Upgrade of seismic safety evaluation considering dispersion of R/C column's shear strength

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ABSTRACT: Two R/C school buildings in Ibaraki Prefecture, Japan were damaged by 2011 Tohoku Pacific Earthquake. Dynamic response analyses with the 3-D model of those buildings were carried out applying several input ground motions. Obtained analytical response showed consistency with inspected earthquake damage of buildings. The seismic index; I_S conducted from the current method for the Seismic Safety Evaluation had difference with the analytical response. The modified seismic index; I_{Sb} was proposed in order to consider dispersion of R/C column's shear strength for upgrading the Seismic Safety Evaluation. It was confirmed that I_{Sb} was more suitable than I_S for expressing the seismic performance of the objective buildings.

1 INTRODUCTION

On March 11th 2011, a great earthquake, 2011 Tohoku Pacific Earthquake occurred in Japan, unfortunately. Terrible damages were caused by the tsunami and seismic shaking of the earthquake at the large area of East Japan, and lots of buildings were collapsed or damaged severely. In order to confirm safety about school buildings at the disaster-stricken region, the damage inspection project was conducted by initiative of AIJ (the Architectural Institute of Japan) and MEXT (the Ministry of Education, Culture, Sports, Science and Technology). Inspected buildings' data was reported in several references, e. g. AIJ (2012).

Two R/C school buildings in an elementary school in Ibaraki Prefecture were inspected particularly by authors after the earthquake as a part of the damage inspection project. Those were objective buildings in this paper. Dynamic response analyses with the 3-D model considering severe earthquakes and the Seismic Safety Evaluation were carried out to quantitate the seismic performance of the objective buildings. Comparing with the inspected earthquake damages and analytical response of buildings, it was revealed that the current method for the Seismic Safety Evaluation had a problem should be improved. A modifying idea considering the dispersion of R/C column's shear strength was proposed and discussed in this paper in order to upgrade the Seismic Safety Evaluation.

2 OBJECTIVE SCHOOL BUILDINGS

2.1 Buildings' information

The elementary school was located in the plain of a valley, which were located in the mid west area of Ibaraki Prefecture. The site and circumstance environment were shown in Figure 1. The seismic intensity of JMA (Japan Meteorological Agency) was estimated as 6 minor around this area. Since the ground condition of the site was not firm, all of major buildings in the school were supported with piles in the foundation.

Two R/C school buildings, The North bldg. and the South bldg. shown in the Figure 1 and Figure 2 were investigated by authors. Those buildings were connected by corridors installed expansion joints. Both buildings' data are summarized in Table 1.

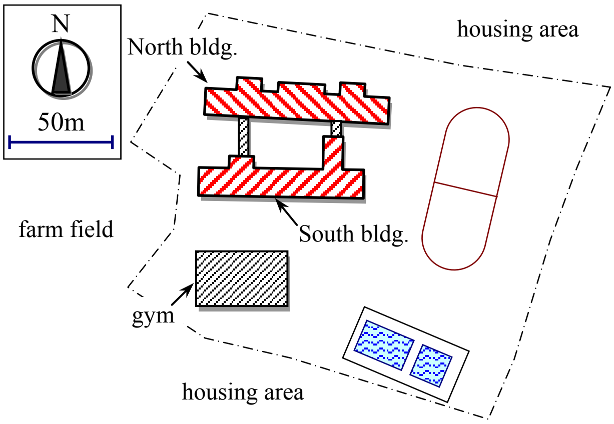


Figure 1. Site and layout of the elementary school

Table 1. Data of buildings at the school

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

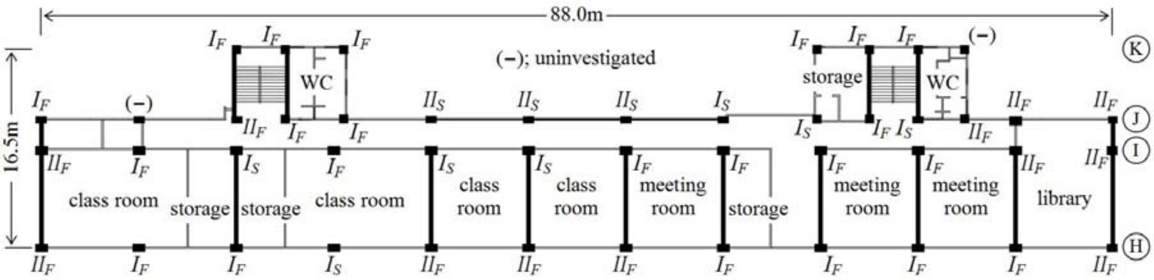
Figure 2. Objective R/C buildings of the elementary school viewed from southeast

2.2 *Investigation of Seismic Damages*

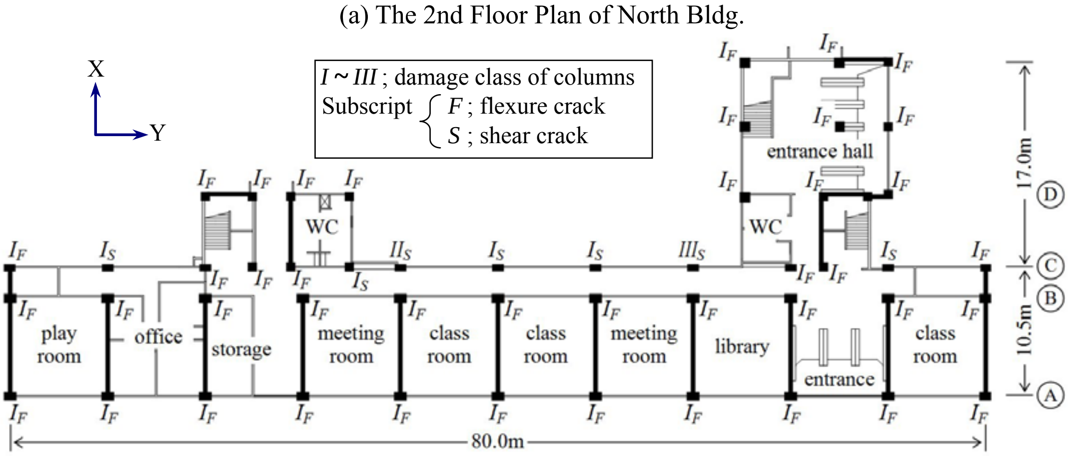
Structural damages of those buildings were investigated with reference to the guideline proposed by JBDPA (the Japan Building Disaster Prevention Association) (2005). The guideline is containing criteria of damage class for R/C structural members and the judgment procedure for damage level of a building. In the procedure, damages on R/C members, mainly columns and walls, of a building were checked respectively in order to determine the damage class according to the criteria as shown in Table 2. The damage level of the building was judged by Table 3 depending on the Residual Seismic Capacity; *R*, which calculated from counting of damage classes 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. were shown in Figure 3 with the damage class of each column. Each building had remarkable damages in the X direction on the floor drawn in the figure. Several short columns had serious shear cracks in the X direction at the frame J of the North bldg. and at the frame C of the South bldg. Residual

Seismic Capacity; *R* and the damage level in the X direction of each building were shown in Table 4. Both of them were judged as the minor damage in the X direction.



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



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

Figure 3. 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	$95 \le R < 100$ (%)
Minor damage	$80 \le R < 95$ (%)
Moderate damage	$60 \le R < 80$ (%)
Severe damage	$R < 60$ (%)
Collapse	$R = 0$

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 DYNAMIC RESPONSE ANALYSIS

3.1 3-D model of the objective building

Dynamic response analyses of objective buildings were carried out in order to confirm the elasto-plastic behavior during severe earthquakes. Each building was translated to a 3-D frame model. The 3-D model of the North bldg. was shown in Figure 4 as an example. All of columns and beams were represented spring models illustrated in Figure 5 (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 were shown in Figure 5 (b) (c), while the axial spring was assumed linear. 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 shear failure.

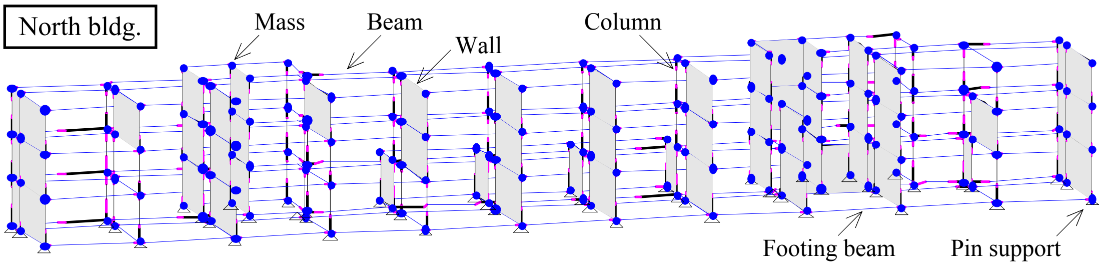


Figure 4. 3-D Model of building (case of the North bldg.)

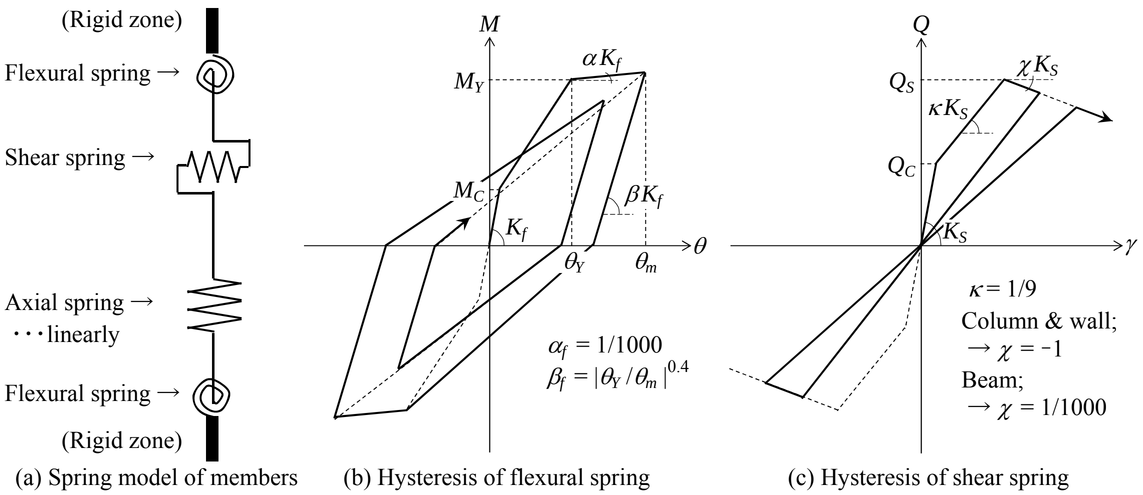


Figure 5. Model of members and hysteresis rules of spring

3.2 Execution of dynamic response analysis

Dynamic response analyses of building models were executed utilizing software; SNAP (ver. 6008, Kozo System Inc.). The time step was 0.01 sec. and the damping factor was 3% proportional to the instantaneous stiffness in the analysis.

Several earthquake waves were employed as input ground motions shown in Table 5. 'Elc', 'Taf' and 'Kob' were recorded earthquake data, while 'Bcj' was an artificial earthquake data simulated a severe earthquake by BCJ (the Building Center of Japan). All of waves were normalized to the maximum velocity as 0.5 m/sec in order to regard as the severe ground motion with a possibility which bring serious damage to building structures.

Elasto-plastic behavior of building models during severe earthquakes were obtained by the analyses. The maximum story drift was shown in Figure 6 as an example of analytical results. It was confirmed that the 2nd story of the North bldg. and the 1st story of the South bldg. were the most injured story of each building, corresponding to the minimum R-values in Table 4.

Table 5. 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

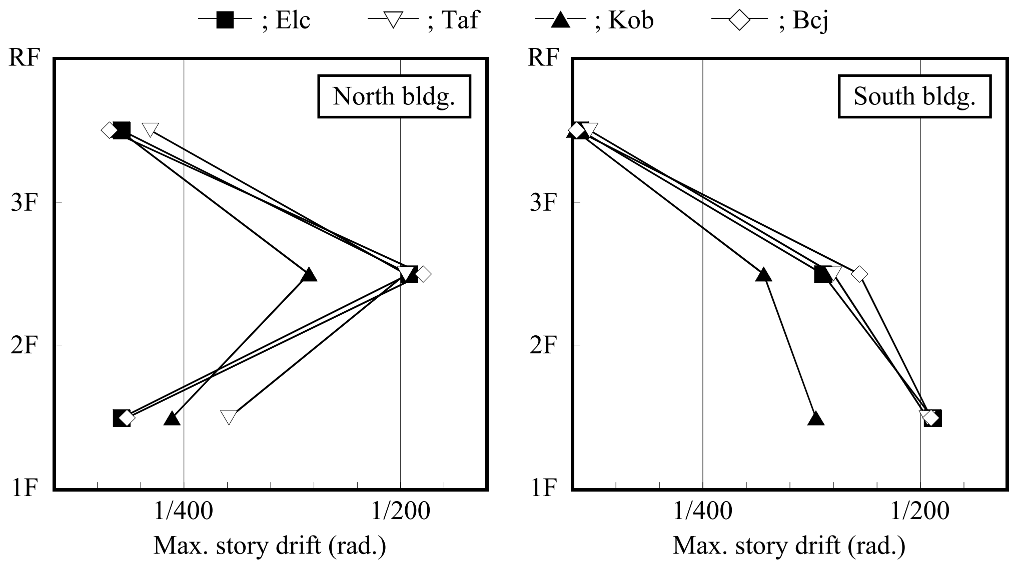


Figure 6. Maximum story drift during each earthquake response

4 THE SEISMIC SAFETY EVALUATION

4.1 Outline of the Seismic Safety Evaluation

The Seismic Safety Evaluation is 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 (2001) was applied in this paper. 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 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 detail and accurate however it takes much more calculations. The 1st stage is the easiest method used as 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.

4.2 *Execution of the current method for the Seismic Safety Evaluation*

The current method for the 2nd stage of the Seismic Safety Evaluation was applied to both buildings. The results are summarized in Table 6 about 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 injured especially by the dynamic response analysis as shown in Figure 6. It was revealed that the current method for the Seismic Safety Evaluation had a problem should be improved.

Table 6. Result of the Seismic Safety Evaluation (the 2nd stage)

	[North Bldg. (X direction)]					[South Bldg. (X direction)]				
Story	E_0	S_D	T	I_S	Judge	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

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

4.3 *Improved idea for the Seismic Safety Evaluation*

Kuwamura, et al. (1996) indicated that dispersion of strength and ductility of brittle columns caused degrading of seismic performance. According to this knowledge, the dispersion of shear strength of R/C columns was focused in this paper. An improved idea for the Seismic Safety Evaluation considering the dispersion of shear strength was shown in the followings.

For the 1st step, the prime frame which bore the maximum lateral force in each story of the building should be selected. The prime frame was supposed to have high stiffness corresponding to high lateral force. Summation of C/F (C; strength index, F; ductility index) of vertical members at each X-direction frame was shown in Table 7. C/F represented the pseudo secant stiffness at the 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; CV of vertical member's shear strength at each story of the prime frame should be calculated mathematically. Figure 7 showed calculated CV at each story of each frame. It was found that only the prime frame had over 30% of CV excepting the effect of seismic walls.

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

Story \ Frame	[North Bldg.] H	I	J	K	[South Bldg.] 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				▼ Prime frame	

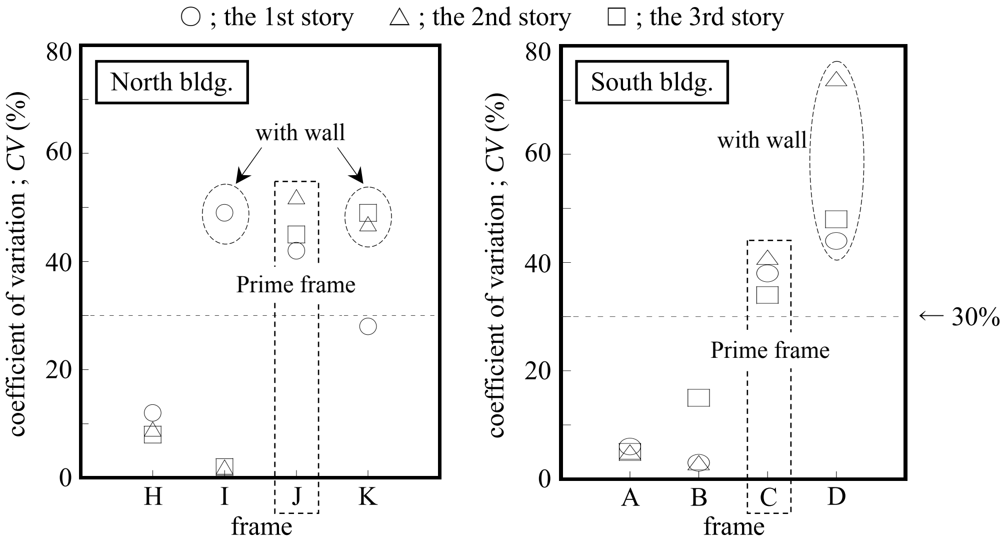


Figure 7. *CV* of vertical members' shear strength at each story of each frame

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 represented the reduction coefficient for I_S based on *CV*. '0.3' in the Eq. (5) corresponded to the '30%' in the Figure 7. The seismic performance of the story, representing as I_{Sb}, was downgraded with b_R if *CV* was over 30%, while I_{Sb} was equal to I_S in the case of less than 30% of *CV*. A list of calculated I_{Sb} of each building was shown in Table 8. All of I_S were downgraded considering dispersion of column's shear strength.

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

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

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

The Distribution of $1/I_S$ and $1/I_{Sb}$ of each story was shown in Figure 8. The maximum story drift obtained by the dynamic response analysis (case of Kob, shown in Figure 6) was also illustrated in the figure. The shape of $1/I_{Sb}$ was fitting to the maximum story drift than $1/I_S$ in each building. It was confirmed that proposed I_{Sb} was suitable for expressing the seismic performance of the objective buildings.

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

Story	[North Bldg.] I_S	Pr.frame	CV	b_R	I_{Sb}	[South Bldg.] I_S	Pr.frame	CV	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

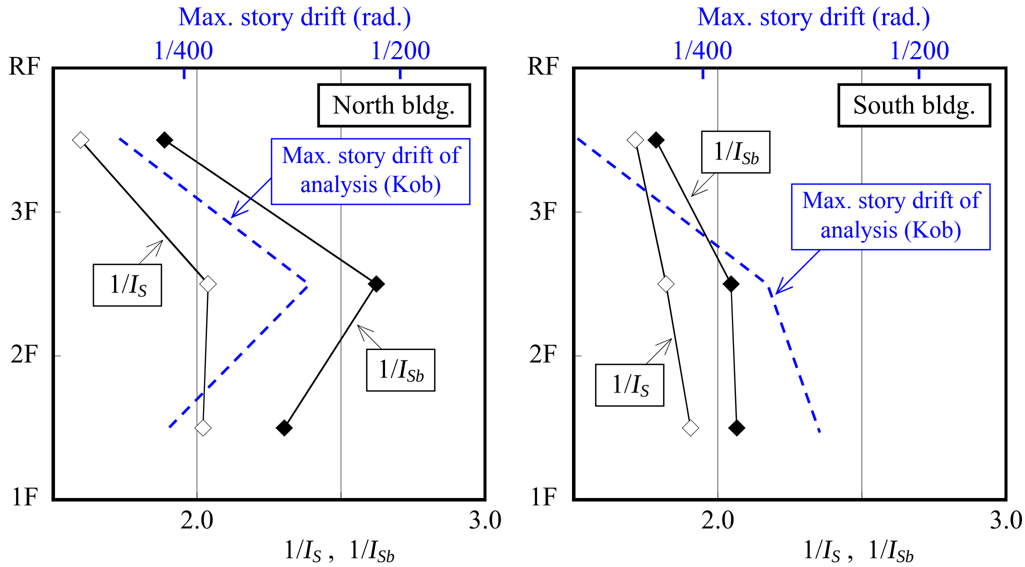


Figure 8. Distribution of reciprocal of I_S and I_{Sb} with max. story drift of analysis

5 CONCLUSIONS

For two school R/C buildings (the North bldg. and the South bldg.) which damaged by 2011 Tohoku Pacific Earthquake, the dynamic response analysis and the Seismic Safety Evaluation were executed. The followings were obtained from discussion about them.

- As an analytical result, 2nd story of the North bldg. and the 1st story of the South bldg. were the most injured story of each building, corresponding to the inspected earthquake damage.
- For upgrading the Seismic Safety Evaluation, the modified seismic index; I_{Sb} was proposed in order to consider dispersion of R/C column's shear strength.
- Proposed I_{Sb} was more suitable than the ordinary seismic index; I_S for expressing the seismic performance of the objective buildings.

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