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# SEISMIC CAPACITY OF R/C BUILDINGS DAMAGED DUE TO 1995 JANUARY 17 HYOGO-KEN NANBU EARTHQUAKE

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## ABSTRACT

The 1995 January 17 Hyogoken-nanbu Earthquake caused destructive damage to buildings, bridges, highways and lifelines that led to more than 5,500 fatalities and significant disruptions in social and economic activities in Hanshin-Awaji District. Immediately after the quake, the Architectural Institute of Japan set up a special committee on seismic capacity of school buildings under the cooperation of Japanese Ministry of Education. The author, as a member of the committee, carried out field surveys of reinforced concrete public buildings including school buildings in the affected area to identify their damage levels. This paper describes damage levels and results of seismic evaluation of surveyed buildings in the epicentral region, and the correlation between their damage levels and seismic capacities is discussed.

## KEYWORDS

Hyogo-ken Nanbu Earthquake; Awaji Island; reinforced concrete building; seismic capacity; seismic evaluation; Is-index; damage level classification; damage class; damage-index.

## INTRODUCTION

In the early morning on January 17, 1995, the Hanshin-Awaji District was strongly shaken and a large number of buildings were destructively damaged. The author carried out field surveys of reinforced concrete public buildings in the affected area, and their damage levels were investigated. This paper describes damage levels and the results of seismic evaluation of affected buildings in Awaji Island which includes the epicenter in its north ridge, and the correlation between their damage levels and seismic capacities is discussed.

## INVESTIGATED BUILDINGS AND THEIR DAMAGE LEVELS

Figure 1 shows the epicenter of Hyogoken-Nanbu Earthquake and the location of six reinforced concrete buildings investigated herein. The damage level of an entire building was judged basically in accordance with the Japanese Guideline for Damage Level Classification (JBDPA, 1991); i.e. damage to each structural member was first categorized into one of 5 classes (class I through V) according to the damage definitions shown in Table 1, and the damage level of the entire building was then identified from D-index calculated in accordance with the Guideline. The definition of D-index is briefly described in Appendix 1. Damage to each investigated building can be summarized as follows.

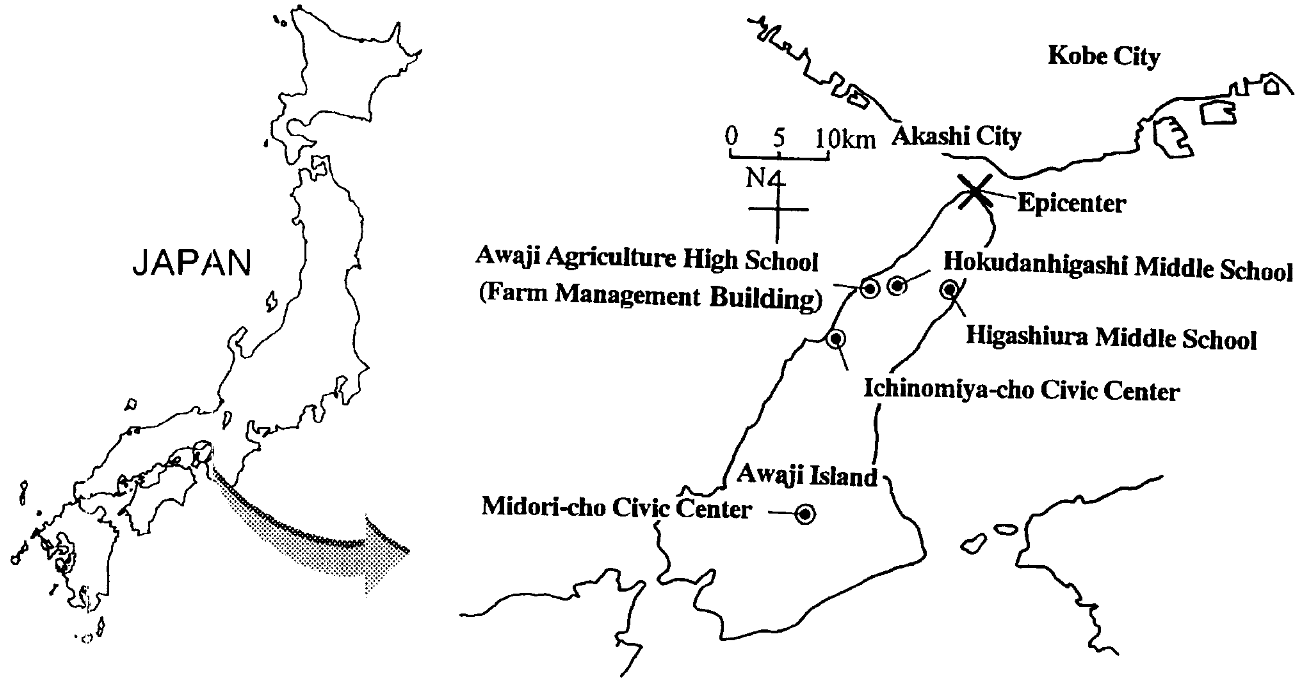



Fig. 1. Location of epicenter and investigated buildings in Awaji Island

*Midori-cho Civic Center*

Damage in the first story is shown in Fig. 2 (1). This building was a three story reinforced concrete building constructed in 1977. Remarkable damage was observed in frame 1 in the first story and the staircase connected with frame 1. Although a column at C-1 sustained severe shear failure with exposed and buckled reinforcement and was categorized in Class V, many other columns had only slight flexural-shear failures categorized in Class I. The damage level of the entire building defined by D-index was "moderate". It should be noted, however, that judging from the field survey the damage level should be identified "light", because severe damage was localized.

*Hokudanhigashi Middle School*

Damage in the first story is shown in Fig. 2 (2). The building was a four story reinforced concrete building constructed in 1963. Ground failure was observed around the school. Spandrel walls and columns of the north-west frame sustained cracks that might be caused by differential settlement due to the ground failure. Damage in columns ranged from Class I to III, and the damage level defined by D-index was "moderate".

*Higashiura Middle School*

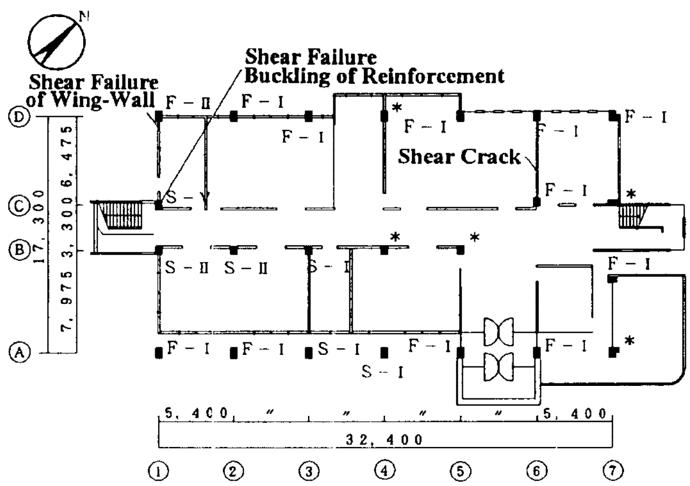
Damage in the first story is shown in Figs. 2 (3) and (4). The school consisted of three buildings referred to as Building-A, -B and -C. These three buildings were three story reinforced concrete buildings constructed in 1967 and located in parallel on a hill. Building-B and -C were partially placed on the refilled soil above the slope and more severely damaged while building-A had few damage. Building-B had differential settlement caused by soil subsidence in four spans of the west zone located on the refilled soil. Columns in the first and second story had many shear cracks due to differential settlement, and the damage level of Building-B defined by D-index was "moderate". Soil subsidence was also observed in the south-west zone of Building-C and one span of the west frame tilted about 1 to 2 degrees. Remarkable damage was generally observed in columns of the first story. Many columns in the south and north frame were shaken and failed in shear and resulted in Damage Class V. The damage level of Building-C defined by D-index was "collapse".

*Awaji Agriculture High School (Farm Management Building)*

Damage in the third story is shown in Fig. 2 (5). This building was a three story reinforced concrete building constructed in 1984. Minor damage to the building was observed in columns of each story. The damage level defined by D-index was "moderate". It should be noted, however, that judging from the field survey the damage level should be identified "slight", because each damage was not severe.

Table 1. Definition of Damage Class (JBDPA, 1991)

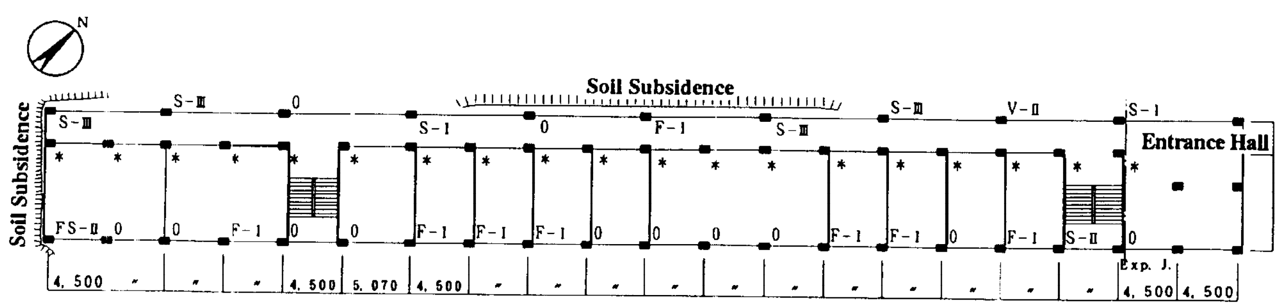
| Damage Class | Description of Typical Damage |
|---|---|
| I | • Visible narrow cracks on concrete surface (Crack width is less than 0.2 mm) |
| II | • Visible clear cracks on concrete surface (Crack width is about 0.2 to 1.0 mm) |
| III | • Local crush of covering concrete<br>• Remarkable wide cracks (Crack width is about 1.0 to 2.0 mm) |
| IV | • Remarkable crush of concrete with exposed reinforcing bars<br>• Spalling of covering concrete (Crack width is more than 2.0 mm) |
| V | • Buckling of reinforcing bars<br>• Cracks in core concrete<br>• Visible vertical deformation in columns and/or walls<br>• Visible settlement and/or inclination of the building |




(1) Midori-cho Civic Center (first story)

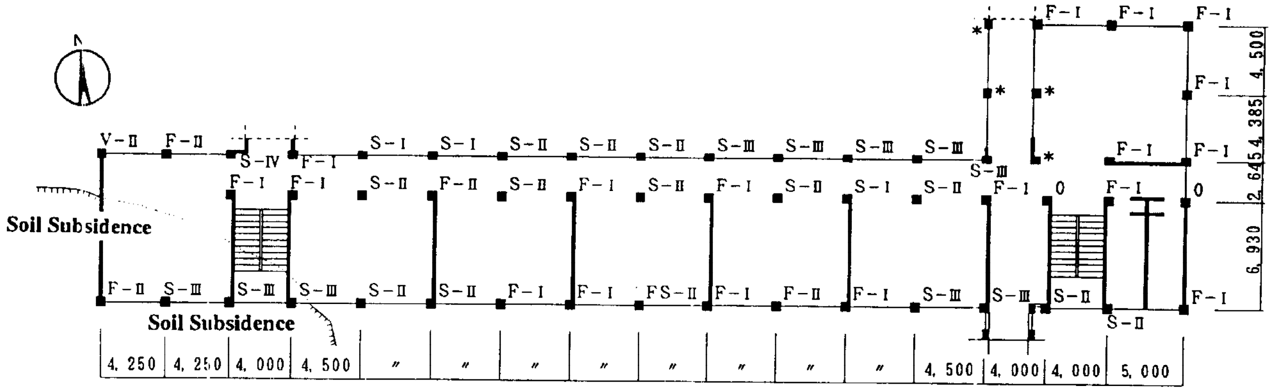
**Notes) Roman numerals indicate the damage class of structural members (see also *Table 2*). Alphabetic letters indicate crack types as shown below.**

**S : Shear Crack**
**F : Flexural Crack**
**FS : Flexural-Shear Crack**
**V : Vertical Crack**
*** : Not inspected**

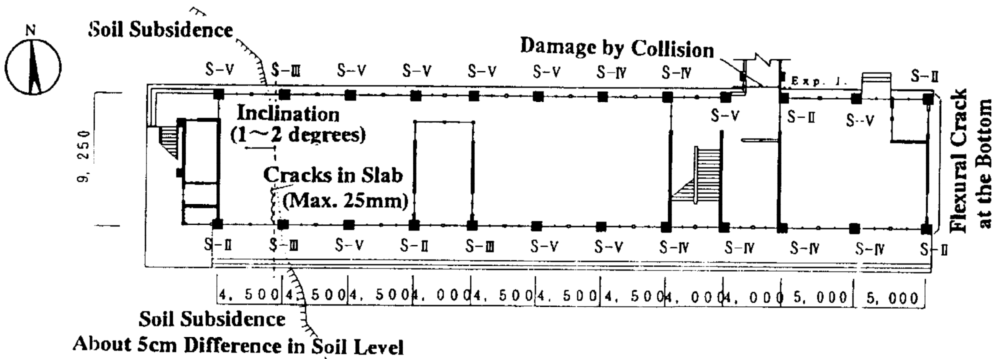



(2) Hokudanhigashi Middle School (first story)

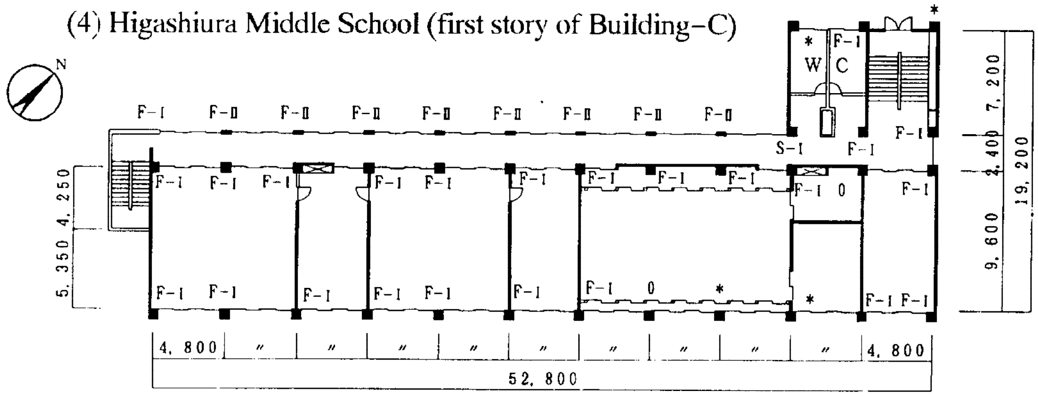
Fig. 2. Damage description of investigated buildings (continued)



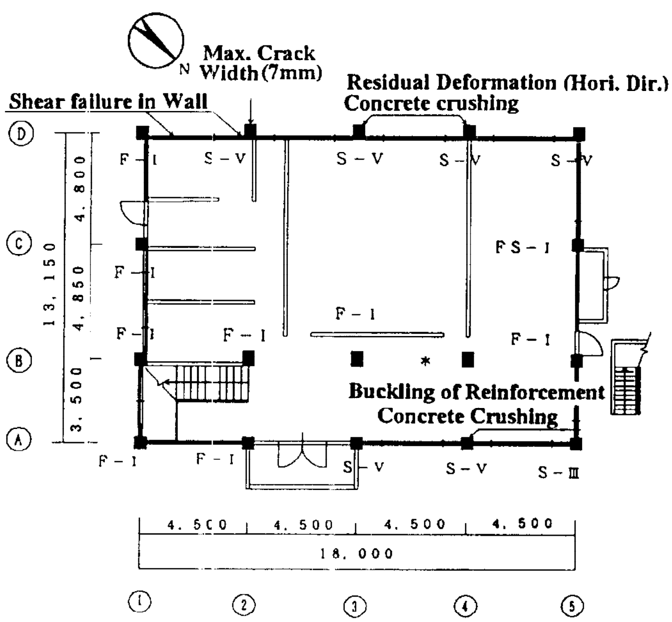

(3) Higashiura Middle School (first story of Building−B)




(4) Higashiura Middle School (first story of Building−C)




(5) Awaji Agriculture High School (third story of Farm Management Building)




Notes) Roman numerals indicate the damage class of structural members (see also *Table 2*). Alphabetic letters indicate crack types as shown below.

- S : Shear Crack
- F : Flexural Crack
- FS : Flexural-Shear Crack
- V : Vertical Crack
- * : Not inspected

(6) Ichinomiya−cho Civic Center (first story)

Fig. 2. Damage description of investigated buildings

*Ichinomiya-cho Civic Center*

Damage in the first story is shown in Fig. 2 (6). This building was a three story reinforced concrete building constructed in 1969. Major damage was generally observed in the first story, and many columns in the first story sustained severe shear failures or shear cracks. In particular, six columns in the exterior frames without shear walls failed in shear and were categorized in Class V. The damage level defined by D-index was "collapse"

The outline of each damaged building is summarized in Table 2. According to D-index defined in the Guideline, the damage level of (1) Midori-cho Civic Center and (5) Awaji Agriculture High School was classified in "moderate". As stated earlier, however, the damage level classified according to D-index seemed to be overestimated and these buildings should be classified in "light" and "slight", respectively. This is revealing that the method of damage level classification described in the Guideline should be reexamined particularly when the D-index lies around the boundary between moderate and light damage.

Table 2. Summary of damage to investigated buildings

| ID | Name of Buildings | No. of Stories | Construction Year | Observed Damage (D-index, Damage Level) |
|---|---|---|---|---|
| (1) | Midori-cho Civic Center | 3 | 1977 | Shear failure of columns located in C-1 of the first story (D=17.3 (1F), Light*) |
| (2) | Hokudanhigashi Middle School | 4 | 1963 | Shear cracks in a few columns, slight ground damage (D=14.4 (1F), Moderate) |
| (3) | Higashiura Middle School (Building-B) | 3 | 1967 | Shear cracks in columns due to the differential settlement (D=26.5 (1F), Moderate) |
| (4) | Higashiura Middle School (Building-C) | 3 | 1967 | Shear failure in many columns of the first story (D=97.4 (1F), Collapse) |
| (5) | Awaji Agriculture High School (Farm Management Building) | 3 | 1984 | Minor flexural cracks (D=11.7 (3F), Slight*) |
| (6) | Ichinomiya-cho Civic Center | 3 | 1969 | Shear failure in many columns of the first story (D=58.8 (1F), Collapse) |

*) The damage level defined by D-index was "moderate". Judging from the field survey, however, the damage level should be classified in "light" and "slight", respectively, as shown in the Table.

## SEISMIC EVALUATION OF DAMAGED BUILDINGS

The seismic capacity of each surveyed building was evaluated. In the seismic evaluation, the Japanese Standard for Evaluation of Seismic Capacity of Existing Reinforced Concrete Buildings (JBDPA, 1990) was applied. The basic concept for the seismic evaluation can be found in Appendix 2.

*Assumptions in Seismic Evaluation*

To evaluate the seismic capacity of each building, the following common assumptions were employed: (1) building weight per unit area was assumed 1.2 tonf/m$^2$, (2) the dimension of structures and material properties were determined according to drawings and field survey results, (3) T-index which signifies deterioration after construction was assumed 1.0, and (4) Evaluation was carried out using the computational program (JBDPA, 1980) coded according to the Standard.

*Correlation between Seismic Capacity and Damage Level*

The correlation between seismic capacity index (Is–index) and the damage level (D–index) is shown in Fig. 3. Figure 4 shows the correlation between D–index and the construction year of six buildings described above, together with other surveyed buildings in Awaji Island.

Figure 3 shows that excluding (1) Midori–cho Civic Center which had a few shear walls in the longitudinal direction, the seismic capacity in the transverse direction is significantly higher than that in the longitudinal direction, because more shear walls were provided in the transverse direction than in the longitudinal direction. Figure 3 also indicates that buildings with higher seismic capacity index had less damage. If the damage levels of (1) Midori–cho Civic Center and (5) Awaji Agriculture High School identified by the author were taken into account, the boundary to avoid damage such as moderate, heavy and collapse during this event in the epicentral region may be around 0.6 in terms of Is–index. Since this value corresponds to the criteria to avoid serious structural damage to buildings in Hachinohe city during 1968 Tokachi–oki Earthquake and in Sendai city during 1978 Miyagiken–oki Earthquake, the ground motion level experienced in the investigated area may be similar to that in these cities during the past two earthquakes.

Is–indices of buildings constructed before 1971 were significantly lower and sustained more serious damage than those constructed after 1971 as shown in Fig. 4. This result can be attributed to the enhancement of design in shear due to the code revision in 1971, i. e. reduction in allowable maximum spacing of lateral column reinforcement.

## CONCLUSIONS

The seismic capacity of six reinforced concrete buildings in Awaji Island which were damaged by 1995 Hyogoken–Nanbu Earthquake was evaluated and the correlation between the seismic capacity and the damage level was discussed. The major findings are: (1) buildings constructed before the code revision in 1971 were more seriously damaged than those constructed after 1971, (2) buildings with higher seismic capacity index had less damage and the boundary to avoid serious damage during this event in the epicentral region may be around 0.6 in terms of Is–index, and (3) the method of damage level classification defined in the Guideline needs to be reexamined since the damage level classified according to D–index seemed to be overestimated in several buildings particularly when the D–index lay around the boundary between moderate and light damage.

## ACKNOWLEDGMENTS

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## REFERENCES

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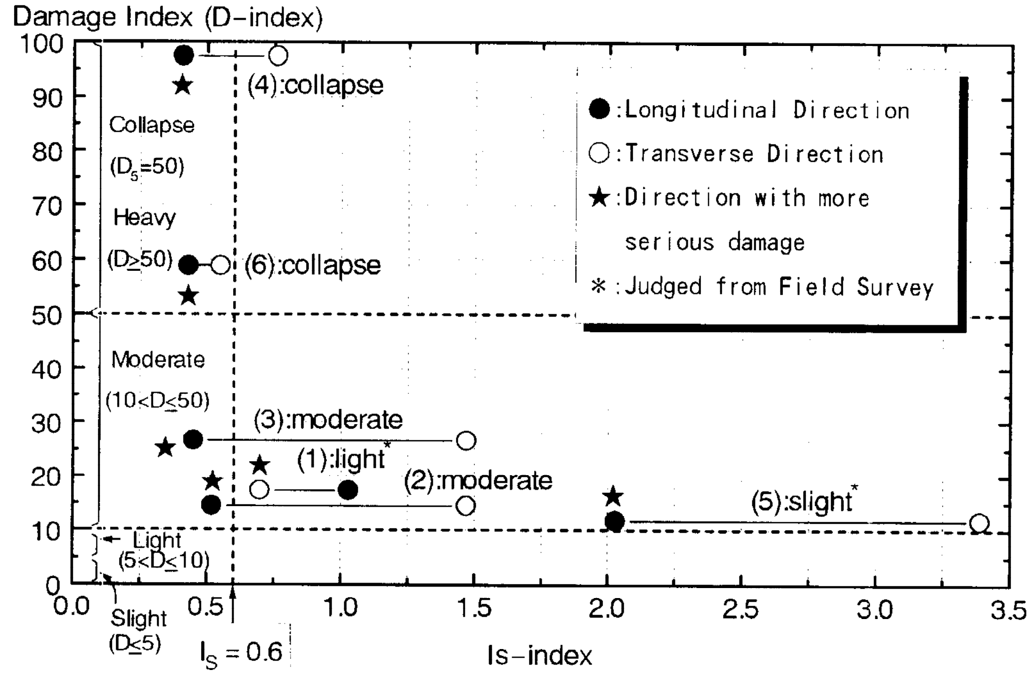
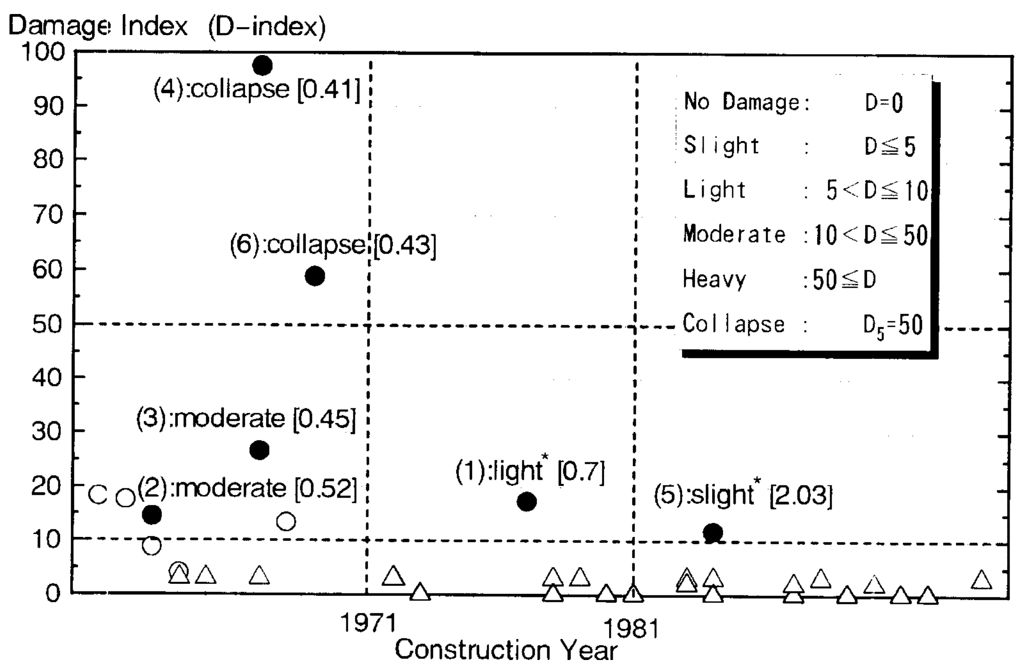



Fig. 3. Correlation between Is-index and Damage Index
(Numerals in parentheses correspond to ID in Table 1)




△ : D-index was assumed as follows since damage level was identified only by quick inspection of the exterior. No Damage : D=0, Light Damage : D=3.
* : The damage level defined by D-index was "moderate". Judging from the field survey, however, the damage level should be classified in "light" and "slight", respectively, as shown in the figure.

Fig. 4. Correlation between Construction Year and Damage Index
(Numerals in parentheses and square brackets correspond to ID in Table 1 and Is-index, respectively)

APPENDIX 1 [Basic Concept of the Damage Level Classification (JBDPA, 1991)]

The procedure to identify damage level of an entire building is defined in the Guideline as follows.

(1) Damage Class Identification of Each Structural Member: According to the damage survey, each structural member is categorized in one of Class I to V defined in Table 1.

(2) Calculation of Damage Sub-Index (Di) of Each Damage Class: Damage Sub-Index of each damage class can be calculated in each story as follows.

$$D_1 = 10B_1 / A \quad (=5 \quad \text{in case of } B_1 / A > 0.5)$$
$$D_2 = 26B_2 / A \quad (=13 \quad \text{in case of } B_2 / A > 0.5)$$
$$D_3 = 60B_3 / A \quad (=30 \quad \text{in case of } B_3 / A > 0.5)$$
$$D_4 = 100B_4 / A \quad (=50 \quad \text{in case of } B_4 / A > 0.5)$$
$$D_5 = 1000B_5 / 7A \quad (=50 \quad \text{in case of } B_5 / A > 0.35)$$

In the above definition, Bi and A are the number of structural members categorized in damage class i (i = I to V) defined in Table 1 and the number of inspected members in each story, respectively.

(3) Damage Level Classification: By summing Di defined above in each story, the Damage Index (D-index) which represents the damage level of a certain story is classified as follows. The largest value among stories defines the Damage Index of the entire structure.

$$D = \Sigma Di$$
$$D \leq 5 \quad : \text{slight}$$
$$5 < D \leq 10 \quad : \text{light}$$
$$10 < D \leq 50 \quad : \text{moderate}$$
$$50 < D \quad : \text{heavy}$$
$$D_5 = 50 \quad : \text{collapse}$$

APPENDIX 2 [Basic Concept of the Seismic Evaluation (JBDPA. 1990)]

The Standard evaluates the seismic capacity at each story and in each direction of the building by the following index.

$$Is = Eo \cdot S_D \cdot T \tag{1}$$

where,
Eo = basic structural index calculated by ultimate horizontal strength, ductility, number of stories and story level concerned.
$S_D$= structural design index to modify the Eo-index due to the grade of the irregularity of the building shape and distribution of stiffness along the height.
T = time index to modify the Eo-index due to the deterioration of strength and ductility.

The standard values of the $S_D$- and T-index are 1.0. The Eo-index for a single structural system can be expressed by the product of the ultimate horizontal strength index in terms of story shear coefficient (C), ductility index (F) and story index $\phi$. Story index ($\phi$) at the first story level is 1.0. Therefore, the Eo-index at the first story level of the simple structure can be defined as:

$$Eo = C \cdot F \tag{2}$$

In evaluating F-index in Eq.(2), the shear-span-to-depth ratio, flexural strength, shear strength etc. are considered. Basically, F=1.0 for brittle (shear failure type) members and F=1.27 to 3.2 for ductile (flexural failure type) members in the Standard.