIMIC PERFORMANCE EVALUATION

To understand the correlation between the observed damage levels of investigated buildings and their seismic capacities, seismic performance indices of approximately 100 RC school buildings were calculated. The damage levels of the buildings were: 10 collapsed, 12 severe damage, 40 moderate damage, 12 minor damage and 27 slight damage. In the seismic evaluation, "Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings [JBPDA, 1990]" was applied.

3.1 Basic Concept for Seismic Evaluation

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

In the Standard, the seismic performance index of a building is expressed by the *Is*-Index for each story and each direction, as shown in Eq. (7)

$$Is = E_0 \times S_D \times T \tag{7}$$

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 (most 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. Basically in the Standard, a simple formula of $\phi = \frac{n+1}{n+i}$ is employed for the i-th story level of an n-storied building by assuming straight mode and uniform mass distribution.

S_D- and T-Index are reduction factors to allow for the disadvantages in the seismic performance of structures. S_D-Index, basically ranging from 0.4 to1.0, is for modifying E_0-Index due to unbalanced distribution of stiffness both in the horizontal plane and along the height of the structure, resulting from irregularity and complexity of structural configuration. T-Index, ranging from 0.5 to 1.0, is employed to allow for the deterioration of strength and ductility due to age after construction, fire and/or uneven settlement of foundation.

2.2 Assumption in Seismic Evaluation

To evaluate the seismic performance of the school buildings, the following assumptions were employed.

1) Compressive strength of concrete cores sampled from some of the investigated buildings was 25MPa in average [CMC, 1996] in which exceptionally low strength was not found. The compressive strength of concrete was therefore assumed equal to the specified strength which was generally 18MPa or 21MPa for investigated buildings.
2) The yield strength was assumed 300 MPa for plain bars and specified minimum yielding point plus 50 Mpa for deformed bars, respectively.
3) Unit weight of each floor of the buildings was assumed 1.2 ton/m^2.
4) In the first level procedure, T-Index was based on only construction age, i.e., 0.8 for 30 years or older, 0.9 for 20 through 30 years old, and 1.0 for 20 years old or younger. In the second level procedure, T-Index was assumed 1.0.
5) Shear failure of extremely short and brittle columns was supposed not to induce fatal collapse of an entire building, and these columns were neglected in calculating *Is*-Index.

4. APPLICATION OF FIRST LEVEL PROCEDURE

In general, seismic capacity of RC school buildings in the transverse direction is much higher than that in the longitudinal direction because shear walls are placed between classrooms. Major structural damage to RC school buildings was therefore observed in the longitudinal direction. **Figure 1** shows the relationship between the first level seismic performance indices Is_1 in the longitudinal direction of most damaged story (mostly first story) and the damage level indices *D*-Index evaluated according to the Damage Classification Standard [JBDPA, 1991], together with damage levels estimated by the engineering judgement of investigators. As can be found in the figure, no significant differences between both damage classifications can be found, although the Standard tends to classify the damage one rank higher than the investigators' judgement for the moderately or less damaged buildings. For example, most buildings with *D*-Index of 10 or less were categorized into slight damage by investigators' judgement. Half of those with *D*-Index of 10 through 20 and some of those with *D*-Index of 20 through 30 were classified into minor damage. To harmonize with investigators' classification, the border between slight and minor damage and that between minor and moderate damage should be raised to 10 and 20, respectively.

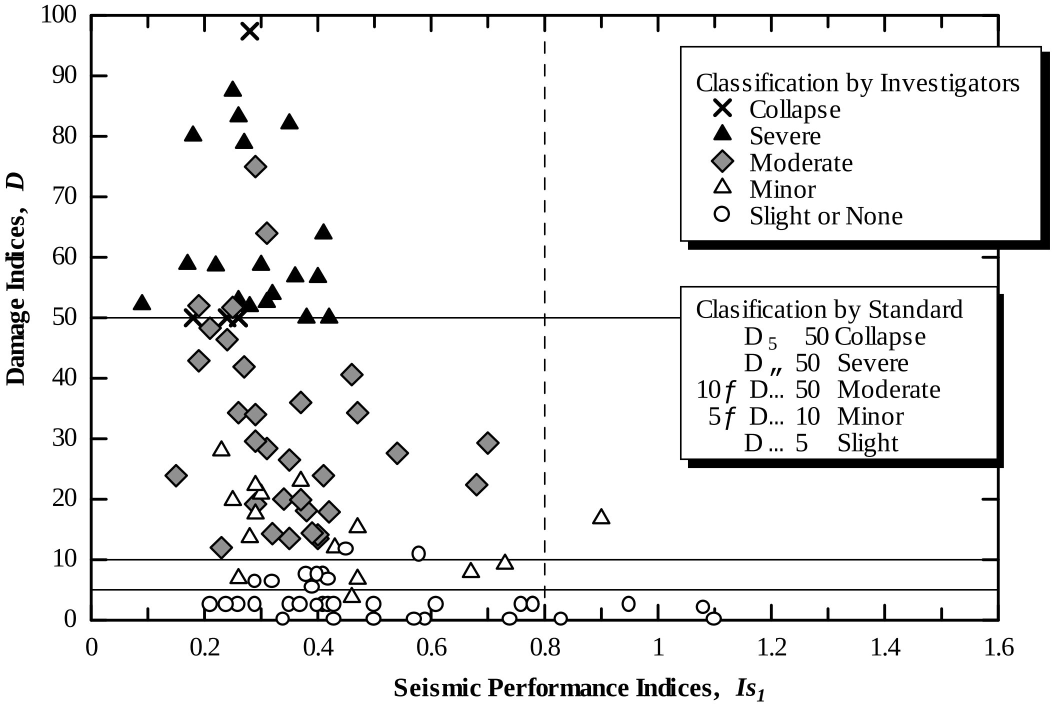

Figure 1: The first seismic performance indices and damage indices

Is_1 values of collapsed or severely damaged buildings were generally lower than 0.4 as shown in **Figure 1**. Buildings with Is_1 of 0.4 through 0.8 suffered from moderate damage or less and those with Is_1 values higher than 0.8 slight damage. The Standard for Seismic Evaluation recommends that Is_1 Index higher than 0.8 needs to be provided to prevent major structural damage. The criterion of 0.8 was found to be the border between moderate and minor damage, even though subjected to the strong ground motion of the 1995 Hyogo-ken Nambu Earthquake. These results described above demonstrated that the buildings with relatively high lateral strength avoided serious damage and the first level procedure was effective to identify buildings with good seismic performance, although the procedure was very simple and conservatively estimated the strength and ductility of structural members.

From a practical point of view for seismic retrofit, it is strongly recommended that the higher level procedure be adopted after screening vulnerable buildings according to the simple first level procedure. In general, few existing RC buildings in Japan have Is_1 Indices higher than 0.8 in all stories and in both directions. Considering the facts that few buildings with Is_1 value higher than approximately 0.5 suffered from collapse or severe damage even in the 1995 Hyogo-ken Nambu Earthquake, the criterion to identify seismically vulnerable buildings can be set lower than 0.8. Is_1 equal to 0.55, which may correspond to the upper bound of the lateral strength required in the present seismic design code, can be a candidate for the criterion to identify buildings with highest priority of seismic retrofit.

5. APLICATION OF SECOND LEVEL PROCEDURE

Is_2 Indices in the longitudinal and transverse directions of most damaged story (mostly first story) were shown in **Figure 2**. As stated earlier, Is_2 value in the transverse direction was generally higher than that in the longitudinal direction since enough shear walls were provided between classrooms in typical school buildings. Major damage was, therefore, found in the longitudinal direction in each building, and no clear correlation between Is_2 value in the transverse direction and damage level could be found. In the subsequent discussions, seismic capacities in the longitudinal direction will be mainly focused.

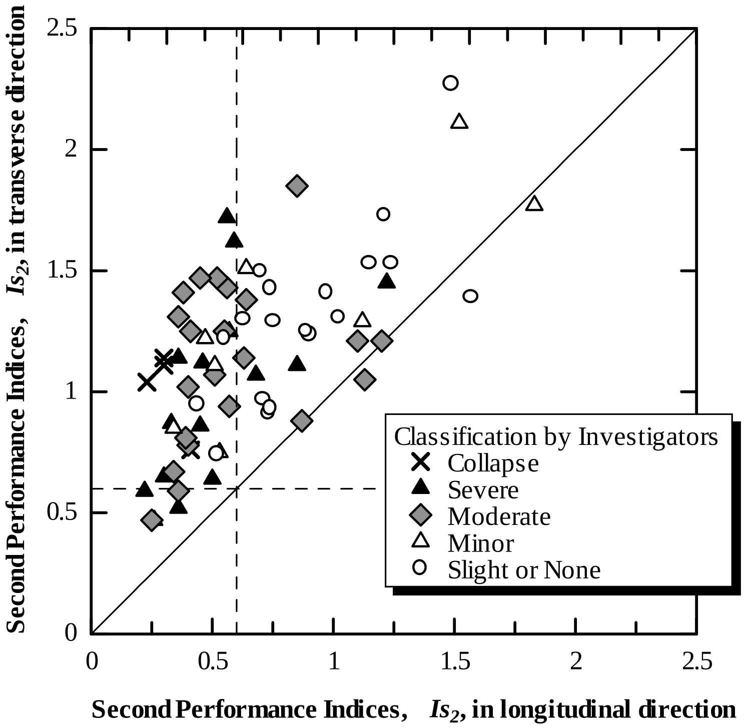

Figure 2: Correlation between damage and the second level seismic performance indices in longitudinal and transverse direction

Figure 3 shows the relationship between the second level seismic performance indices Is_2 in the longitudinal direction and construction age. The Standard for Seismic Evaluation recommends as the demand criterion of the second level procedure that Is_2 Index higher than 0.6 should be provided with buildings to prevent major structural damage or collapse. This criterion is based on the correlation study from the past earthquake damage and the calculated indices for the damaged buildings. Past experiences of 1968 Tokachi-Oki, 1978 Miyagi-ken-Oki and other earthquakes reported that buildings with Is_2 indices higher than 0.6 suffered from moderate or less damage. As can be found in **Figure 3**, Is_2 indices for most of the buildings constructed before 1971 were less than 0.6, whereas they were more than 0.6 for those constructed after 1981. As mentioned earlier, the Japanese seismic design codes for buildings were revised in 1971 and 1981. The results shown in **Figure 3** indicated that seismic capacities of reinforced concrete school buildings in Japan were successfully improved due to the revisions of seismic design codes.

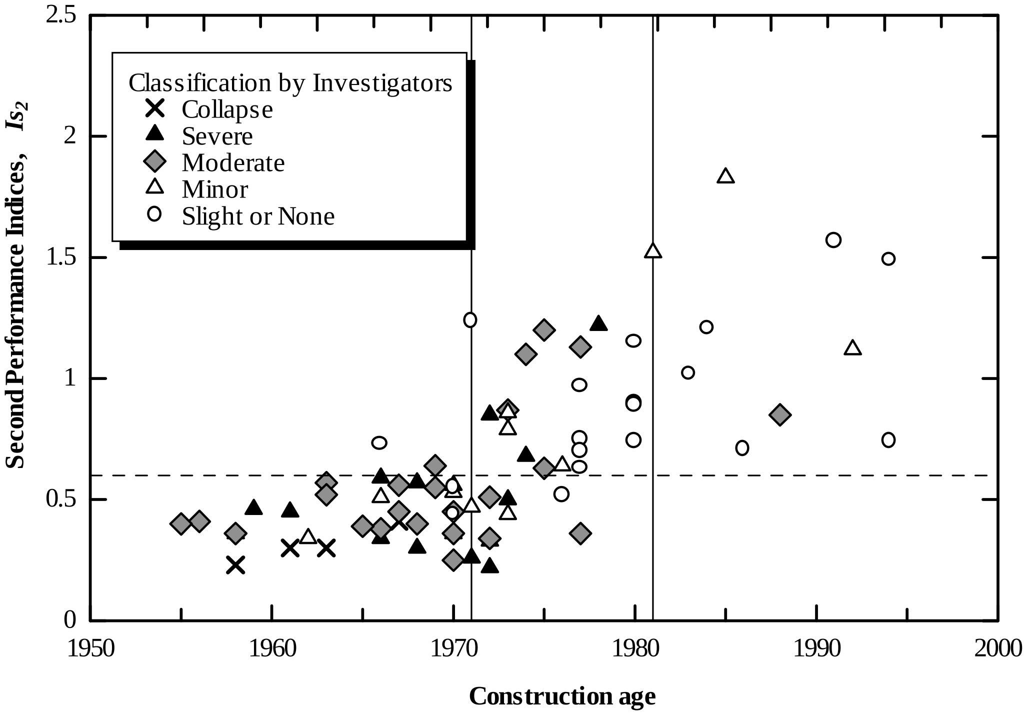

Figure 3: Construction age vs. the second seismic performance indices in the longitudinal direction

Figure 4 shows the relationship between Is_2 Index in the longitudinal direction and damage level indices *D*-Index. A fair inverse correlation was observed between calculated seismic performance indices and observed damage. Most of the buildings with Is_2 values lower than 0.4 had major damage (D > 30) and half of them were severely damaged or collapsed. Most buildings with Is_2 values lower than 0.3 were severely damaged or collapsed. Those with Is_2 values of 0.4 through 0.6 were moderately damaged or more. Many buildings with Is_2 values higher than 0.6 avoided severe damage and had minor damage or less (D < 20). However, it should be noted that serious damage (D > 50) was observed in six buildings although their Is_2 values were higher than 0.6, which was different from the past experiences. They were Central building of Uegahara junior high school, C-, D- and E-building of Nishinomiya high school, and Main- and North-building of Nisinomiya-kita high school. They were all 4 storied buildings constructed after 1972 and located in the north of Nishinomiya City. One of the possible reasons for such serious damage may be attributed to the directivity of ground motion in Nishinomiya area where the predominant shaking agreed with the longitudinal weak direction of these buildings. Another reason was their failure modes different from other buildings with serious damage. In these 6 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. However, these 6 buildings were classified into *nearly collapsed* due to their relatively large residual displacements.

Major damage to Central building of Uegahara junior high school, which had Is_2 value of 0.68, was bond splitting and shear failure in columns of the first story. Residual drift angle in columns of the first story was larger than 1/50. These columns, sufficiently confined by lateral reinforcement, still sustained gravity loads carrying capacity even though bond splitting and shear failure occurred. Columns in C-, D- and E-building of Nishinomiya high school were expected to have ductile flexural behaviors since sufficient lateral reinforcement provided in columns, flexural yielding hinges developed at ends of the columns, the soft story mechanism, and visible residual story drifts were found. Calculated *F*-Indices of these columns were nearly 3.2, which corresponded to most ductile flexural member. C-, D- and E-building therefore showed large Is_2 values of 1.20, 1.22 and 0.85, respectively, although their lateral strengths (*C*-Indices) were relatively low. Damage to Main- and North-building of Nishinomiya-kita high school was similar to Nishinomiya high school, and buckling of reinforcing bars and flexural failure were found in most columns. In Main-building which had Is_2 value of 0.87, shear failures in extremely short columns (clear height-to-depth ratio = 1) and in shear walls were also observed. If the extremely short and hence brittle columns were regarded as fatal to the overall structural performance, Is_2 value of Main-building was as low as 0.28.

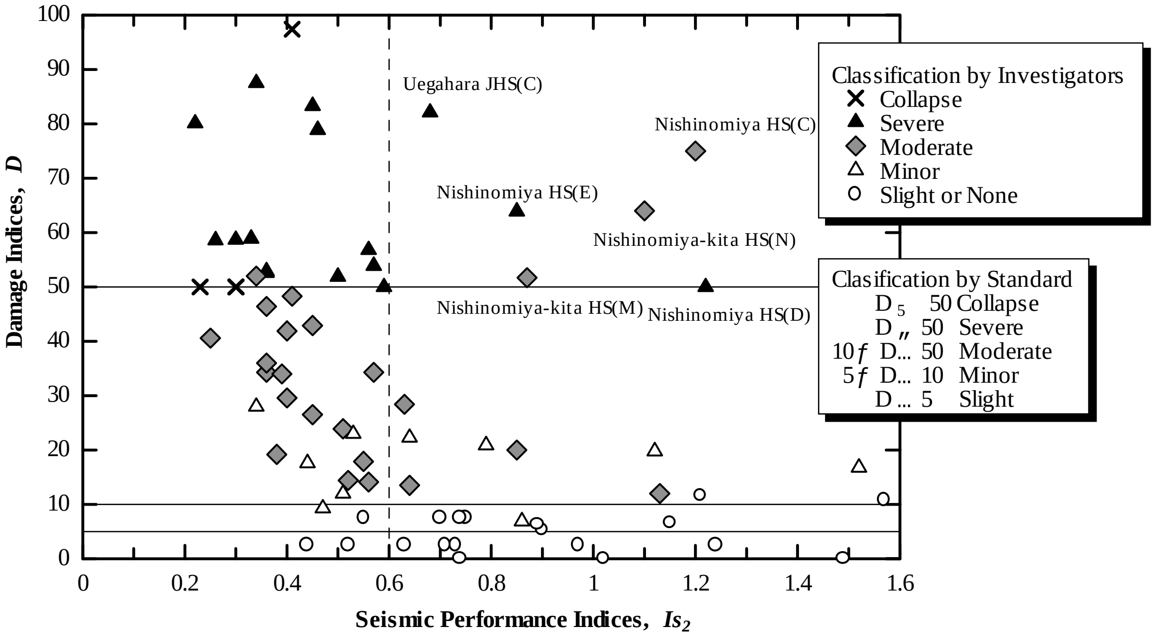

Figure 4: The second seismic performance indices and damage indices

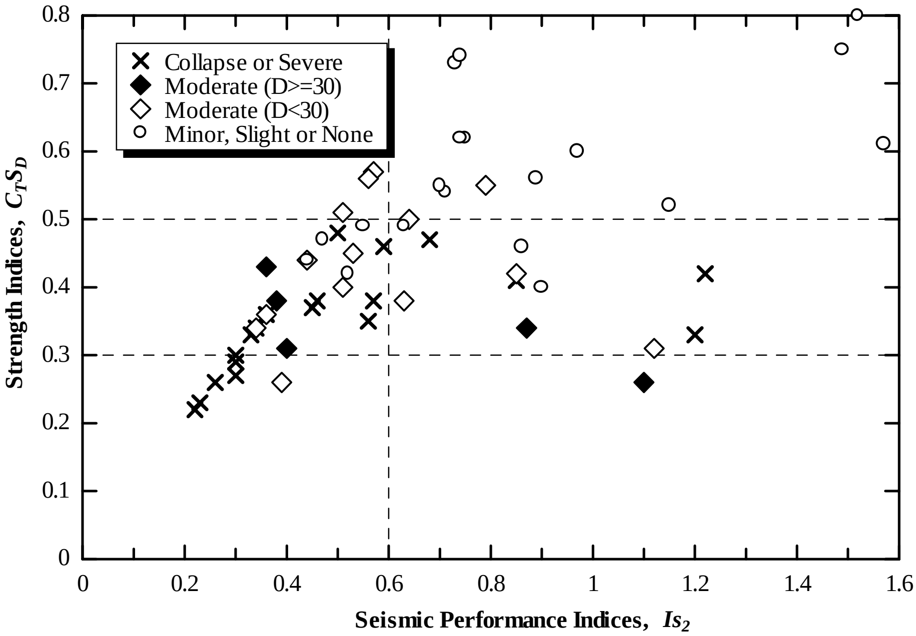

Figure 5: Strength indices, the second seismic performance indices and damage levels

Although ductile, almost all columns of the buildings described above were categorized in damage class 5 due to their large residual drift angles, and these buildings were classified into severely damaged or collapsed according to the Damage Classification Standard. From serviceability and reparability point of view, these damage levels should be considered equivalent to severely damaged or collapsed because it was very difficult to restore such large residual deformations. However, damage to these buildings and their structural performance should be discussed apart from other typical brittle structures with severe damage since these ductile columns still sustained gravity loads in spite of large deformation and the residual capacity for structural safety would have been larger than other brittle structures.

Figure 5 shows the relationship between C_T x S_D and Is_2, in which C_T was defined as C-Index when columns failed in shear (F=1.0) and was nearly equal to the lateral strength in terms of base shear coefficient. As can be found in the figure, C_T x S_D values of collapsed or severely damaged buildings were lower than 0.5. Most buildings with C_T x S_D of 0.45 or less suffered from serious damage (D>30). On the other hand, most buildings with C_T x S_D higher than 0.5 were slightly damaged (D<30). Six exceptional buildings discussed earlier, which suffered from serious damage in spite of relatively high Is_2 values, had C_T x S_D values generally lower than 0.4. Since large plastic deformation was expected to absorb seismic energy in these ductile frame structures, their responses were larger than strong but brittle structures even when they had the same seismic performance index. It is therefore necessary to provide enough strength Index C_T x S_D higher than 0.45, for example, as well as Is_2 Index of 0.6 to minimize structural damage and residual deformation especially of ductile frame structures.

6. CONCLUSIONS

The major findings in this study are summarized as follows:

1) Most of the heavily damaged school buildings were designed before 1981 and had low seismic performance indices.
2) Most schools with higher indices suffered from minor or less damage except for some buildings which experienced large displacement due to relatively low lateral strength and were classified into *nearly collapsed*.
3) To screen seismically vulnerable buildings and to identify retrofit candidates with highest priority, the first level procedure could be more practically applied through slight modification of the criterion to Is_1 equal to 0.55.
4) Strength Index C_T x S_D as well as Is_2 Index was significantly essential to control structural damage and residual deformation of ductile buildings.

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8. REFERENCES

AIJ / The Architectural Institute of Japan (1997), *Report of damage survey of reinforced concrete buildings due to the 1995 Hyogo-ken Nambu Earthquake*. (in Japanese)

CMC / Committee for Material and Construction established in Kinki Branch of the AIJ (1996), *Report of damage survey on materials and construction due to the 1995 Hyogo-ken Nambu Earthquake*. (in Japanese)

JBDPA / The Japan Building Disaster Prevention Association (1990), *Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings*. (in Japanese)

JBDPA / The Japan Building Disaster Prevention Association (1991), *Standard for Damage Level Classification of Reinforced Concrete Buildings*. (in Japanese)