Seismic Capacity of Reinforced Concrete Buildings Damaged by 1995 HYOGOKEN-NANBU Earthquake

by
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1. 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 authors 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, and the correlation between their damage levels and seismic capacities is discussed.

2. Investigated Buildings and Their Damage Levels

Fig. 1 shows the epicenter of Hyogoken-Nanbu Earthquake and the location of investigated six reinforced concrete buildings. The outline of each damaged building is summarized in ***Table 1***.

The damage level of an entire building was judged basically in accordance with *the Japanese Guideline for Damage Level Classification[1]*; i.e. damage to each structural member was first categorized into one of 5 classes (I ～V) shown in ***Table 2***, 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.

2.1 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. The structure consisted of reinforced concrete frames and a few shear walls in the longitudinal and transverse direction. This building had a reinforced concrete pile foundaton.

Remarkable damage was observed in frame 1 in the first story and the staircase connected with frame 1. A column at C-1 sustained severe shear failure with exposed and buckled reinforcement and was categorized in Class V. A wing-wall provided between frames C and D showed shear failure with concrete crush and exposed reinforcement. Slight flexural-shear failures categorized in Class I were observed in many columns of the first story. 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 the severe damage to the building was localized.

2.2 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. Shear walls were provided only in the transverse direction.

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.

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Damage in columns ranged from Class I to Ⅲ, and the damage level defined by D-index was "moderate".

2.3 Higashiura Middle School

Damage in the first story is shown in ***Figs. 2.3*** and ***2.4.*** The school consisted of three buildings referred to as Building-A, -B and -C. These three building were three story reinforced concrete buildings constructed in 1967 and located in parallel on a hill. Each building had shear walls in the transverse direction. Building-B and -C were partially placed on the refilled soil above the slope and more severly damaged while building-A had few damage. The outline of damage to Building-B and -C is as follows.

1) Building-B: Differential settlement caused by soil damage was observed 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 defined by D-index was "moderate".

2) Building-C: Soil subsidence was observed in the south-west zone of the building. 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 defined by D-index was "collapse".

2.4 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. Shear walls were provided mainly in the transverse direction.

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.

2.5 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. Shear walls were provided in the transverse and longitudinal direction. This building had a reinforced concrete pile foundation.

Major damage to this building 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. Columns at D-3 and D-4 had severe shear failures and the residual horizontal deformation was observed. The column at A-3 suffered from shear failure, concrete crushed and reinforcement was exposed. The damage level defined by D-index was "collapse".

According to D-index defined in ***Reference[1]***, the damage level of Midori-cho Civic Center and Awaji Agriculture High School (Farm Management Building) 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 ***Reference[1]*** should be reexamined particularly when the D-index lie around the boundary between moderate and light damage.

3. Seismic Evaluation of Damaged Buildings

The seismic capacity of each surveyed building was investigated. In the seismic evaluation, *The Japanese Standard for Evaluation of Seismic Capacity of Existing Reinforced Concrete Buildings[2]* was applied. The basic concept for the seismic evaluation can be found in ***Appendix 2.***

3.1 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 tf/m^2.
(2) The dimension of structure was determined according to drawings and field survey results.
(3) T-index which signifies deterioration after construction was assumed 1.0.
(4) Evaluation was carried out using the computational program[3] coded according to *the Standard*.

Other assumptions for each investigated building are shown in ***Table 3.***

3.2 Correlation between Seismic Capacity and Damage Level

The correlation between Is-index and the damage level (D-index) is shown in ***Fig. 3.*** ***Fig. 4*** shows the correlation between D-index and the construction year of six buildings described in this paper, together with other surveyed buildings in Awaji-Island. From the figures, the following findings can be obtained.

(1) Excluding 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 shear walls in the transverse direction were more provided than in the longitudinal direction ***[Fig. 3].***
(2) Judging from the correlation between the seismic capacity index and the damage level, buildings with higher seismic capacity had less damage. If the damage levels of Midori-cho Civic Center and Awaji Agriculture High School (Farm Management Building) identified by the authors were taken into account, the boundary to avoid serious damage during this event in this district may be around 0.6 in terms of Is-index ***[Fig. 3].***
(3) Is-indices of buildings constructed before 1971 were significantly lower and sustained more serious damage than those constructed after 1971. This result can be attributed to the improvement of the shear design due to the code revision in 1971 ***[Fig. 4].***

4. 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 results can be summarized as follows.

(1) Buildings constructed before the code revision in 1971 were more seriously damaged than those constructed after 1971.
(2) Buildings with higher seismic capacity had less damage. The boundary to avoid serious damage during this event in this district may be around 0.6 in terms of Is-index.
(3) In several buildings, the damage level classified according to D-index seemed to be overestimated particularly when the D-index lay around the boundary between moderate and light damage. The method of damage level classification defined in ***Reference[1]*** needs to be reexamined.

Acknowledgments

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References

[1] Japan Building Disaster Prevention Association, "Guideline for Damage Level Classification and Rehabilitation of Damaged Buildings," 1991. (in Japanese)
[2] Japan Building Disaster Prevention Association, "Standard for Evaluation of Seismic Capacity of Existing Reinforced Concrete Buildings," 1977, revised in 1990. (in Japanese)

[3] SPRC Committee, "Computational Program for Seismic Evaluation of Existing Reinforced Concrete Buildings (Screen Edition-2)," Japan Building Disaster Prevention Association, 1980

Appendix 1 [Damage Level Classification][1]

The procedure to identify damage level of an entire building is defined in ***Reference[1]*** 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 2.***

2) Calculation of Damage Sub-Index (Di) of each damage class

Damage Sub-Index of each damage class can be calculated as follows:

$D_1 = 10B_1/A$ [In case of $B_1/A \leqq 0.5$]
$= 5$ [In case of $B_1/A > 0.5$]
$D_2 = 26B_2/A$ [In case of $B_2/A \leqq 0.5$]
$= 13$ [In case of $B_2/A > 0.5$]
$D_3 = 60B_3/A$ [In case of $B_3/A \leqq 0.5$]
$= 30$ [In case of $B_3/A > 0.5$]
$D_4 = 100B_4/A$ [In case of $B_4/A \leqq 0.5$]
$= 50$ [In case of $B_4/A > 0.5$]
$D_5 = 1000B_5/7A$ [In case of $B_5/A \leqq 0.35$]
$= 50$ [In case of $0.35 < B_5/A \leqq 0.5$]
(In case of $B_5/A > 0.5$, Collapse)

notes) Bi : Number of structural members categorized in damage class i (i = 1 to 5) corresponding to the damage class I to V defined in ***Table2***

A : Number of inspected members

3) Damage Level Classification

By summing Di defined above, the Damage Index (D) which represents the damage level of an entire structure is classified as follows:

$D = \Sigma Di$
$D \leqq 5$: slight
$5 < D \leqq 10$: light
$10 < D \leqq 50$: moderate
$D > 50$: heavy
$D_5 = 50$: collapse

Appendix 2 [Basic Concept of the Standard][2]

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

$$Is = Eo \cdot S_D \cdot T \qquad (1)$$

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 ϕ. Story index (ϕ) 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:

$$Eo = C \cdot F \qquad (2)$$

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*.

Table 1: Outline of Damage to investigated Buildings

Name of Buildings	No. of Stories	Construction Year	Observed Damage (D-index, Damage Level)
Midori-cho Civic Center	3	1977	Shear failure of columns located in C-1 of the first story (D=17.3 (1F), Light*)
Hokudanhigashi Middle School	4	1963	Shear cracks in a few columns, slight ground damage (D=14.4 (1F), Moderate)
Higashiura Middle School (Building-B)	3	1967	Shear cracks in columns due to the differential settlement (D=26.5 (1F), Moderate)
Higashiura Middle School (Building-C)	3	1967	Shear failure in many columns of the first story (D=97.4 (1F), Collapse)
Awaji Agriculture High School (Farm Management Building)	3	1984	Minor flexural cracks (D=11.7 (3F), Slight*)
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 in ***Reference[1]*** was "moderate". Judging from the field survey, however, the damage level should be classified into "light" and "slight", respectively, as shown in the table.

Table 2: Definition of Damage Class

Damage Class	Description of 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 0.2～1.0 mm)
III	• Local crush of covering concrete • Remarkable wide cracks (Crack width is about 1.0～2.0 mm)
IV	• Remarkable crush of concrete with exposed reinforcing bars • Spalling of covering concrete (Crack width is more than 2.0 mm)
V	• Buckling of reinforcing bars • Cracks in core concrete • Visible vertical deformation in columns and/or walls • Visible settlement and/or inclination of the building

Table 3: Assumptions in Seismic Evaluation

Name of Buildings	Strength of Concrete (MPa)	Yield Strength of Reinforcing Bars (MPa)	Remarks
Midori-cho Civic Center	21	350	
Hokudanhigashi Middle School	18	300	In the seismic evaluation, the entrance hall (1F) was excluded.
Higashiura Middle School (Building-B)	18	300	In the seismic evaluation, the connecting corridor and kitchen (1F) were excluded.
Higashura Middle School (Building-C)	18	300	
Awaji Agriculture High School (Farm Management Building)	21	350	
Ichinomiya-cho Civic Center	18	300	Diameter of reinforcing bars and spacing of shear reinforcement were determined from field survey.

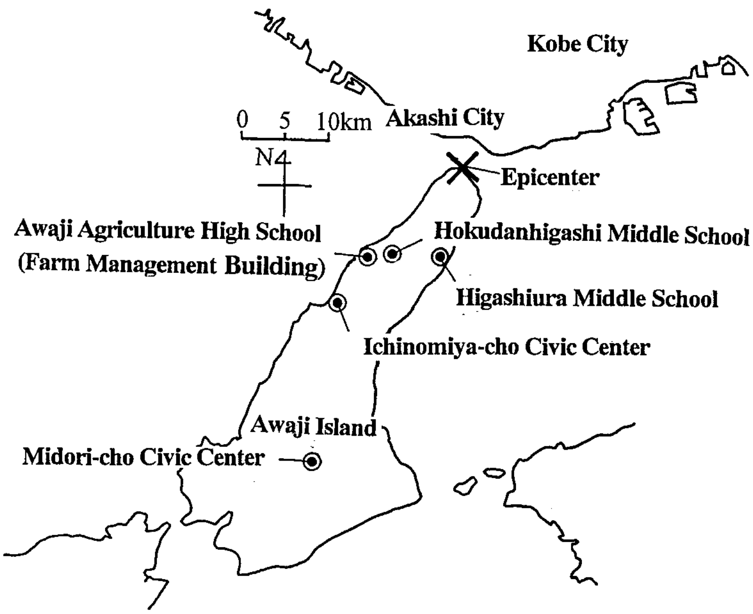


Fig.1: Epicenter and Location of the Investigated Buildings

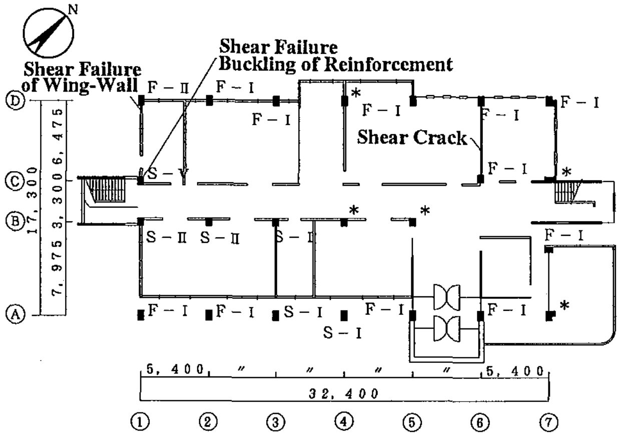


Fig.2-1: Midori-cho Civic Center (First Story)

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**

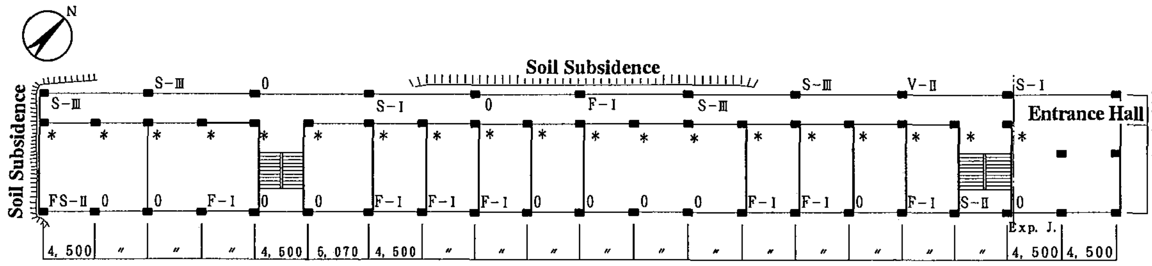


Fig.2-2: Hokudanhigashi Middle School (First Story)

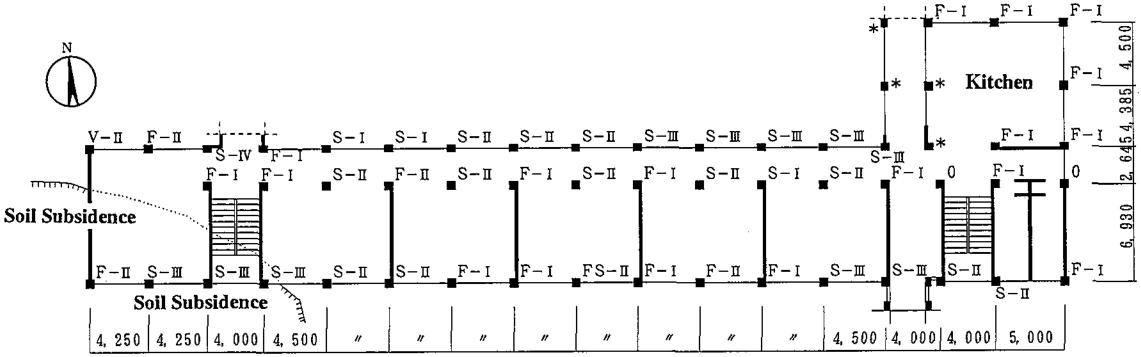


Fig.2-3: Higashiura Middle School (First Story of Building-B)

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**

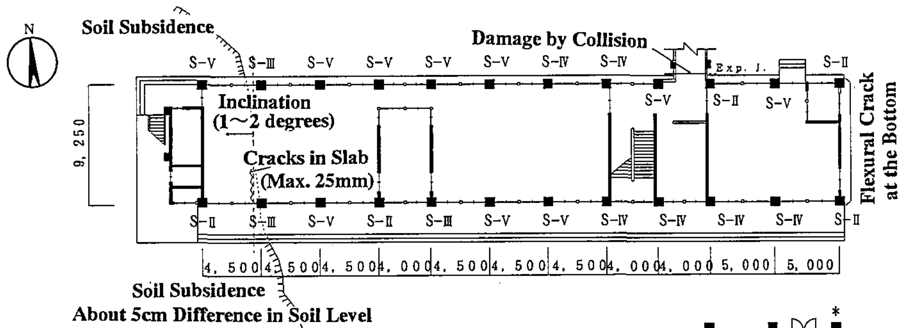


Fig.2-4: Higashiura Middle School (First Story of Building-C)

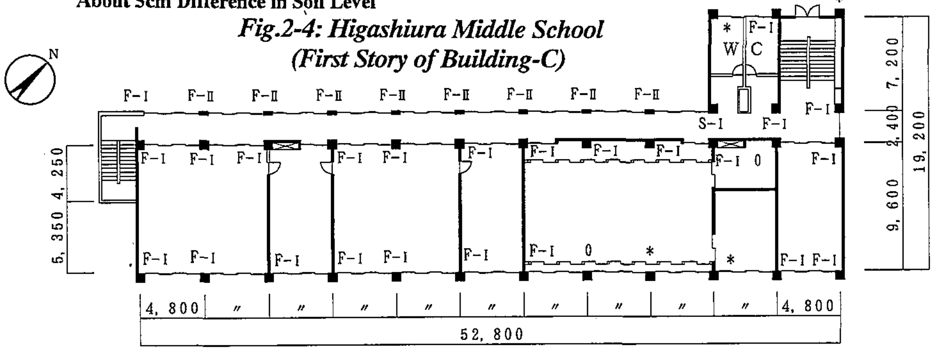


Fig.2-5: Awaji Agriculture High School (Third Story of Farm Management Building)

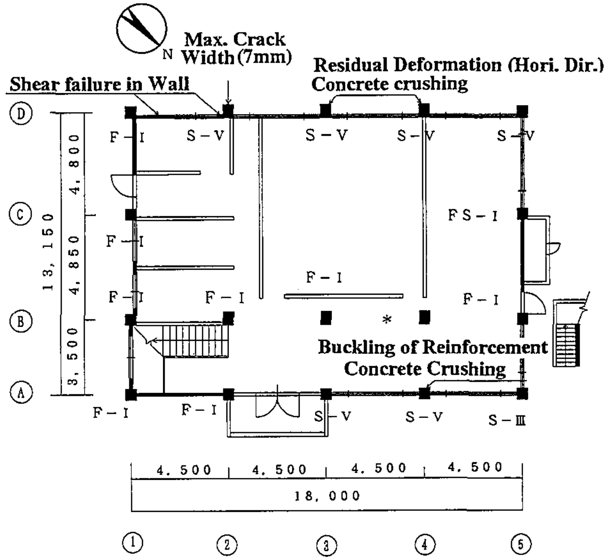


Fig.2-6: Ichinomiya-cho Civic Center (First Story)

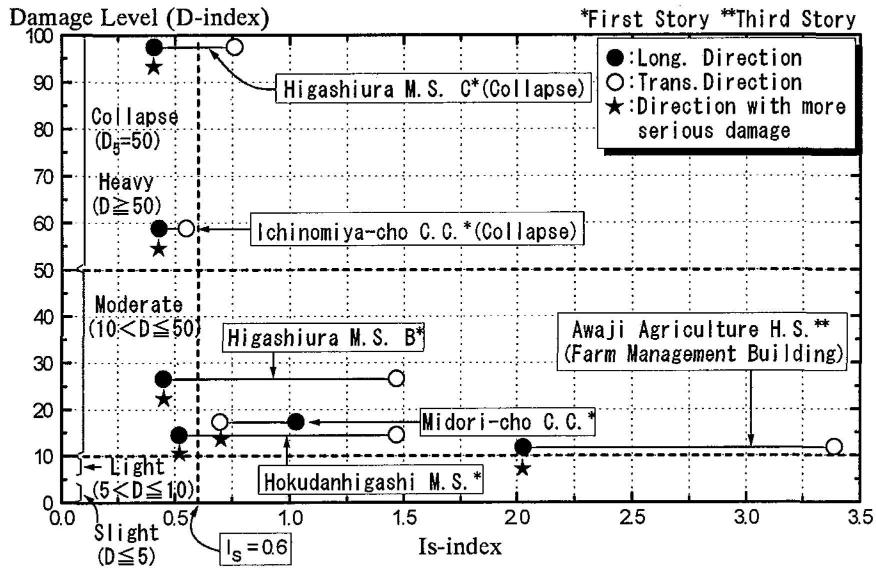
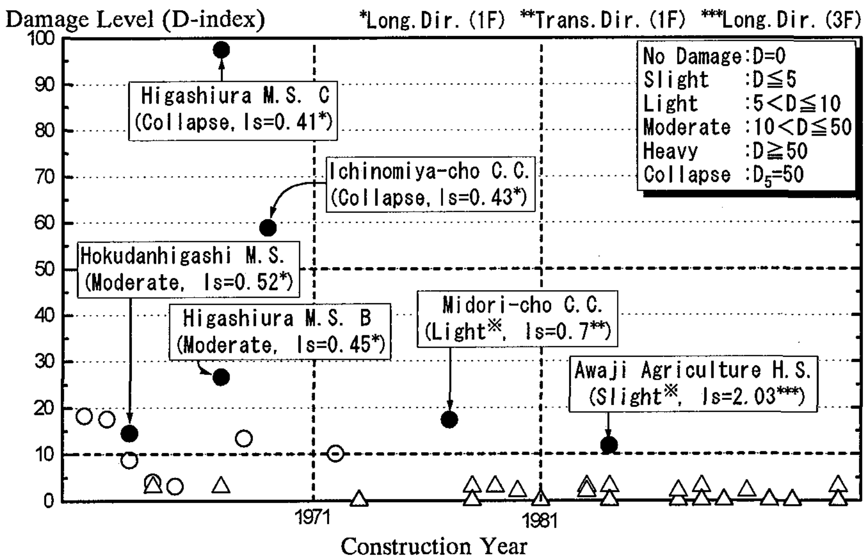


Fig.3: Correlation between Is-index and Damage Level



△ : D-index was assumed as follows since damage level was identified only by quick inspection. No Damage : D=0, Light Damage : D=3.

※ : The damage level defined by D-index in ***Reference[1]*** was "moderate". Judging from the field survey, however, the damage level should be classified into "light" and "slight", respectively, as shown in the figure.

Fig.4: Correlation between Damage Level and Construction Year (Awaji-Island)