Residual seismic capacity evaluation of RC frame with weak-beams based on energy absorption capacity

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ABSTRACT

The objective of this study is to develop a method to evaluate residual seismic capacity of damaged RC frames with weak-beams after earthquakes. For this purpose, the residual seismic capacity ratio, which is defined as the ratio of residual energy absorption capacity to the initial (pre-earthquake) energy absorption capacity of an overall frame, is proposed for the weak-beam RC frames (detailed calculation method). Furthermore, a simplified calculation method for residual seismic capacity ratio is developed employing visual damage information such as maximum residual crack width of members.
In this paper, two evaluation methods, i.e. detailed and simplified methods, for residual seismic capacity of weak-beam RC frames mentioned above are applied to two test results. The relationships between the residual seismic capacity ratio and damage ratings such as slight, light, moderate, heavy and collapse are discussed and then the validity is confirmed based on the detailed calculation method. It is also revealed that the simplified calculation method can successfully evaluate the residual seismic capacity of weak-beam RC frames from the visual damage information based on the comparison results of detailed and simplified calculation methods.

Keywords: residual seismic capacity evaluation, weak-beam RC frames, energy absorption capacity, residual seismic capacity ratio, damage rating

1. INTRODUCTION

The major concern for damaged buildings after an earthquake is their safety to the aftershocks, and also quick damage inspections are needed. In the next stage following the quick damage inspections, a damage evaluation should be more precisely and quantitatively performed, to identify necessary actions required for the damaged buildings. For this purpose, the Guidelines for Post-Earthquake Damage Evaluation and Rehabilitation (JBDPA, 2001) originally developed in 1991 was revised in 2001 in Japan. In the guidelines, the damage classes of structural members should be classified first from the damage state. Then, a seismic capacity reduction factor η which is defined as the ratio of the absorbable hysteretic energy after an earthquake to the original absorbable energy of each structural member should be calculated corresponding to the damage classes of members. Considering the seismic capacity reduction factor η, a residual seismic capacity ratio index R which is defined as the ratio of post-earthquake seismic capacity to original capacity can be calculated. Finally, the damage of a building can be rated based on the damage rating criteria.

However, the current Japanese guidelines mentioned above mainly consider vertical members such as columns and walls. Since RC buildings with weak-beams are generally designed and constructed in recent years, the guidelines are often difficult to apply to those buildings. Accordingly, in this paper, a detailed calculation method of residual seismic capacity ratio index SI_{margin} is proposed for the weak-beam RC frames. Then, a simplified calculation method for the index SI_{margin} is developed employing visual damage information such as the maximum residual crack width of each structural member. Furthermore, the detailed and simplified methods proposed to calculate the index SI_{margin} are applied to two weak-beam RC specimens, and the relationships between the index SI_{margin} and damage rating are discussed and their validity is verified based on the detailed calculation method. The validity of the simplified calculation method is also confirmed based on the comparison results of the detailed and simplified calculation methods.

2. RESIDUAL SEISMIC CAPACITY EVALUATION METHOD

2.1 Detailed calculation method of index SI_{margin}

The basic concept of residual seismic capacity evaluation method for the weak-beam RC frames is illustrated in Figure 1.

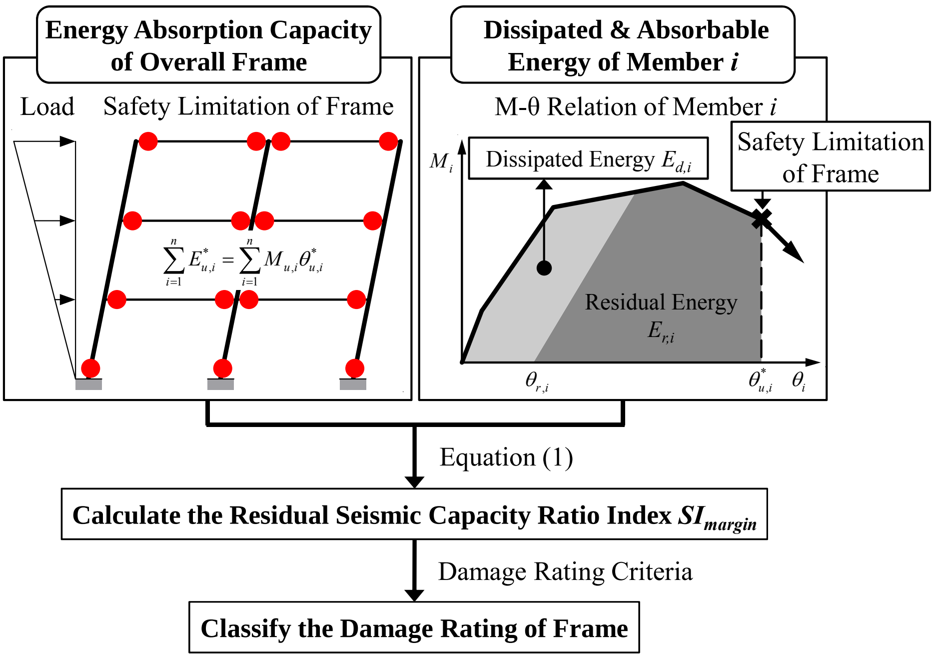


Figure 1: Basic concept of residual seismic capacity evaluation method

In this paper, the seismic capacity of building structure is evaluated based on the energy absorption capacity of overall frame considering the principle of virtual work. The energy absorption capacity of overall frame can be calculated as the total absorbable energy of structural members until the safety limitation of a frame, where this safety limitation is defined as the moment in which the maximum lateral strength of a frame deteriorates to its 80%. Then, the residual seismic capacity ratio index SI_{margin} of overall frame is defined as the ratio of total residual energy absorption capacity to the total initial energy absorption capacity of structural members as shown in Equation (1).

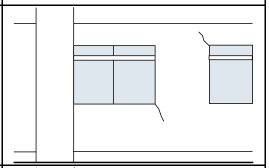
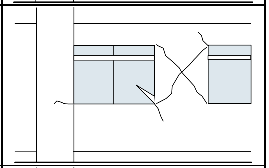
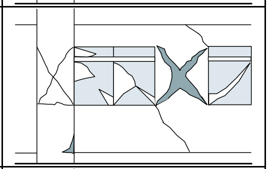
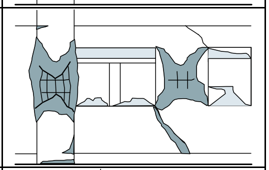
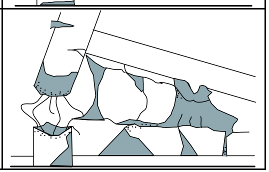
$$SI_{margin} = \left(\sum_{i=1}^{n} E_{r,i} \Big/ \sum_{i=1}^{n} E^{*}_{u,i} \right) \times 100 \ (\%) \tag{1}$$

where, $\sum E^{*}_{u,i}$: total absorbable energy of structural members before earthquake, $\sum E_{r,i}$: total residual absorbable energy of structural members after earthquake

2.2 Definition of damage rating for weak-beam RC frames

In Japan, the damage ratings for weak-column RC buildings such as slight, light, moderate, heavy and collapse are generally classified from the state of observed damage of buildings as shown in Table 1 (AIJ, 1980).

Table 1: Definition of damage rating for weak-column RC buildings (AIJ, 1980)

Damage rating	Description of damage	Sketch
Slight	Slight or almost no damage on the columns and walls.	
Light	Slight damage on the columns and shear walls, visible shear cracks on secondary walls.	
Moderate	Visible clear flexural and shear cracks on columns, visible shear cracks on shear walls, remarkable heavy damage on nonstructural members.	
Heavy	Exposing and bucking of reinforcing bars on columns, considerable lateral strength deterioration of buildings with remarkable wide shear cracks on shear walls.	
Collapse	Remarkable heavy damage on columns and shear walls, overall or partial collapse on buildings.	

However, such a damage rating is not clearly defined for weak-beam RC buildings. Therefore, in this paper, the authors propose the criteria to define the damage rating of weak-beam RC frames through the engineering demand parameter (EDP) as shown in Table 2 and Figure 2.

Table 2: Damage rating criteria for weak-beam RC Frames

Damage rating	Description of engineering demand parameter (EDP)
No damage	
	Initial cracking of member
A	
	Initial yielding of member
B	
	Formation of yield mechanism
C	
	Maximum lateral strength of frame (P_{max})
D	
	80% of P_{max}
E	

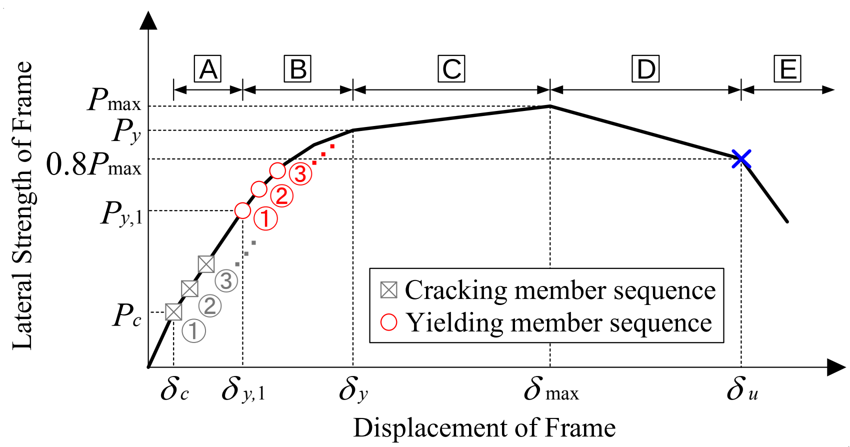
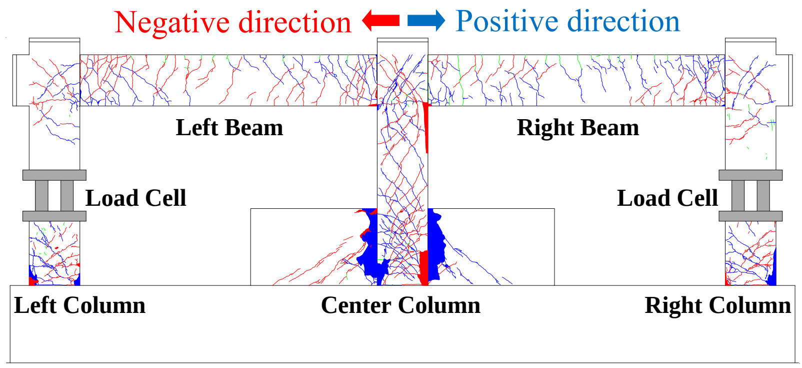


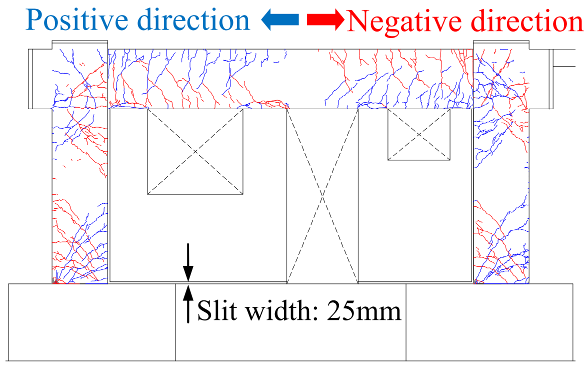
Figure 2: Conceptual diagram of damage rating

2.3 Application to weak-beam RC specimens

To discuss the relationships between the index SI_{margin} and damage ratings, in this section, the detailed calculation method for the index SI_{margin} is applied to the following two weak-beam RC specimens as shown in Figure 3, which illustrates the state of damage as well. 2SH-64 specimen is half-scale, two-bay, single-story bare frame specimen (IIS & HAEI, 2011) with load cell for each corner column. The lateral and vertical load carrying capacity of each column can be measured from the two load cells, and the load-deflection curve of each beam also can be illustrated from the difference of vertical load between the two columns which are connected with the end of the beam. 1SF specimen is full-scale, one by one-bay, single-story specimen, (BRI, 2011) with non-structural wall initially separated from the inner surface of the structural members by slit with width of 25mm. Since there is no load cell for this specimen, the lateral and vertical load carrying capacity of each member can not be measured.



(a) Damage state of the 2SH-64 specimen at 3.03% drift angle



(b) Damage state of the 1SF specimen at 2% drift angle

Figure 3: Damage state of the two specimens

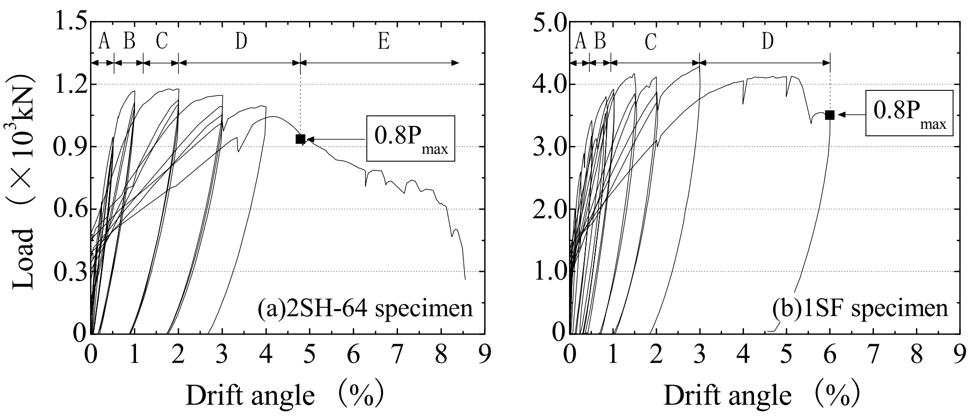


Figure 4: Load-drift angle relations of the two specimens

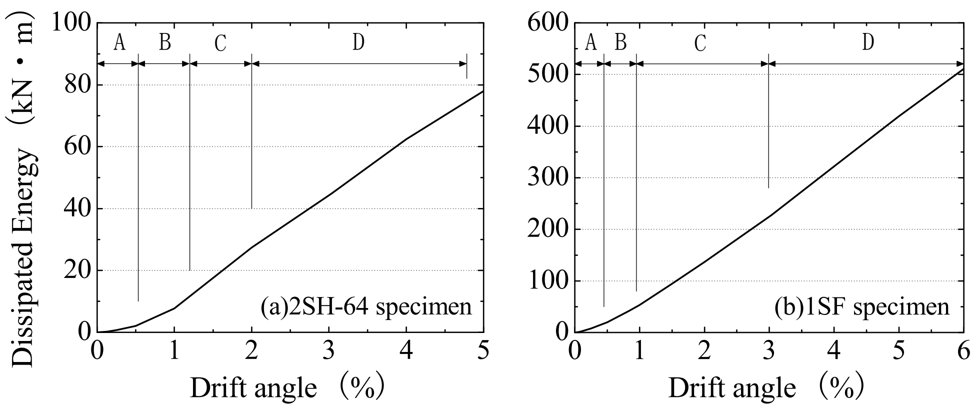


Figure 5: Dissipated energy-drift angle relations of the two specimens

2.3.1 Test results of two specimens

The load-drift angle relations of the two specimens are shown in Figure 4. Since the connection between the spandrel wall and the center column of the 2SH-64 specimen was compromised, the center column is damaged as flexible member. The load of the 1SF specimen was increased after the non-structural wall touched to the columns at 2% drift angle.

The relationships between the dissipated energy, which is calculated from the load-drift angle skeleton curves of specimens, and the drift angle of the two specimens are shown in Figure 5. The dissipated energy of the two specimens is increased gradually at the damage ratings A and B, then the dissipated energy is inversely proportional to the drift angle at the damage ratings C and D.

2.3.2 Relationships between index SI_{margin} and damage ratings

The index SI_{margin} of the two specimens, which is calculated by the detailed calculation method defined as Equation (1), is shown in Figure 6. The residual and initial energy absorption capacity of 2SH-64 specimen is calculated as the total residual and initial energy absorption capacity of structural members such as three columns and two beams. Since there is no load cell for 1SF specimen to measure the load carrying capacity of each member, the residual and initial energy absorption capacity of 1SF specimen are calculated from its load-drift angle skeleton curve. Then, the damage ratings of the two specimens are classified based on Table 2, and illustrated in Figure 6 with the index SI_{margin}.

The boundary values of the index SI_{margin} to define damage rating criteria are calculated for two specimens respectively from Figure 6, and shown in Table 3. As a result, the boundary values of the index SI_{margin} for the two specimens are similar to each other for damage rating classification points, and it can be considered that the damage rating criteria is valid for those two specimens.

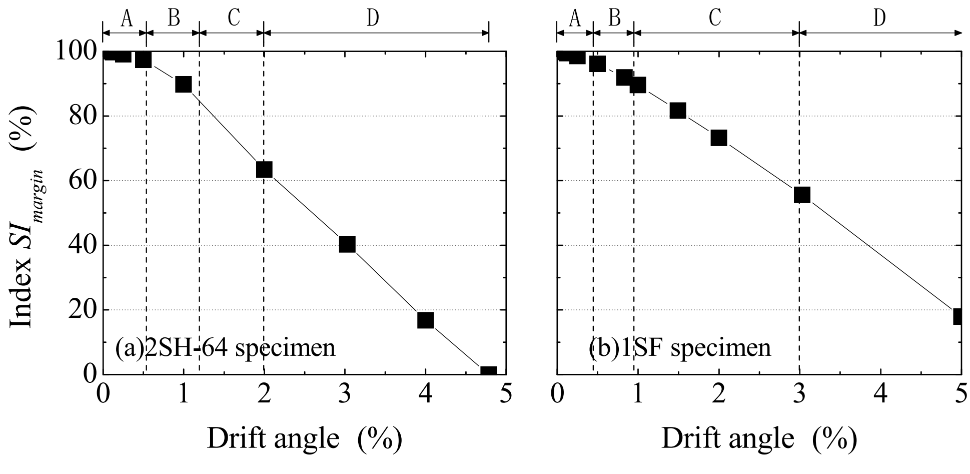


Figure 6: Index SI_{margin} of two specimens based on detailed calculation method

Table 3: Damage rating criteria of two specimens

Specimen	Boundary Value of index SI_{margin}		
	A-B	B-C	C-D
2SH-64 specimen	96%	84%	63%
1SF specimen	96%	90%	55%

3. SIMPLIFIED CALCULATION METHOD OF INDEX SI_{margin}

3.1 Flow of simplified calculation method

It is difficult to calculate the dissipated or absorbable energy of each structural member on-site. Therefore, in this chapter, a simplified calculation method for the index SI_{margin} is proposed considering factor η corresponding to visual damage information such as maximum residual crack width of each structural member. The basic concept of the simplified calculation method is shown in Figure 7.

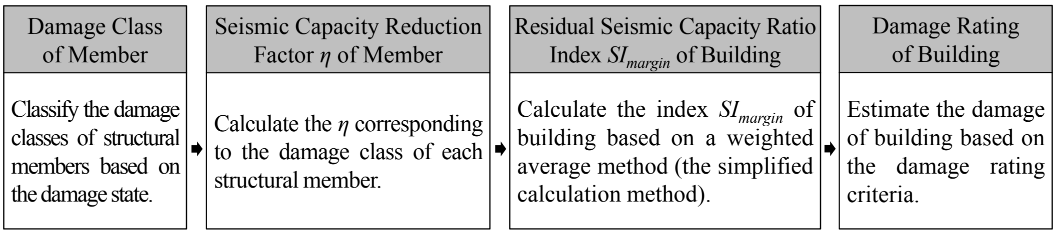


Figure 7: Basic concept of simplified calculation method

3.2 Damage class definition of RC beams

The damage classes of the columns and walls are originally defined based on the mechanical properties, such as yielding of tensile rebars (JBDPA, 2001). In order to classify the damage class easily on-site, the relationships between the damage class and visual damage information, such as maximum residual crack width, are defined as well (JBDPA, 2001).

Since such a damage class is not clearly defined for RC beams, in this paper, their damage classes are first defined by the mechanical properties, such as cracking, yielding of reinforcement and maximum shear strength, as shown in Figure 8. Then, the maximum residual crack widths according to the damage classes are calculated based on Figure 9, which is obtained from the 2SH-64 specimen test results. Considering the crack width of 1mm, which is widely used as boundary of the damage class in previous research, damage class Ⅱ of the RC beams is divided into Ⅱ$^{-}$ and Ⅱ$^{+}$, even though it is not governed by mechanical properties. The damage class definition for the RC beams is described in details as shown in Table 4.

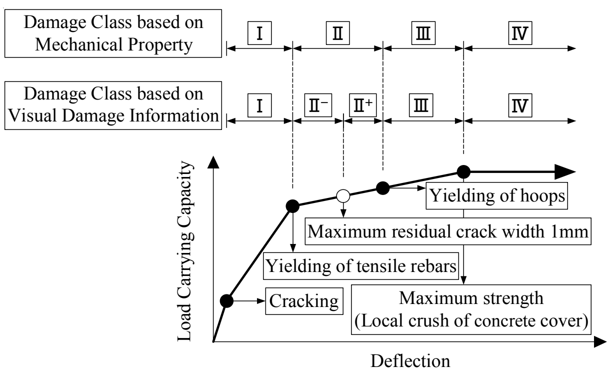


Figure 8: Damage class definition of RC beams based on mechanical property

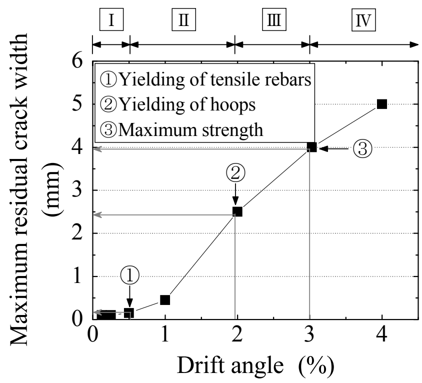


Figure 9: Relations of damage class and maximum residual crack width

Table 4: Damage class definition of RC beams

Damage class based on mechanical property	Detail of properties	Boundary value of w_{max}	Damage class based on visual damage information
I	Yielding of tensile rebars	w_{max}=0.2mm	I
II	–	w_{max}=1.0mm	II$^-$
II	Yielding of hoops	w_{max}>2.0mm	II$^+$
III	Yielding of hoops	w_{max}>2.0mm	III
IV	Maximum strength	w_{max}>4.0mm Local crush of concrete cover	IV

w_{max}: maximum residual crack width

3.3 Seismic capacity reduction factor *η* of RC beams

The seismic capacity reduction factor η of a RC beam is calculated based on the previous method developed by BUNNO et al. in 2000. The factor η calculated from the load-deflection curve of left beam in 2SH-64 specimen, which is measured from the difference of vertical load between the left and center column, is shown in Figure 10. Also, the lower limit value of the factor η according to each damage class of the RC beams mentioned above is shown in Table 5.

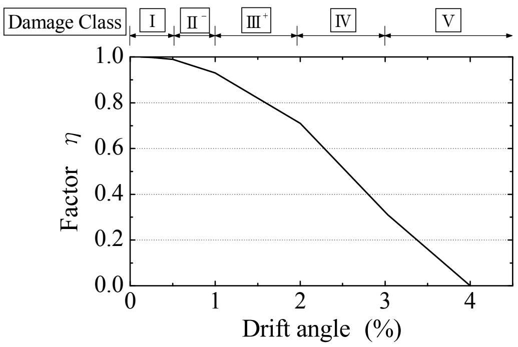


Figure 10: Calculation results of factor η (left beam of 2SH-64 specimen)

Table 5: Relationships between factor η and damage classes

Damage Class	Factor *η*
I	0.99
II$^-$	0.90
II$^+$	0.70
III	0.30
IV	0

3.4 Energy contribution coefficient *α* of structural members

The energy contribution coefficient α of a structural member, which means the energy absorption rate of the member for a building, is originally defined as the ratio of its dissipated energy to the dissipated energy of particular member. In this research, the particular member, which is also named critical member, is defined as the member that yields last. Since the dissipated energy of each structural member is difficult to grasp on-site, in this paper, the coefficient α of the member is defined as the ratio of its yield moment to the yield moment of the critical member. If the definition is valid, the coefficient α can be taken as a fixed value.
In order to compare these two methods mentioned above, the coefficient α of the different members is calculated based on the 2SH-64 specimen test results (left

column is taken as a critical member) as shown in Table 6. It can be found that the coefficient α calculated by these two methods is approximately equal to each other. As a result, the calculation method for coefficient α based on the yield moment of members is validated.

Since the center column of 2SH-64 specimen is damaged as flexible member due to the damage of the spandrel wall, the value of its coefficient α is taken as 1.0 in this paper. For the 1SF test specimen in that the beam is the critical member, the coefficient α of each column is taken as 1.39.

Table 6: Coefficient α of members for the 2SH-64 specimen

Member	**Coefficient α**	
	Based on dissipated energy	**Based on yield moment**
Right column	0.97	1.0
Right beam	0.63	0.65
Left beam	0.62	0.65

3.5 Definition of simplified calculation method for index SI_{margin}

According to the above results, the simplified calculation method of index SI_{margin} can be defined as Equation (2).

$$SI_{margin} = \frac{\sum_{k}(\alpha_k) \times \sum_{D=\mathrm{I}}^{\mathrm{V}}(\eta_{k,D} \cdot A_{k,D})}{\sum_{k} \alpha_k \cdot A_k} \times 100\ (\%) \tag{2}$$

where, k: type of the member (such as ductile/brittle column or beam), D: the damage class of member (0 through Ⅴ), α_k: the energy contribution coefficient of k type member, $\eta_{k,D}$: seismic capacity reduction factor of k type member having the damage class D, $A_{k,D}$: the number of k type members having the damage class D, A_k: the number of k type members.

4. COMPARISON BETWEEN DETAILED AND SIMPLIFIED CALCULATION METHOD OF INDEX SI_{margin}

In order to verify the validity of the simplified calculation method for the index SI_{margin}, the detailed and simplified methods are applied to the 2SH-64 specimen and 1SF specimen test results, and calculation results of the index SI_{margin} are compared as shown in Figure 11.

Figure 11(a) shows that the index SI_{margin} of the 2SH-64 specimen based on the detailed and simplified methods is approximately equal to each other. However, the index SI_{margin} of the 1SF specimen calculated by the simplified method as shown in Figure 11(b) is lower than the calculation result based on the detailed method. It can be considered that the simplified calculation method is not suitable for evaluating the effect of non-structural walls to the residual seismic capacity of overall frame. Therefore, it is necessary to propose an upgraded simplified calculation method for the index SI_{margin}, which will also consider the damage of non-structural walls in the further research.

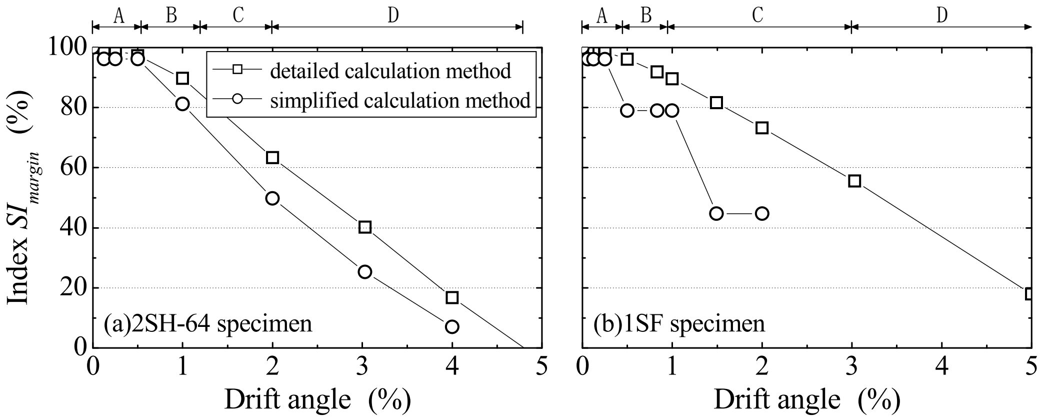


Figure 11: Detailed vs. simplified calculation method for index SI_{margin}

5. CONCLUSIONS

In this paper, a method which can evaluate the residual seismic capacity of weak-beam RC frames damaged by earthquakes is developed. The results can be summarized as follows:

(1) The boundary values of the index SI_{margin} classifying the damage ratings (From A to D) are calculated to define the damage rating criteria.
(2) The damage classes of RC beams are defined based on their mechanical properties. Then, the maximum residual crack width and the seismic capacity reduction factor η corresponding to the damage classes are calculated using the 2SH-64 specimen test results.
(3) The energy contribution coefficient α calculated by the dissipated energy ratio and calculated by yield moment ratio has almost the same value.
(4) The index SI_{margin} of the 2SH-64 specimen is similar when it is calculated based on the detailed and simplified calculation methods. However, the index SI_{margin} of the 1SF specimen is estimated to have smaller value for the simplified calculation method.

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