



RESIDUAL SEISMIC CAPACITY EVALUATION FOR RC BUILDINGS CONSIDERING REDUCTION OF SEISMIC PERFORMANCES

Linfei Hao⁽¹⁾, Yusuke Suzuki⁽²⁾, Masaki Maeda⁽³⁾

⁽¹⁾ Ph. D student, Graduate School of Eng, Tohoku University, hao@rcl.archi.tohoku.ac.jp

⁽²⁾ Assistant Professor, Graduate School of Eng, Osaka City University, ysuzuki@archi.eng.osaka-cu.ac.jp

⁽³⁾ Professor, Graduate School of Eng, Tohoku University, maeda@rch.archi.tohoku.ac.jp

Abstract

In order to evaluate residual seismic capacity of reinforcement concrete (RC) structures damaged due to earthquakes quantitatively, kinds of evaluation methods have been proposed by the previous researchers. In this paper, a method based on internal work (IW) of the structure and seismic capacity reduction factor of the members, for which numerical analysis is not needed, is reviewed. At the same time, a more accurate method based on the capacity spectrum method (CSM), which considers the reduction in strength, deformation capacity and hysteretic energy dissipation capacity of the damaged structural members separately, is also reviewed. To compare the CSM based method and the IW based method, reduction in the different seismic performances (e.g. strength, deformation capacity and hysteretic energy dissipation capacity) are considered integrally as the reduction in energy dissipated by the member. Then the seismic capacity reduction factor utilized in the IW based method is replaced by the energy dissipation residual ratio, and reduction in the difference seismic performances can be also considered in the IW based method. Through application of both the CSM based and IW based method on prototype frame models, result of the IW based method is found to be not conservative compared with the CSM based one due to ignoring difference among deformation of the members. To include influence of the member deformation, the IW based method is modified then and the following verification shows that the modified IW based method gives accurate and conservative estimation on result of the CSM based method without need of numerical analysis.

Keywords: Residual seismic capacity evaluation, Internal work, Capacity spectrum method, Seismic performance reduction, Difference among member deformation

1. Introduction

Large number of building structures will be damaged in different level due to an earthquake. In order to ensure their safety against the aftershock as well as future earthquakes and make decisions about repair, retrofitting or demolition, it is very important to evaluate the residual seismic capacity of damaged buildings appropriately.

Evidently, due to damaging of structural members, reduction in seismic capacity can be expected for both the members and the whole structure. In order to establish a quantitative method for structural residual seismic capacity evaluation, seismic capacity reduction of the damaged members should be quantitatively evaluated first. For this purpose, seismic capacity reduction factor, η , is proposed by Bunno et al. [1] based on residual energy dissipation capacity of the member. On the other hand, considering the reduction happens in different seismic performances, Ito et al. [2] investigated the reduction in strength, deformation capacity and hysteretic energy dissipation capacity of beams and columns based on the experimental database, and recommended the residual ratio of each of the performances (η_b , η_d , η_h), for the member in different damage classes. Residual seismic capacity of the damaged member thus can be evaluated from different seismic performances separately.

After residual seismic capacity is evaluated for the damaged members, the next step is to evaluate residual seismic capacity of the whole structure, based on the members. By utilizing the seismic capacity reduction factor, Bao et al. [3] proposed an evaluation method based on Internal Work (IW) of the structure. Ultimate strength and seismic capacity reduction factor of the members is considered in this method and numerical analysis is not needed for the evaluation. On the other hand, as a more accurate method, Miura et al. [4] proposed another evaluation method based on the Capacity Spectrum Method (CSM), in which the reduction in strength,

deformation capacity and hysteretic energy dissipation capacity can be considered separately. By modifying the restoring force models of the damaged members, according to their damage classes, model of the damaged structure is built in this method. By conducting the pushover analysis, the Seismic Capacity Indicator (SCI) [5] of both the intact and damaged structural model can be obtained, based on which the residual seismic capacity is evaluated. Relationship among the residual seismic capacity evaluation for the member and structure mentioned above can be shown as Table 1.

Table 1 – Relationship among the previous related research and the research of this paper

		Residual seismic capacity of the member	
		Seismic capacity reduction factor (η)	Seismic performance residual ratios (η_b, η_d, η_h)
Residual seismic capacity of the structure	IW based method	Existing method	Proposed in this paper
	CSM based method		Existing method

Comparison

In this paper, in order to compare the IW based and CSM based method, reduction in the different seismic performances (e.g. strength, deformation capacity and hysteretic energy dissipation capacity) are integrated into reduction of energy dissipated by the member. So that the different seismic performance reductions can be considered in the IW based method as well. Both the IW based and CSM based method are applied on prototype frame models to compare their evaluation results of residual seismic capacity. To improve the accuracy, the IW based method is modified so that the difference among deformation of the members can be taken into consideration. The modified IW based method is compared again with the CSM method to verify the efficiency of the modification.

2. Review of the IW based and CSM based evaluation method

The IW based method, in which the seismic capacity reduction factor is utilized, and the CSM based method, in which the different seismic performance reductions are considered, are reviewed respectively in the following.

2.1 Evaluation method based on IW

The IW based evaluation method proposed by Bao et al. [3] considers the structural seismic capacity through the IW of the virtual work principle, the IW dissipated by the member is approximately considered as product of the ultimate bending moment (M_{ui}) and rotation angle (θ_i). IW of the intact structure ($\sum M_{ui}\theta_i$) is reduced by the seismic capacity reduction factor of each member, η_i , to evaluate IW of the damaged structure ($\sum \eta_i M_{ui}\theta_i$). As shown in Fig.1, the seismic capacity reduction factor is defined by considering the residual energy dissipation of a damaged member [1]. Value of η is given for the member in each of the damage classes (I, II, III, IV and V) as shown in Table 2. In the post-earthquake investigation, the damage class is determined by the investigator, based on the damage states (crack width, concrete spalling, etc.) for each member, and according to the *Guideline for Post-Earthquake Damage Evaluation* [6] of Japan.

The structural seismic capacity residual ratio, R , is considered as residual ratio of the IW dissipated by the damaged structure relative to the intact one. In this method, only the frame with total collapse mechanism is evaluated, which means flexural yielding is expected to appear at ends of the beams and base of the columns, and the structure finally collapses in a total collapse mechanism as shown in Fig.2. In the case of low-rise typical frame, after the collapse mechanism is formed, rotation angles at ends of the beams (θ_i) and base of the columns (θ_j) are assumed to be all the same. Based on this assumption, the R can be expressed as a weighted average of the η_i , and the ultimate bending moment of the members, M_{ui} , can be seen as the weight, as shown in Eq. (1).

$$R = \frac{\sum (\eta_i M_{ui})}{\sum M_{ui}} \quad (1)$$

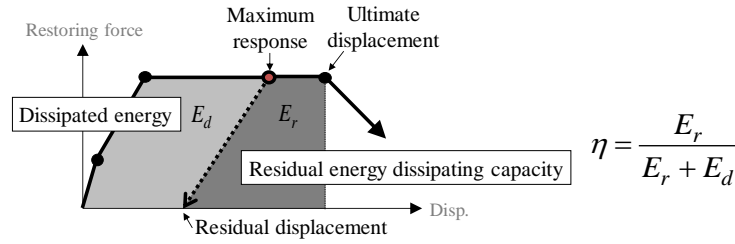


Fig. 1 – Concept of the seismic capacity reduction factor

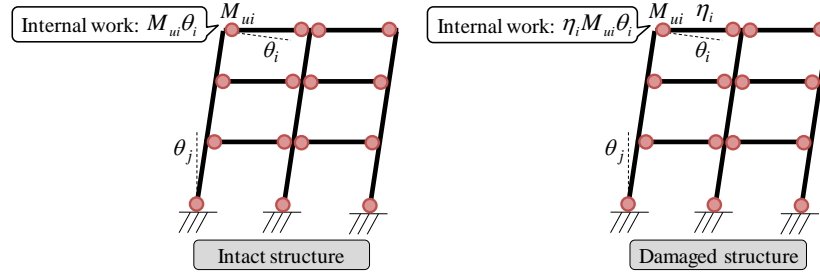


Fig. 2 – Internal work in the flexural yielding and total collapse frame

2.2 Evaluation method based on CSM

As a more accurate evaluation method, Miura et al. [4] proposed a method based on CSM, in which the structural seismic capacity residual ratio is defined by using Seismic Capacity Indicator (SCI) [5]. Flowchart of this method is shown in Fig.3. For the intact structure, after the restoring force model of each of the intact members is determined, model of the intact structure is built and its capacity spectrum (CS) can be obtained by conducting the pushover analysis.

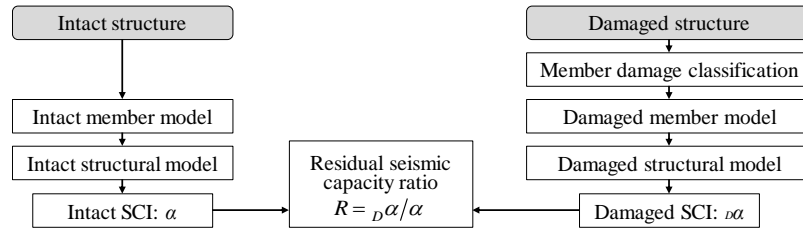


Fig. 3 – Flowchart of the CSM based method

On the other hand, for the damaged structure, after damage class of each member is determined, according to the residual ratios for strength (η_{bi}) and deformation capacity (η_{di}) corresponding to each damage class (Table 2), restoring force model of each damaged member is reduced. For the damaged members, their restoring force models can be obtained by Eq. (2) and Eq. (3). Yielding deformation of the damaged member is assumed to be equal to that of the intact one (Fig.4). When $\theta_i < \theta_{yi}$, the damaged restoring force model is considered to be a straight line joining the origin and the yielding point.

$${}_D M_i = M_i - M_{yi}(1 - \eta_{bi}), \quad \theta_i \geq \theta_{yi} \quad (2)$$

$${}_D \theta_i = \theta_i - \theta_{ui}(1 - \eta_{di}), \quad \theta_i \geq \theta_{yi} \quad (3)$$

where ${}_D M_i$ and ${}_D \theta_i$ are bending moment and rotation angle of the damaged member. M_i and θ_i are bending moment and rotation angle of the intact member. M_{yi} and θ_{ui} are yielding bending moment and ultimate rotation angle of the intact member. θ_{yi} is yielding rotation angle of the intact member.

Table 2 – Seismic capacity reduction factor and performance residual ratios (beam/column fails in flexure) [1][2]

Damage Class	Seismic capacity reduction factor η	Strength residual ratio η_b	Deformation capacity residual ratio η_d	Equivalent damping residual ratio η_h
I	0.95	1.0	1.0	0.95
II	0.75	1.0	0.95	0.8
III	0.5	1.0	0.85	0.75
IV	0.1	0.6	0.75	0.7

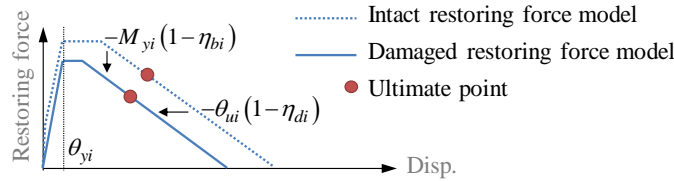


Fig. 4 – Restoring force model for the damaged members

Then the damaged restoring force model of each of the damaged members, of which the yielding bending moment and ultimate deformation are reduced according to the damage class, are utilized to build the model of the damaged structure. By conducting the pushover analysis, capacity spectrum of the damaged structure (damaged CS) can be obtained. The damaged CS is expected to reduce from the intact one due to the strength and deformation capacity reduction of the members (Fig.4). The equivalent damping ratio of the structure can be estimated according to Eq. (4) by the equivalent damping ratio and potential energy of the members [7]. With regard to the intact and damaged members, the equivalent damping ratio can be estimated by utilizing Eq. (5) [5] and Eq. (6) [2].

$$h = \frac{\sum (W_{ei} h_i)}{\sum W_{ei}} \quad (4)$$

$$h_i = 0.05 + 0.25 \left(1 - \frac{1}{\sqrt{\mu_i}} \right) \quad (5)$$

$${}_D h_i = 0.05 + 0.25 \eta_{hi} \left(1 - \frac{1}{\sqrt{\mu_i}} \right) \quad (6)$$

where h is equivalent damping ratio of the structure. h_i and ${}_D h_i$ are equivalent damping ratio of the intact and damaged member. W_{ei} , μ_i and η_{hi} are potential energy, ductility coefficient and equivalent damping residual ratio of the member, respectively.

After the intact and damaged CS are both determined and the equivalent damping ratios corresponding to their safety limits are obtained, the SCI, which is represented by α , at the safety limit of the intact and damaged structure can be calculated by Eq. (7) respectively. As shown in Fig.5, SCI is defined as the ratio of seismic intensity required by the safety limit on the CS to the seismic intensity required by the design code and reduced by the response reduction factor, F_h , which is a function of the equivalent damping ratio (Eq. (8)). For the damaged structure, F_h increase because the equivalent damping ratio reduce from h to ${}_D h$. As shown in Eq. (9), relative to the intact structure, the residual seismic capacity factor of the damaged structure, R , is defined as the residual ratio of its SCI, relative to the intact structure. In this paper, the safety limit of structure is conservatively defined as the moment when the first member in the structure reaches its safety limit.

$$\alpha = \frac{\text{Design seismic intensity reduced by } F_h}{\text{Seismic intensity required by safety limit}} = \frac{S_{au}}{S_{a0} F_h} \quad (7)$$

$$F_h = \frac{1}{1+10h} \quad (8)$$

$$R = \frac{D\alpha}{\alpha} \quad (9)$$

where α and ${}_D\alpha$ are SCI at the safety limit of the intact and damaged structure. S_{au} is acceleration response at the safety limit of CS. S_{a0} is acceleration response of design response spectrum at the period of the safety limit. F_h is response reduction factor, and h is equivalent damping ratio of the structure.

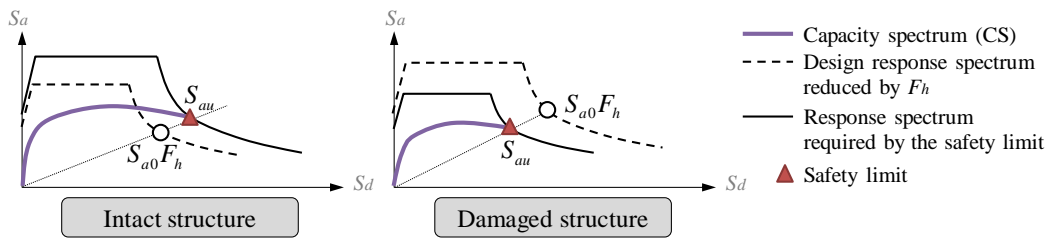


Fig. 5 – Seismic Capacity Indicator (SCI) for the intact and damaged structure

3. Comparison of the IW based and CSM based method

The IW based method needs no numerical analysis thus can be applied in real post-earthquake damage evaluation more easily. To investigate the accuracy of its result, the IW based method is compared with the CSM based method, which is considered to be more accurate, by applying them on prototype frame models.

3.1 Integration of the different seismic performance reductions

As introduced above, residual seismic capacity of the member is considered in different way in these two methods. In order to compare the IW based method to the CSM based one, the reduction in different seismic performances (e.g. strength, deformation capacity and hysteretic energy dissipation capacity) which is considered in the CSM based method should also be considered in the IW based method.

As shown in Fig.6(a), the equivalent damping ratio of the member, h_i , is defined as Eq. (10), and can be also expressed as a function of ductility coefficient as Eq. (5).

$$h_i = \frac{W_i}{4\pi W_{ei}} \quad (10)$$

where W_i is energy dissipated by the member.

If the ultimate bending moment can be approximately replaced by the yielding bending moment, M_{yi} , then the W_{ei} at ultimate state can be obtained by M_{yi} and θ_{ui} , and at the same time the energy dissipated in a plastic hinge, W_i , can be calculated by M_{yi} , θ_{ui} and h_i , as shown in Eq. (11).

$$W_i = 4\pi W_{ei} \cdot h_i = 4\pi \cdot \frac{M_{yi} \theta_{ui}}{2} \cdot h_i \quad (11)$$



Fig. 6 – Energy dissipated in one circle by the intact and damaged member

As shown in Fig.6(b), when the member is damaged, due to the reductions in strength, deformation capacity and hysteretic energy dissipation capacity, the energy dissipated in a plastic hinge becomes smaller. Same as the intact member, by utilizing the reduced yielding bending moment, ultimate deformation and equivalent damping factor, the energy dissipated by the damaged member, ${}_D W_i$, can be expressed as Eq. (12).

$${}_D W_i = 2\pi \cdot \eta_{bi} M_{yi} \cdot \eta_{di} \theta_{ui} \cdot \left[0.05 + 0.25 \eta_{hi} \left(1 - \frac{1}{\sqrt{\mu_i}} \right) \right] \quad (12)$$

By considering the seismic capacity reduction factor as residual ratio of the W_i , it can be redefined based on the residual ratios of strength, deformation capacity and equivalent damping as shown in Eq. (13). Thus the different seismic performance reductions can be considered separately.

$$\eta_{wi} = \frac{{}_D W_i}{W_i} = \eta_{bi} \cdot \eta_{di} \cdot \frac{0.05 + 0.25 \eta_{hi} (1 - 1/\sqrt{\mu_i})}{0.05 + 0.25 (1 - 1/\sqrt{\mu_i})} \quad (13)$$

where η_{wi} is residual ratio of energy dissipated by in one circle by the member.

Finally, as shown in Eq. (14), by replacing the η_i in Eq. (8) by the η_{wi} mentioned above, the different seismic performance reductions can be also considered in the IW based method. Then the IW based and CSM based method can be compared based on the same residual seismic capacity evaluation of member.

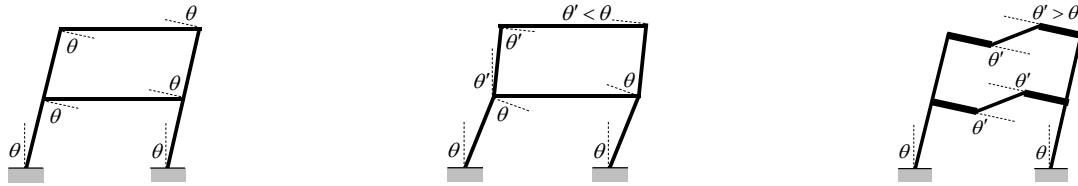
$$R = \frac{\sum (\eta_{wi} M_{yi})}{\sum M_{yi}} \quad (14)$$

3.2 Prototype frame models information

The IW based method shown in Eq. (14) is based on the assumption that rotation angle of the hinges (θ_i) at ends of the members are all the same. However, due to the structure form and distribution of story drift along the structural height, rotation angles are not the same among the members and the assumption cannot be satisfied. As shown in Fig.7, rotation angles of the member belonging to the story which has smaller drift are relatively small. On the other hand, when the clear length of beams become shorter due to existence of wing wall for example, beams will have bigger rotation angles compared with the columns.

To investigate how the difference among members rotation angles influence result of the IW based method, both the CSM based method and IW based method are applied on kinds of prototype frame models, to compare evaluation results of them.

To include the influence of story drift on the rotation angles of members, a four stories and a twelve stories typical frame model are utilized for evaluation. To include the influence of clear length of members, a four stories and a twelve stories frame model with wing walls are utilized, and the clear length of beams are set to be 0.3 and 0.4 of the span, respectively. Geometries of the frame models are shown in Fig.8. Dimension and reinforcement ratio of the member sections are shown in Table 3.



(a) Rotation angles are assumed to be all the same (b) Rotation angles change due to difference among story drifts (c) Rotation angles change due to shorter clear length of beams

Fig. 7 – Difference among rotation angles of the members

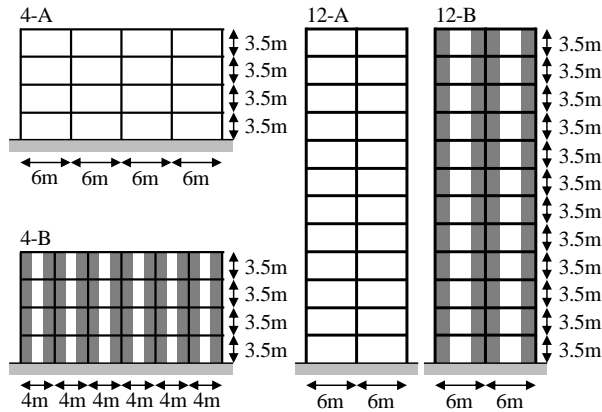


Fig. 8 – Frame model geometries

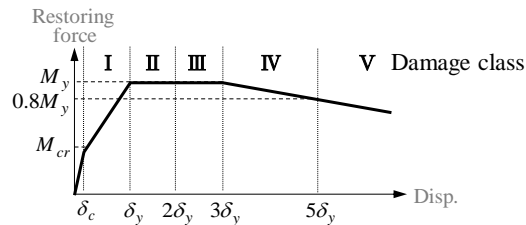


Fig. 9 – Damage classes defined by ductility coefficient

Table 3 – Dimension and reinforcement ratio of the member sections

Frame	Column sectional dimension (cm)	Reinforcement ratio (%)	Beam sectional dimension (cm)	Reinforcement ratio (%)	Wing wall sectional dimension (cm)
4-A	70x70	1.5	40x70	1.5	----
4-B	70x70	1.5	35x50	2.2	20x105
12-A	100x100	1.2	60x100 (story 1-4) 55x95 (story 5-8) 50x80 (story 9-12)	1.6 1.9 2.6	----
12-B	100x100	1.2	60x90 (story 1-4) 55x85 (story 5-8) 50x80 (story 9-12)	1.9 2.4 2.9	20x130

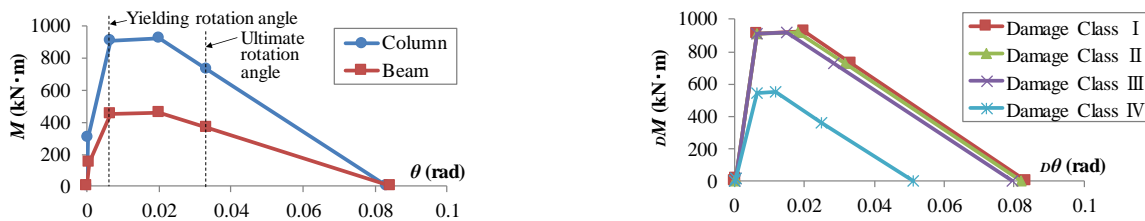
All of the members are assumed to yield in flexure, and idealized by nonlinear rotational springs at both ends. As shown in Fig.9, Yielding rotation angle is set to be 1/150rad, and an ultimate ductility coefficient of 5 is assumed, for all of the members. Cracking bending moment is set to be 1/3 of the yielding moment, and bending

moment at the ultimate rotation angle reduces to 80% of the yielding one. The damage classes of the members is defined according to the ductility coefficient.

3.3 Application and comparison of the IW based and CSM based evaluation method

Pushover analysis is conducted on the frame models, which can be seen as the intact structure. At each of the calculation steps, damage class of the members is decided from their ductility coefficients. Damage of the frames increase along with the pushover process, and the residual seismic capacity is evaluated at four of the calculation steps, named Critical State I, II, III and IV. When the first member in the frame reaches damage class II at some step, the previous step is defined as the Critical State I, if it reaches damage class III, the previous step is defined as the Critical State II, and so on. The Critical State IV is also the safety limit of the frame.

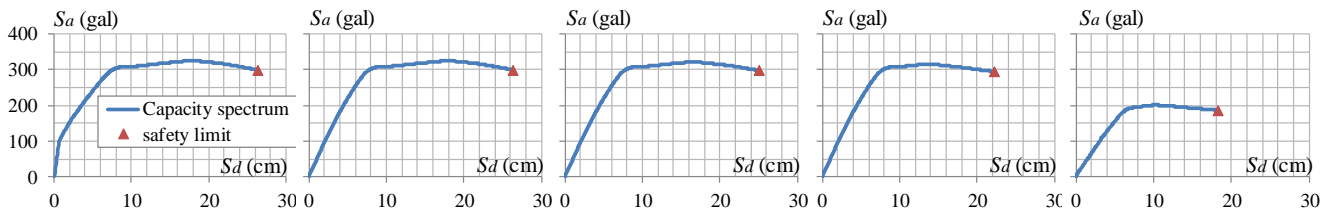
Take frame 4-A as an example, intact restoring force model of the columns at the first story and the beams are shown in Fig.10(a). Corresponding to each of the damage classes, the damaged restoring force model obtained by reducing the strength and deformation capacity according to the residual ratios (Table 2) are shown in Fig.10(b).



(a) Restoring force models for the intact beams and columns (b) Restoring force models for the columns in each of the damage classes

Fig. 10 – Restoring force model of the intact and damaged members (frame 4-A)

To conduct the CSM based residual seismic capacity evaluation method, the intact frame are modeled by using intact restoring force model of the members. For damaged frames at the Critical State I, II, III and IV, the damaged frame models are built by using damaged restoring force model of the members, according to their damage classes. By conducting the pushover analysis on the intact and damaged frame models, their intact CS and damaged CSs are obtained. For frame 4-A, the intact CS and damaged CSs at the Critical State I, II, III and IV are shown in Fig.11. As introduced in 2.1, the seismic capacity residual ratio, R , can be calculated based on the SCI by using Eq. (7). On the other hand, to conduct the IW based method, for damaged frames at each of the Critical States, damage class of each member are decided according to their ductility coefficient. By using the η_{wi} corresponding to their damage classes, the R is calculated according to Eq. (14). Evaluation results given by the CSM based and IW based method are compared in Fig.12.



(a) Intact (b) Critical State I (c) Critical State II (d) Critical State III (e) Critical State IV
Fig. 11– Capacity spectrums (CSs) of the intact frame and frame at each of the Critical States

Evaluation error by the IW based method relative to the CSM based method is shown in Fig.13. The IW based method can estimate seismic capacity residual ratio, R , by the CSM based method conservatively in the case of frame 4-A. However in the cases of frame 4-B, 12-A and 12-B, at some Critical States the IW based method gives estimations higher than the CSM based method which is not conservative. At the Critical State IV of frame 12-A and 12-B, R of the IW based method exceed the CSM based method by about 15%.

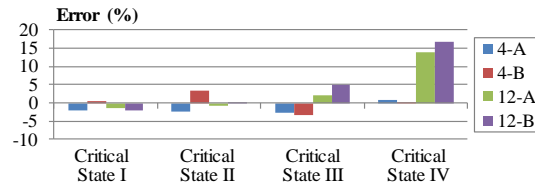
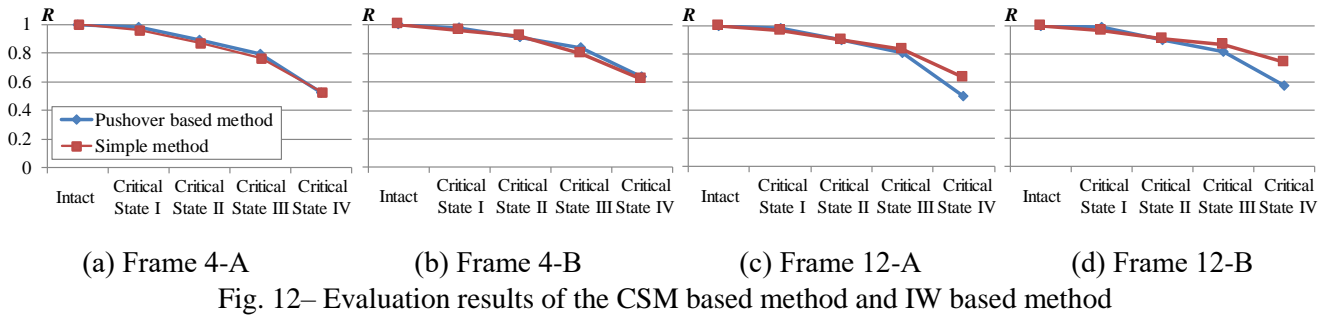


Fig. 13– Estimation error of the IW based method relative to the CSM based method

3.4 Influence of different deformation of the members

As mentioned before, the IW based method evaluates residual seismic capacity through the residual ratio of IW dissipated by the damaged structure relative to the intact one. The seismic capacity residual ratio is defined as average of the η_{wi} of members, weighted by their IW ($M_{yi}\theta_i$). Rotation angles of all of the members are assumed to be the same in Eq. (14). However, as shown in Fig.7, because daformation of the members (θ_i) changes due to different story drift along the structural height and existance of wing walls, the energy dissipation evaluated by Eq. (14) is just an approximation and somtimes the error will be considerable.

As the target frames collapse in the total collapse mechanism, energy is expected to be dissipated at ends of the beams and base of the columns. Based on this, at the Critical State IV, average rotation angles of the beams at each story and columns at the first story are calculated from the pushover analysis result, and compared with the same deformation assumption of Eq. (14) as shown in Fig.14. It can be seen that rotation angles of beams at the upper stories are smaller compared with the lower stories. Difference between the story drifts becomes bigger when the frame is higher. For frame 4-B and 12-B, clear length of the beams is shorter due to existance of the wing wall, so the difference of rotation angles between the beams and columns becomes bigger compared with the typical frames.

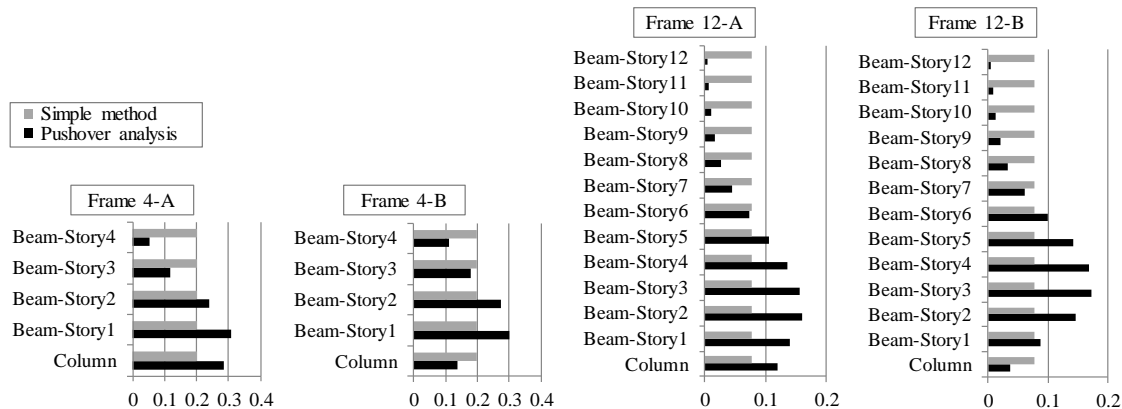


Fig. 14– Proportion of rotation angles at the beam ends and column bases

From the pushover analysis result, proportion of the energy dissipated by the beams at each story and columns at the first story until the Critical State IV is calculated. This proportion is considered to be closer to the

reality and compared with the assumption of IW based method as shown in Fig.15. In the IW based method, proportion of the energy dissipated by the members equals proportion of their yielding bending moment. From Fig.15, it can be seen that energy dissipated by the beams at upper stories is smaller due to their smaller deformations, compared with the beams at lower stories. The IW based method does not consider difference among the member deformations thus energy dissipation is overestimated for the upper story beams and underestimated for the lower story beams. For the higher structure, difference among the beam deformations increase and the error in energy dissipation becomes bigger. On the other hand, in the case of frame 4-B and 12-B, due to existence of the wing wall, deformation of the columns becomes smaller compared with the typical frames. Until the frames reach the Critical State IV in the pushover analysis, energy dissipated by the columns is smaller than the assumption of IW based method.

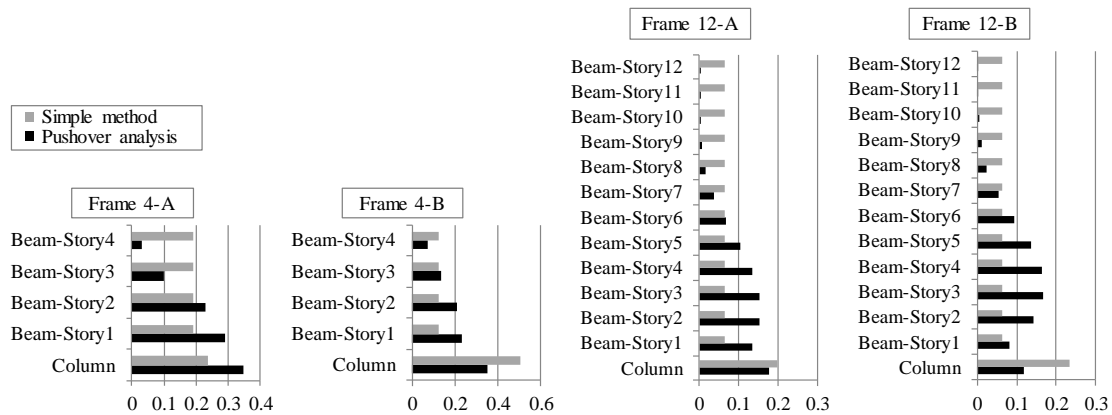


Fig. 15– Proportion of energy dissipated at the beams ends and column bases

At the calculation step when the frames reach each of their Critical States, averages of η_{wi} of the beams at each story and columns at the first story are shown in Fig.16. Due to the difference among the story drifts, deformation of the upper story beams is smaller as well as their damage classes, and the average of η_{wi} is higher. On the other hand, in the case of frame 4-B and 12-B which includes the wing wall, deformation and damage class of the columns becomes smaller and the average of η_{wi} becomes higher, compared with the typical frames.

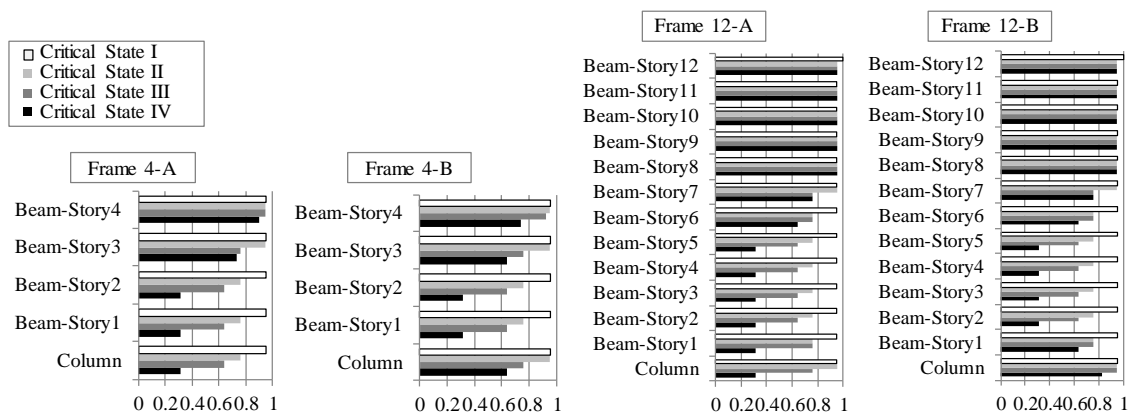


Fig. 16– Average of the η_{wi} of beams and columns at each of the Critical States

The IW based method does not consider difference among deformation of the members when calculating average of the η_{wi} weighted by IW of the members. Therefore the IW is overestimated for the upper story beams and underestimated for the lower story beams. At the same time η_{wi} is relatively higher for the upper story beams and lower for the lower story ones. Therefore, evaluation result of the IW based method will be higher due to ignoring the difference among deformation of the members. Similarly, as for the frames with wing wall, energy dissipated by the columns is overestimated by the IW based method and at the same time η_{wi} if the columns is

higher compared with the typical frames. Evaluation result of the IW based method thus will become even higher than the typical frames.

In the case of frame 4-A, the error comes from difference among deformation of members is still acceptable and the IW based method can estimate the CSM based method results conservatively. In the case of frame 4-B, 12-A and 12-B, because the error brought by the story drift and clear length of members becomes considerable, the results estimated by the IW based method exceed that of the CSM based method and are found to be unconservative

4. Modification on the IW based method and its verification

Through the discussion above, it is clear that because of ignoring the difference among deformation of the members, the IW based method will fail in giving a conservative estimation for the CSM based method. In order to include the deformation of members into consideration, the IW based method is modified in the next following by the verification on the modification.

4.1 Modification on the IW based method

The IW based method is aimed at the structures with total collapse mechanism. In this case, damage state such as the crack width can be expected to have a positive correlation with the rotation angles and ductility coefficient of members. Deformation of each member thus can be approximately estimated according to its damage class. Based on the relationship between damage classes and ductility coefficient of the member in Fig.9, average of ductility coefficient for the members in each of the damage classes is assumed in Table 4 as a representative ductility coefficient. The representative ductility coefficient is used to consider the deformation of each member and Eq. (14) is modified into Eq. (15).

Table 4 – Representative ductility coefficient

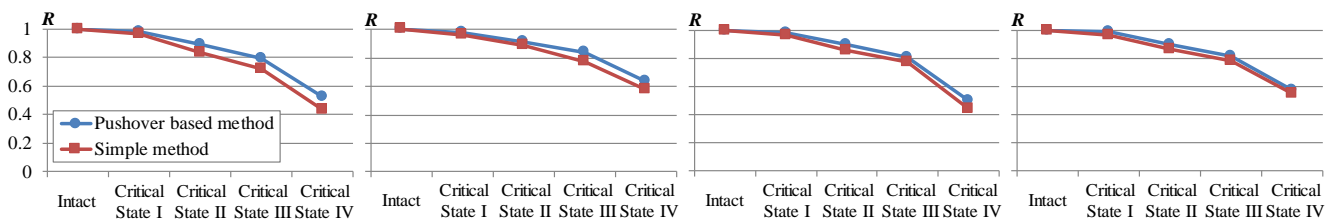
Damage Class	I	II	III	IV
μ_r	0.5	1.5	2.5	4

$$R = \frac{\sum(\eta_{wi}\mu_{ri}M_{yi})}{\sum(\mu_{ri}M_{yi})} \quad (15)$$

where μ_r is representative ductility coefficient of the member.

4.2 Verification of the modified method

The modified IW based method is applied on the frames at each of their Critical States, and the result are compared with that of the CSM based method in Fig.17. It is shown that the modified IW based method can estimate the result of CSM based method slightly conservatively without the need of analysis.



(a) Frame 4-A

(b) Frame 4-B

(c) Frame 12-A

(d) Frame 12-B

Fig. 17– Evaluation results of the CSM based method and modified IW based method

Proportion of energy dissipated by the members until the Critical State IV, from the pushover analysis and the modified IW based method, are compared in Fig.18. Compared with Fig.15, by taking deformation of

members into consideration through the representative ductility coefficient, μ_{ri} , the proportion of energy dissipation becomes closer to the pushover analysis result. Therefore, result of the CSM based method can be estimated more accurately by the modified IW based method.

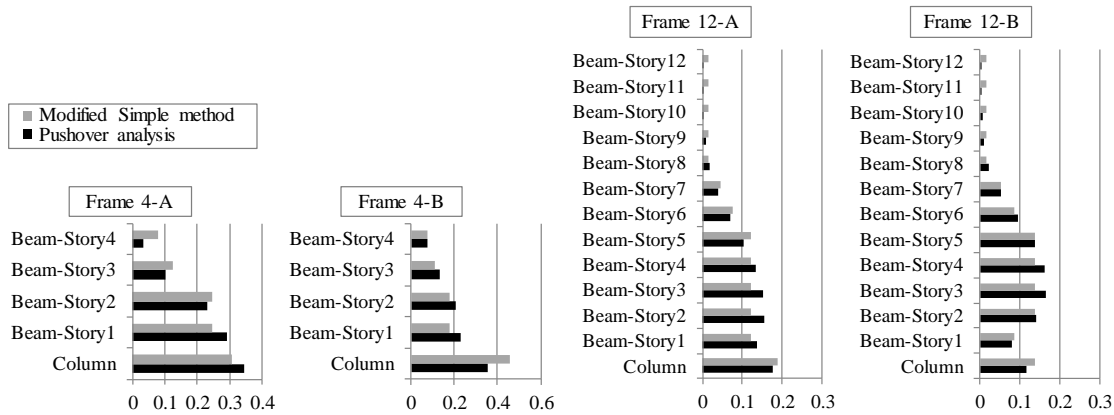


Fig. 18– Proportion of energy dissipated at the beams ends and column bases (modified)

5. Conclusion

Two quantitative methods for residual seismic capacity evaluation of the damaged RC structure, which are based on IW and CSM, were reviewed in this paper. In order to compare these two methods, reduction in strength, deformation capacity and hysteretic energy dissipation capacity, were integrated into reduction of energy dissipated by the member, by which the different reductions can be considered in the IW based method as well as the CSM based one. By applying these two methods on prototype frame models, result of the IW based method was found to be not conservative compared with the CSM based one in some cases due to ignoring the difference among the member deformations. Then the IW based method was modified to take deformation of the members into consideration. The following verification showed that the modified IW based method is able to give an accurate and slightly conservative estimation on the CSM based method without need of numerical analysis, which can be concluded as a simple and effective method for residual seismic capacity evaluation.

6. Reference

- [1] Maeda M and Bunno M (2001): Post-earthquake damage evaluation for R/C buildings based on residual seismic capacity in structural members. *The Third US-Japan Workshop on Performance-Based Earthquake Engineering for Reinforced Concrete Building Structures*, 157-169.
- [2] Ito Y, Suzuki Y, Maeda M (2015): Residual seismic capacity evaluation for RC buildings based on reduction in strength, deformation capacity and damping of damaged structural members. *Proceedings of the Japan Concrete Institute (CD-ROM)*. (in Japanese)
- [3] Bao S, Matsukawa K, Maeda M (2010): An evaluation method of residual seismic capacity for RC buildings with total collapse mechanism. *The 13th Japan Earthquake Engineering Symposium*, 3255-3260. (in Japanese)
- [4] Miura K, Matsukawa K, Maeda M (2011): Residual seismic capacity evaluation for seismic damaged buildings by considering influence of structural members on seismic capacity and expansion to structure with different failure modes. *Proceedings of the Japan Concrete Institute*, 33(2), 901-906. (in Japanese)
- [5] AIJ (Architectural Institute of Japan) (2004). Guideline for performance evaluation of earthquake resistant reinforcement concrete buildings (draft). Tokyo, Japan. (in Japanese)
- [6] Nakano Y, Maeda M, Kuramoto H, Murakami M (2004): Guideline for post-earthquake damage evaluation and rehabilitation of RC buildings in Japan. *The 13th World Conference on Earthquake Engineering (CD-ROM)*.
- [7] Shibata A and Sozen MA (1976). Substitute structure method for seismic design in RC. *Journal of the Structural Division*, 102(1), 1-18.