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THE SEISMIC PERFORMANCE OF R/C SCHOOL BUILDINGS OBTAINED BY THE MODIFIED SEISMIC SAFETY EVALUATION

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Abstract

In Japan, the seismic safety evaluation has been applied widely in order to determine the seismic performance of existing buildings after the 1995 Great Hanshin-Awaji Earthquake Disaster. The seismic safety of a building is judged by comparing the seismic index "I_S" and the required seismic index "I_{S0}" in the seismic safety evaluation. If Eq. (1) is satisfied, the building is considered as safe against the scenario earthquake. The I_S value and the I_{S0} value are calculated by Eq. (2) and Eq. (3), respectively. The basic seismic factor "E_0" in Eq. (2) is the most important item calculated by accumulating vertical member's lateral strength depending on the ductility.

$$I_S \geq I_{S0} \tag{1}$$

$$I_S = E_0 \cdot S_D \cdot T \tag{2}$$

$$I_{S0} = E_S \cdot Z \cdot G \cdot U \tag{3}$$

Where, I_S ; seismic index, I_{S0} ; required seismic index, E_0 ; basic seismic factor, S_D ; shape factor, T ; deterioration factor, E_S ; basic required seismic factor, Z ; zoning factor, G ; ground factor, U ; importance factor.

The strong ground motion during the 2011 off the Pacific coast of Tohoku Earthquake caused the structural damage to two existing R/C school buildings. Inspected earthquake damages of those buildings showed consistency with the numerical response obtained by dynamic response analyses with a 3-D model, although the I_S values of those buildings did not indicated good correspondence to the damages.

Some researchers had indicated that dispersion of lateral strength and ductility of brittle columns caused degrading of seismic performance. In order to upgrade the accuracy of the seismic safety evaluation method, the dispersion of shear strength of R/C columns was focused in this paper. The modified seismic index "I_{Sb}" was proposed by authors as shown in the Eq. (4). The balance factor "b_R" in Eq. (5) represents the reduction coefficient for I_S value based on C_V which is the coefficient of variation of column's shear strength.

$$I_{Sb} = I_S \cdot b_R \tag{4}$$

$$b_R = 1.3 - C_V \tag{5}$$

Where, I_{Sb} ; modified seismic index, b_R ; balance factor, C_V ; coefficient of variation of column's shear strength

The distribution of 1/ I_{Sb} was a better fit to the maximum story drift angle obtained by dynamic response analyses than 1/ I_S for each of the studied buildings. It was confirmed that the proposed I_{Sb} value is more suitable for expressing the seismic performance of the studied buildings.

Keywords: seismic safety evaluation; seismic performance; R/C school building; dynamic response analysis; dispersion of shear strength

1. Introduction

The seismic safety evaluation has been applied widely in order to determine the seismic performance of existing buildings after the 1995 Great Hanshin-Awaji Earthquake Disaster in Japan. Especially, MEXT (the Ministry of Education, Culture, Sports, Science and Technology) of Japan has been promoting aggressively the seismic safety evaluation to R/C school buildings which should be designated as shelters at the time of a disaster. The executing ratio of the seismic safety evaluation for public school buildings (primary schools and junior high schools) is shown in the Fig. 1 [1]. By 2015, the seismic performance of 98.5% of Japanese public school buildings has been assessed by the seismic safety evaluation. The seismic retrofitting construction works in dangerous buildings have been advancing based on the assessment of the seismic performance. It is very important to verify and improve the accuracy of the seismic safety evaluation in order to execute the appropriate seismic retrofitting for existing buildings which have poor seismic performance.

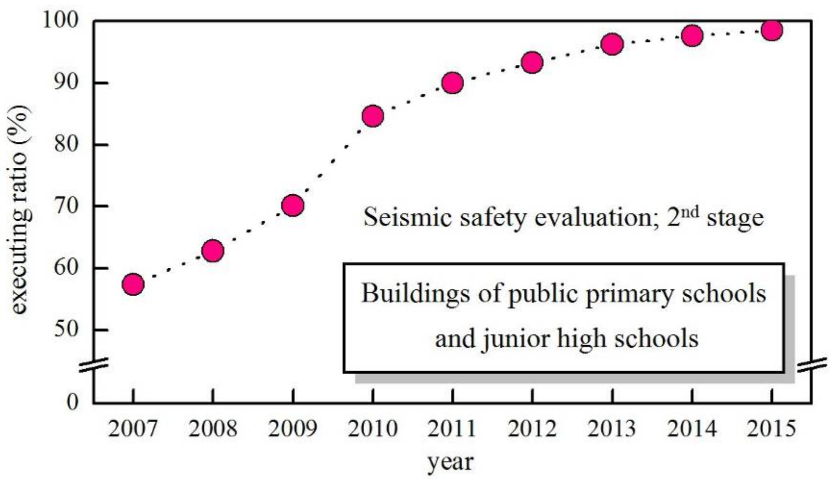


Fig. 1 – Executing ratio of the seismic safety evaluation for public school buildings [1]

The seismic performance of existing R/C buildings calculated by the seismic safety evaluation and dynamic response analyses are compared in order to evaluate the accuracy of the current seismic safety evaluation method in this paper. The studied buildings are two R/C school buildings which had been damaged structurally by the strong ground motion during the off the Pacific coast of Tohoku Earthquake on March 11th, 2011 (hereinafter called as the 3.11 Eq.). A modified technique for the seismic safety evaluation is also proposed in this paper focusing on the dispersion of shear strength of R/C columns.

2. Studied School Buildings

2.1 Buildings' information

Studied buildings are two existing R/C school buildings in an elementary school in Ibaraki Prefecture of Japan. Although the area was far away from the epicenter of the 3.11 Eq. over 300 km as shown in Fig. 2, very strong ground motions were recorded during the earthquake.

The elementary school is located in the plain of a valley, which is located in the mid west area of Ibaraki Prefecture. The site and surrounding environment are shown in Fig. 3. The seismic intensity of JMA (Japan Meteorological Agency) was estimated as the 6 lower around this area. Since the ground condition of the site was not firm, all of major buildings in the school were supported on piles in the foundation.

Two R/C school buildings, the North bldg. and the South bldg. shown in Fig. 3 and Fig. 4 were investigated by authors after the 3.11 Eq.. Those buildings were connected by corridors separated by expansion joints as shown in the figures. Both buildings' data are summarized in Table 1. They were also built in the 1970's before 1981 when the Japanese seismic code has been improved substantially.

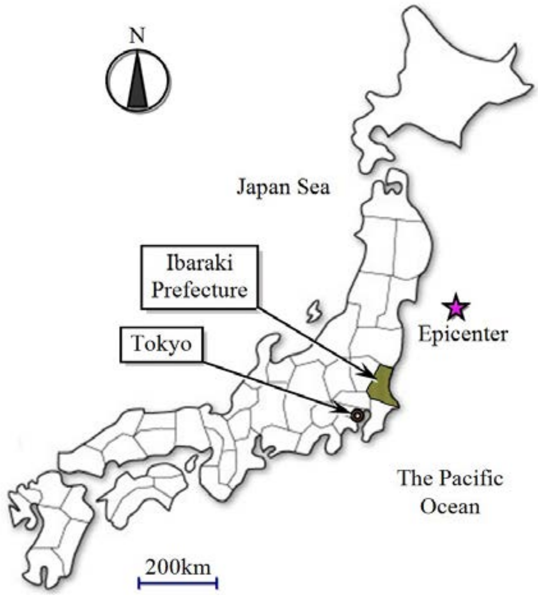


Fig. 2 – The epicenter of the 3.11 Eq. and Ibaraki Prefecture in Japan

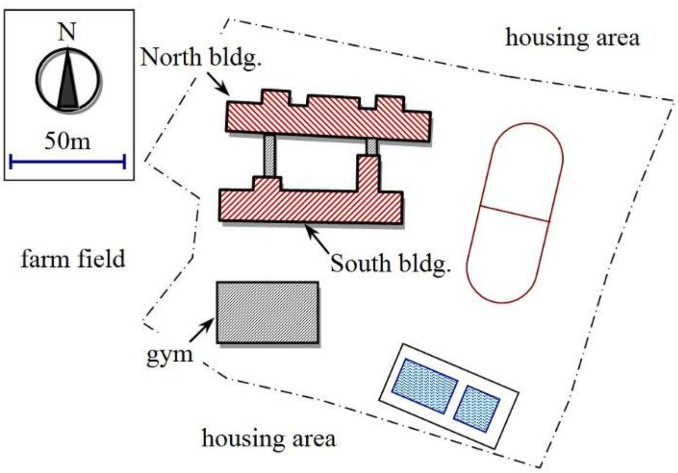


Fig. 3 – Site and layout of the elementary school

Table 1 – Data of studied buildings

Built year	North bldg.; 1974 South bldg.; 1975 (the 3rd story was added in 1980)
Structure	R/C frame with seismic wall
Stories	3 with penthouse (floor height; about 3.7 m)
Foundation	PC Piles (300 or 350mm diameter, 10m length)
Material property	Concrete; F_C =20.5 (N/mm^2) Rebar; SD295 and SR235

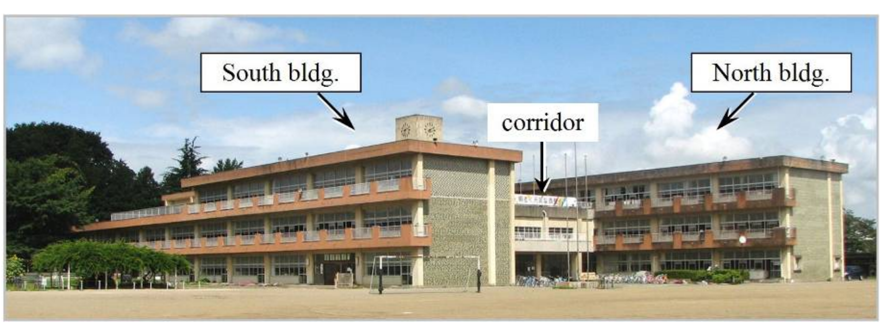
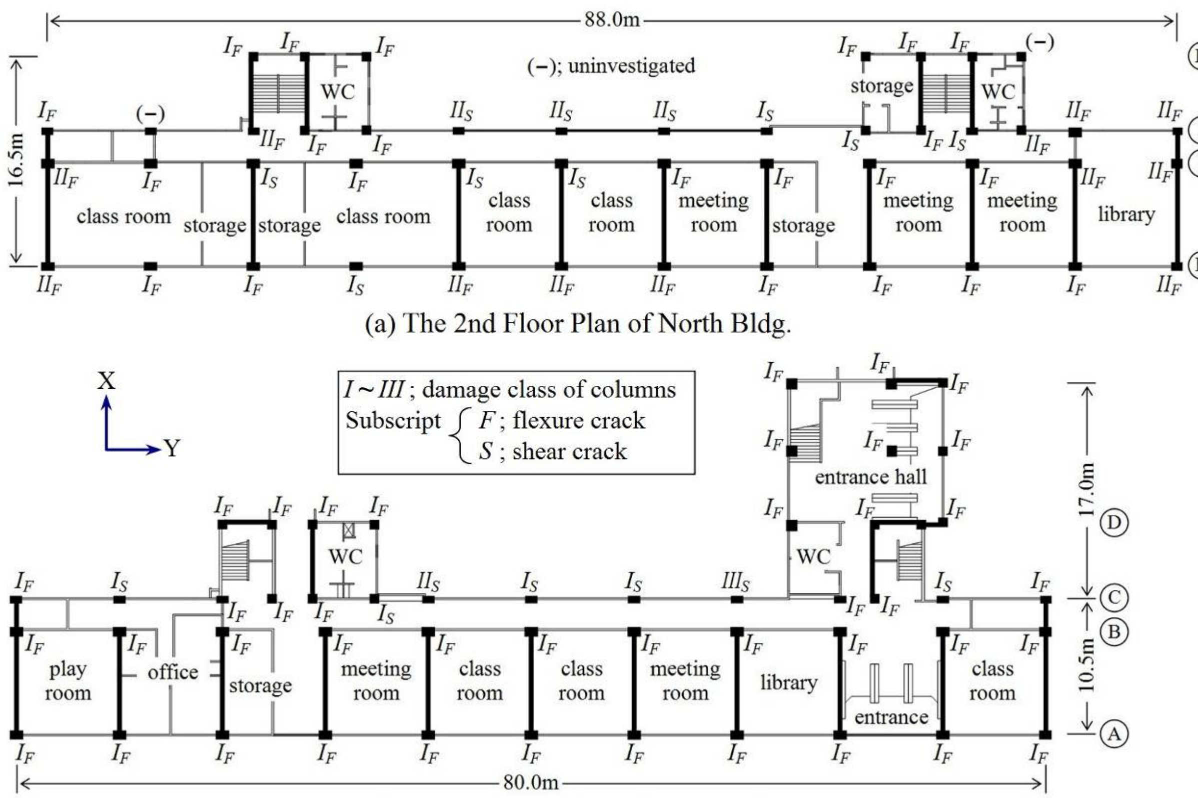


Fig. 4 – Studied R/C buildings of the elementary school viewed from southeast

2.2 Investigation of seismic damages

Structural damages of the studied buildings due to the 3.11 Eq. were investigated with reference to the guideline proposed by JBDPA (the Japan Building Disaster Prevention Association) [2] The guideline is containing criteria of damage class for R/C structural members and the assessment procedure establishing the for damage level of a building. In the procedure, damages on R/C members, mainly columns and walls, of a building are checked in order to determine the damage class according to the criteria as shown in Table 2. The damage level of the building is specified according to Table 3 depending on the Residual Seismic Capacity, *R*, which is calculated by counting the damage class of members for each direction of all stories.

The 2nd floor plan of the North bldg. and the 1st floor plan of the South bldg. are shown in Fig. 5 with the damage class of each column. Each building had distinct damages in the X direction on the floor drawn in



(a) The 2nd Floor Plan of North Bldg.

(b) The 1st Floor Plan of South Bldg.

Fig. 5 – Floor plan of buildings and damage class of columns

Table 2 – Damage class for R/C structural member

Damage class	Observed damage of member
I	Only hair cracks (≤ 0.2mm width)
II	Clear cracks (0.2 ~ 1mm width)
III	Remarkable cracks (1 ~ 2mm width) with some spalling of covering concrete
IV	Severe cracks (> 2mm width) and exposing of rebar due to spalling of covering concrete
V	Vertical deformation with buckling of rebar and crushing of concrete

Table 3 – Damage level and residual seismic capacity; *R*

Damage level	Residual seismic capacity; *R*
No-damage	R = 100 (%)
Slight damage	95 ≤ R < 100 (%)
Minor damage	80 ≤ R < 95 (%)
Moderate damage	60 ≤ R < 80 (%)
Severe damage	R < 60 (%)
Collapse	R = 0

the figure. Several short columns had serious shear cracks in the X direction at frame J of the North bldg. and at frame C of the South bldg. Residual Seismic Capacity, R and the damage level in the X direction of each building are shown in Table 4. Both of them were assessed as having minor damage in the X direction.

Table 4 – R value and damage level of buildings in the X Direction

	North Bldg.		South Bldg.	
Story	R (%)	Damage level	R (%)	Damage level
3	92.1	Minor damage	90.3	Minor damage
2	90.0		92.1	
1	92.1		89.2	

3. Discussion of the Seismic Safety Evaluation

3.1 General information of the seismic safety evaluation

The seismic safety evaluation has been the most popular method to estimate the seismic performance of existing buildings in Japan. The standard for the seismic safety evaluation for R/C buildings proposed by JBDPA [3] was applied in this paper. The seismic safety of a building is assessed by comparing the seismic index; I_S and the required seismic index; I_{S0} in the seismic safety evaluation. If Eq. (1) is satisfied, the building is considered as safe against the earthquake supposed in the standard. I_S and I_{S0} are calculated by Eq. (2) and Eq. (3), respectively. The basic seismic factor; E_0 in the Eq. (2) is the most important item calculated by combination of the strength index; C and ductility index; F of all members.

$$I_S \geq I_{S0} \tag{1}$$

$$I_S = E_0 \cdot S_D \cdot T \tag{2}$$

$$I_{S0} = E_S \cdot Z \cdot G \cdot U \tag{3}$$

Where, I_S ; seismic index, I_{S0} ; required seismic index, E_0 ; basic seismic factor, S_D ; shape factor, T ; deterioration factor, E_S ; basic required seismic factor, Z ; zoning factor, G ; ground factor, U ; importance factor.

There are three stages in the seismic safety evaluation. The higher stage is more detailed and accurate however it requires much more calculations. The 1st stage is the easiest method used as a quick safety check. This stage requires easy calculations using sectional area of vertical members. In the 2nd stage, the flexure and shear strength of vertical members should be determined while beams are assumed rigid. The 2nd stage is suitable for weak-column type buildings. The 3rd stage is suitable for weak-beam type buildings, because the collapse mechanism of each frame should be considered.

3.2 Implementation of the current seismic safety evaluation method

The current method for the 2nd stage of the seismic safety evaluation was applied to the studied buildings. The results of calculation are summarized in Table 5 for the weaker direction X. The shortage of seismic capacity in all stories was clarified as “NG”. The minimum I_S value was in the 2nd floor of the North bldg. and in the 1st floor of the South bldg., corresponding to the minimum R values in Table 4. The I_S values of the 1st and 2nd story in the North Bldg. were almost similar, although the 2nd story was damaged especially as shown in Table 4. Dynamic response analyses of studied buildings should be carried out in order to grasp the accuracy of the current seismic safety evaluation method.

Table 5 – Result of the seismic safety evaluation (the 2nd stage)

Story	[North Bldg. (X direction)] E_0	S_D	T	I_S	Judge	[South Bldg. (X direction)] E_0	S_D	T	I_S	Judge
3	0.72	0.90	0.97	0.63	NG	0.76	0.79	0.97	0.58	NG
2	0.56	0.90		0.49	NG	0.65	0.88		0.55	NG
1	0.57	0.90		0.50	NG	0.62	0.88		0.53	NG

I_{S0} = 0.7 (← E_S = 0.7 (for the 2nd stage), $Z = G = U = 1.0$)

4. Discussion of the Dynamic Response Analysis

4.1 Dynamic response analyses of studied buildings

Dynamic response analyses of studied buildings were carried out in order to confirm the elasto-plastic behavior during severe earthquakes. Each building was modeled as a 3-D frame. The 3-D model of the North Bldg. is shown in Fig. 6 as an example. All of columns and beams were represented by spring models as illustrated in Fig. 7 (a), and seismic walls were assumed as 3 columns with rigid top and bottom beams. Hysteresis rules of the flexural spring and the shear spring are shown in Figs. 7 (b) and (c), while the axial spring was assumed linear elastic. It should be noted that the shear spring for columns and walls had negative stiffness after the shear strength point, in order to consider the strength degradation due to the shear failure.

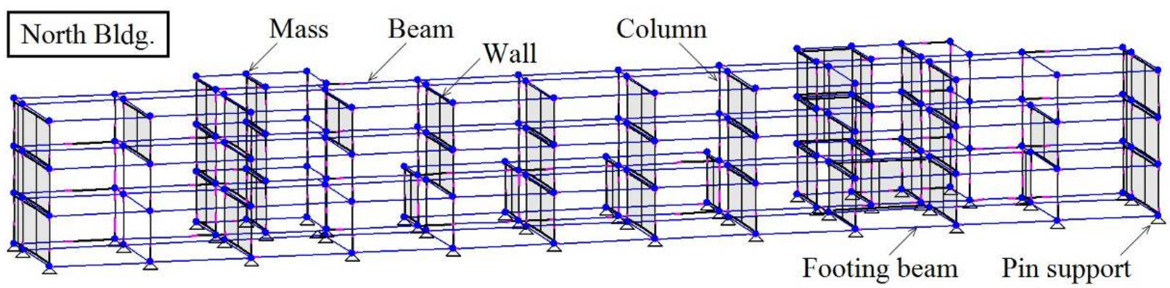


Fig. 6 – 3-D frame model of the North Bldg.

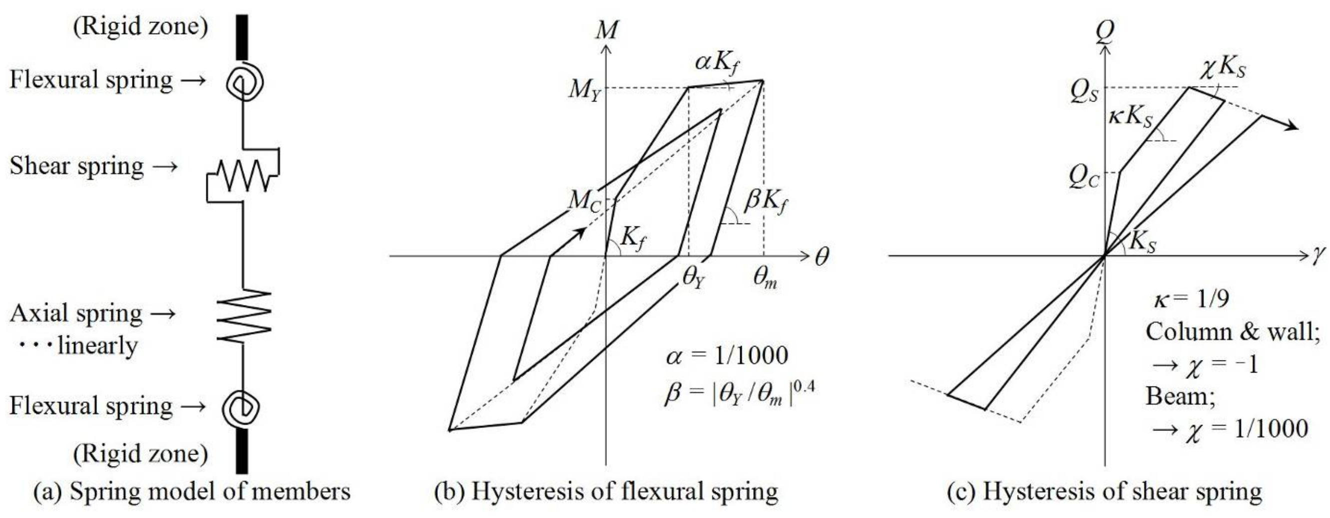


Fig.7 – Analytical model of members and hysteresis rules of spring

Dynamic response analyses of building models were executed utilizing the software, *SNAP* (ver. 6008, Kozo System Inc.). 0.01 sec. was set as the time increment while the damping factor was assumed as 3% proportional to the instantaneous stiffness in the analysis.

Several earthquake waves were employed as input ground motions shown in Table 6. 'Elc', 'Taf' and 'Kob' were recorded major earthquake data, while 'Bcj' was an artificial earthquake data simulating a severe earthquake by BCJ (the Building Center of Japan). All waves were normalized to the maximum velocity as 0.5 m/sec in order to represent the severe ground motion with a possibility of causing serious damage to building structures. Acceleration response spectra of input ground motions are shown in Fig. 8. The calculated natural period of studied buildings (0.229 (sec) in each building) is noted in the figure.

Elasto-plastic behavior of building models during severe earthquakes was obtained by the response analyses. The maximum story drift is shown in Fig. 9 as an example of numerical results. It was confirmed that the 2nd story of the North bldg. and the 1st story of the South bldg. were the most damaged stories of each building, corresponding to the minimum *R* values in Table 4.

4.2 Modification of the seismic safety evaluation

Kuwamura, et al. [4] indicated that dispersion of lateral strength and ductility of brittle columns caused degradation of seismic performance. Based on this knowledge, this paper focused on the dispersion of shear strength of R/C columns. An improved method for the seismic safety evaluation considering the dispersion of shear strength is proposed next.

Table 6 – List of input ground motions (normalized max. velocity as 0.5 m/sec)

Symbol	Name of earthquake [year]	Max. acceleration (m/sec^2)
Elc	El Centro NS [1940]	4.85
Taf	Taft NS [1952]	4.76
Kob	JMA Kobe NS [1995]	4.49
Bcj	Simulated earthquake (level 2) by BCJ	3.56

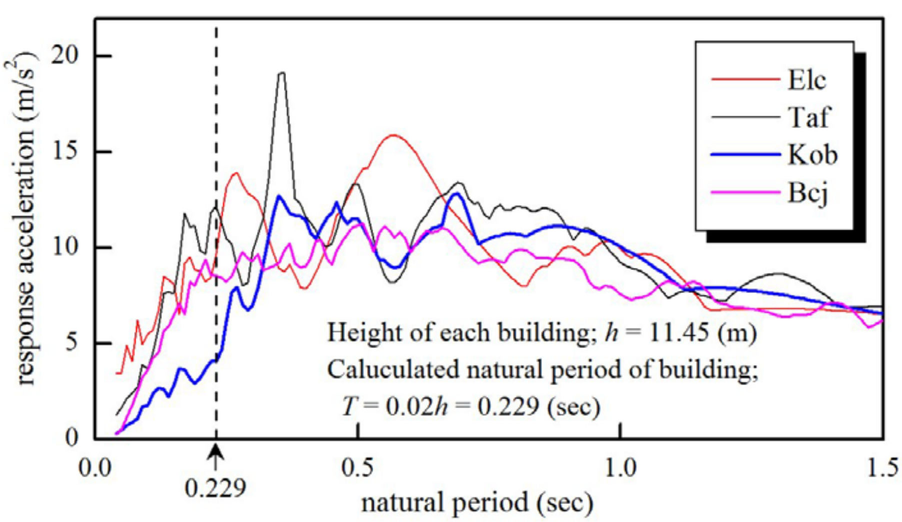


Fig. 8 – Acceleration response spectra of input ground motions

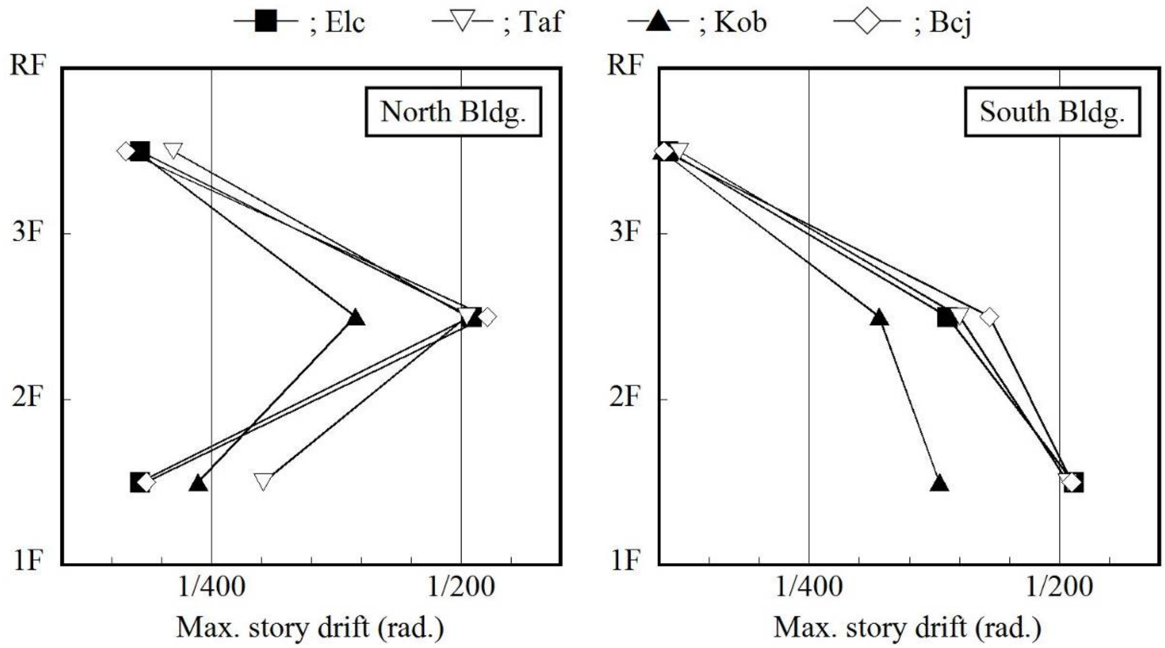


Fig. 9 – Maximum story drift during each earthquake response

For the 1st step, the prime frame which carries the maximum lateral force in each story of the building should be selected. The prime frame is supposed to have high stiffness corresponding to high lateral force. The summation of the ratio *C/F* (*C* ; strength index and *F* ; ductility index were calculated in the seismic safety evaluation) of vertical members at each X-direction frame is shown in Table 7. *C/F* is considered as the pseudo secant stiffness at failure point of each member. The J-frame of the North Bldg. and the C-frame of the South Bldg. were the prime frames in each story, because they had the maximum value of accumulated *C/F*.

For the 2nd step, the coefficient of variation; C_V of vertical member's shear strength at each story of the prime frame should be calculated mathematically. Fig. 10 shows the calculated C_V at each story of each frame. It was found that only the prime frame had over 30% of C_V discounting the effect of seismic walls.

For the 3rd step, the balance factor; b_R and the modified seismic index; I_{Sb} of each story should be calculated utilizing Eq. (4) and Eq. (5). b_R value represents the reduction coefficient for I_S value based on C_V. '0.3' in Eq. (5) corresponds to the '30%' in Fig. 10. The seismic performance of the story, shown as I_{Sb}, was downgraded with the b_R value if C_V was over 30%, while the I_{Sb} value was equal to I_S value in the case when C_V is less than 30%. A list of calculated I_{Sb} value of each building is shown in Table 8. All of I_S values were downgraded considering the dispersion of column's shear strength.

$$I_{Sb} = I_S \cdot b_R \tag{4}$$

$$b_R = \begin{cases} 1.0 & [\ C_V < 0.3\ ] \\ 1.3 - C_V & [\ C_V \geq 0.3\ ] \end{cases} \tag{5}$$

Where, I_{Sb} ; modified seismic index, b_R ; balance factor, C_V ; coefficient of variation of column's shear strength at the prime frame

Table 7 – Summation of C / F ($\times 10^{-3}$) of vertical members at each X frame

[North Bldg.] [South Bldg.]

Story \ Frame	H	I	J	K	A	B	C	D
3	433	243	626	209	190	591	734	250
2	239	197	333	109	235	207	292	121
1	176	187	280	109	150	140	193	163
			▲				▲	

▲ ; Prime frame

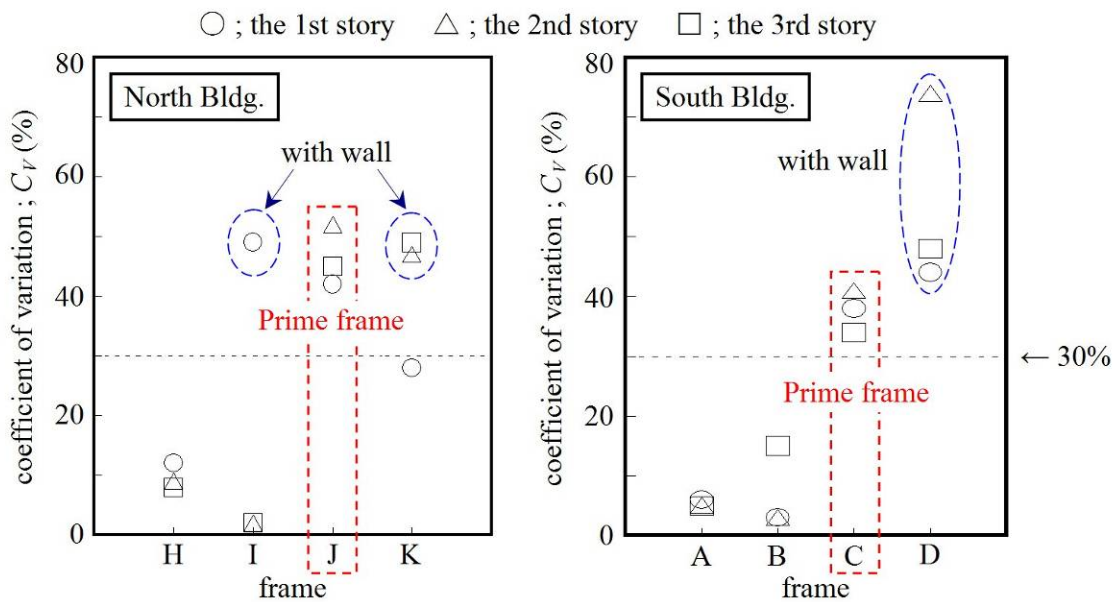


Fig. 10 – C_V of vertical members' shear strength at each story of each frame

The Distribution of $1/I_S$ and $1/I_{Sb}$ of each story is shown in Fig. 11. The maximum story drift obtained by the dynamic response analysis (case of Kob, shown in Fig. 9) is also illustrated in the figure. The shape of $1/I_{Sb}$ has a better fit to the maximum story drift than $1/I_S$ in each building. It is thus confirmed that the proposed I_{Sb} value is more suitable for expressing the seismic performance of the studied buildings.

Table 8 – Modified seismic index; I_{Sb} considering dispersion of column's shear strength

[North Bldg.] [South Bldg.]

Story	I_S	P.F.	C_V	b_R	I_{Sb}	I_S	P.F.	C_V	b_R	I_{Sb}
3	0.63	J	0.455	0.845	0.53	0.58	C	0.340	0.960	0.56
2	0.49	J	0.523	0.777	0.38	0.55	C	0.410	0.890	0.49
1	0.50	J	0.422	0.878	0.43	0.53	C	0.378	0.922	0.48

P.F. ; Prime frame

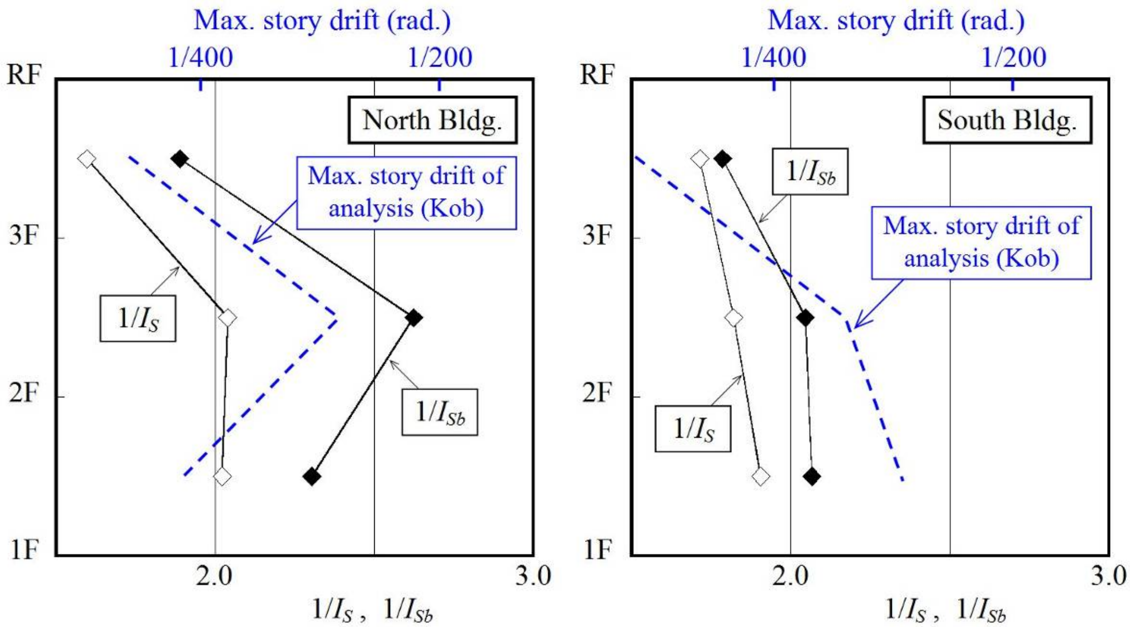


Fig. 11 – Distribution of reciprocal of I_S and I_{Sb} with max. story drift of analysis

5. Conclusions

The seismic performance of two R/C schools buildings (the North Bldg. and the South Bldg.) which were damaged by the 3.11 Eq. calculated by the seismic safety evaluation method was compared to the investigated structural damages and the elasto-plastic behavior obtained through the dynamic response analysis. A modified method was proposed in order to upgrade the accuracy of the seismic safety evaluation technique. The followings conclusions can be drawn from the study.

From the numerical analysis, the 2nd story of the North Bldg. and the 1st story of the South Bldg. were the most damaged stories of each building, corresponding to both of the observed earthquake damages and the result of the seismic safety evaluation.

For upgrading the seismic safety evaluation technique, the modified seismic index, I_{Sb}, was proposed in order to consider the dispersion of R/C column's shear strength.

The proposed I_{Sb} value was more suitable than the ordinary seismic index, I_S, for expressing the seismic performance of the studied buildings. More studies should be performed in order to validate the proposed methodology.

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