Post-Earthquake Damage Evaluation for Reinforced Concrete Buildings with Various Collapse Mechanism

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SUMMARY:
Main purpose of this paper is to investigate residual seismic capacity for RC frame structures. An evaluation method for contribution of each structural element to the performance of the whole structure was proposed based on strength, displacement and energy dissipation. It was shown that the proposed method was of more accuracy and wider applicability compared to previous methods through pushover analyses of prototype frames. Moreover, an approximation method was developed and obtained a sufficient prediction of the contribution factor of each element. Then, the proposed method was applied to a static loading test result of a single-story frame and its applicability was discussed. Finally, effectiveness of the proposed method was confirmed through the application to buildings damaged due to the 2011 Great East Japan Earthquake.

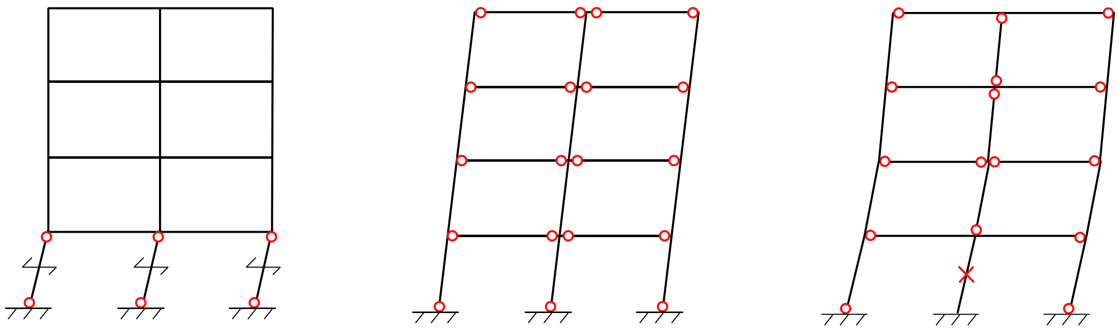
Keywords: Residual seismic capacity, Post-earthquake damage evaluation, Collapse mechanism, Strength deterioration, Damping, Story drift, Contribution factor of structural member

1. INTRODUCTION

To restore an earthquake damaged community as quickly as possible, a well-prepared reconstruction plan is essential. When an earthquake strikes a community and destructive damage to buildings occurs, quick damage inspections are needed to identify which buildings are safe and which are not in the case of aftershocks. However, since such quick inspections are performed within a short period of time, the results are inevitably coarse. In the next stage following the quick inspections, damage evaluation should be more precisely and quantitatively performed. For this purpose, a technical guideline that may help engineers find appropriate actions required in a damaged building is needed. In Japan, the Guideline for Post-Earthquake Damage Evaluation and Rehabilitation originally developed in 1991 was revised in 2001 based on lessons from damaging earthquakes such as the 1995 Kobe Earthquake (JBDPA 2001a).

The authors have developed a method to evaluate the residual seismic capacity of reinforced concrete (RC) structures based on residual seismic capacity patio, *R*-index, which is employed in the Damage Evaluation Guideline revised in 2001 (Maeda 2004). The *R*-index is defined as ratio of residual seismic capacity to the original capacity, and is calculated based on story shear before and after the quake in the Guideline considering that most typical failure mechanism of reinforced concrete buildings observed in the past damaging earthquakes is story collapse mechanism as shown in Figure 1.1(a). Bao et al. proposed evaluation method for building with beam yielding total collapse mechanism as shown in Figure 1.1(b) (Bao 2010). However, these methods are not able to be applied to buildings with unclear collapse mechanism except story collapse and total collapse mechanism.

Main purpose of this paper is to develop an evaluation method of residual seismic capacity, *R*-index for buildings with various collapse mechanism including total collapse mechanism which is recently recommended in structural design. At first, contribution of damage in each structural member to deterioration of seismic capacity of whole structure was studied. Pushover analyses of prototype frame structures were carried out. It was found to be not only strength but also maximum deformation that affects residual seismic capacity from the analytical results. Moreover, the effect of energy dissipation of the member and displacement distribution along the height was discussed. Finally, an approximated evaluation of *R*-index was proposed and correlated with the results of pushover analyses and damage survey of a RC school building.



$R=\sum\left(\dfrac{Q_{ui}}{\sum Q_{ui}}\times\eta_i\right)$ (a) Story collapse mechanism

$R=\sum\left(\dfrac{M_{ui}}{\sum M_{ui}}\times\eta_i\right)$ (b) Total collapse mechanism

$R=\sum(E_{ri}\times\eta_i)$ (c) Collapse mechanism with mixed failure mode

Figure1.1. General concept of R-index and target collapse mechanism

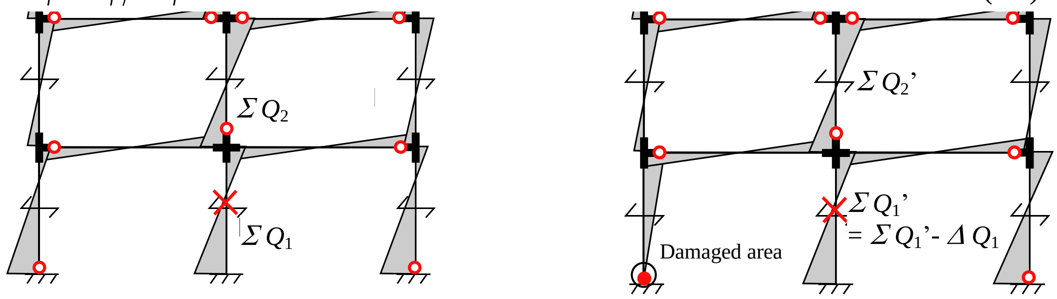
2. BASIC CONCEPT OF CONTRIBUTION OF STRUCTURAL ELEMENTS ON SEISMIC CAPACITY FOR BUILDING STRUCTURE

A contribution factor of a structural element, E_r, is defined as a factor which represents contribution of deterioration in seismic capacity of a structural element due to damage to residual seismic performance for total structure. In this paper, a contribution factor, E_r, is evaluated based on seismic capacity index which can be obtained by push-over analysis and seismic response spectrum (AIJ2004).

Detail of evaluation of a contribution factor, E_r, is as follows;
A frame with plastic hinge and flexural moment distribution as shown in Figure 2.1(a) is considered as an example. One of the plastic hinges is selected as a damaged area as shown in Figure 2.1(b). Push-over analyses of both un-damaged and partial damaged model are carried out. Obtained story shear – displacement curves are reduced to an equivalent single-degree-of-freedom systems for both models as shown in Figure 2.2. Seismic capacity index α is defined as a ratio of intensity of seismic response for ultimate limit state to standard seismic response in the AIJ's "Guidelines for Performance Evaluation of Earthquake Resistant Reinforced Concrete Buildings" (AIJ 2004). Seismic capacity index both for un-damaged model, α, and for partial damaged model, α', are evaluated according to the Gudeline. Deterioration ratio of the seismic capacity index for each plastic hinge, D_r, can be obtained by Eqn. 2.1. A contribution factor, E_r, for each plastic hinge is given by deterioration ratio, D_r, normalized by the summation of D_r, for all the hinges (Eqn. 2.2).

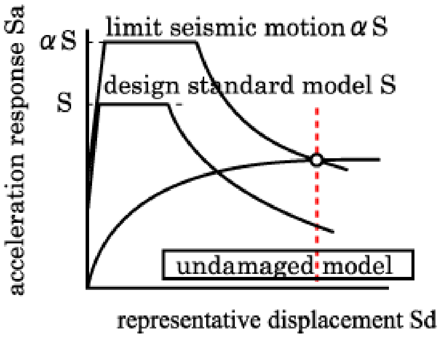
$$D_r = 1-\alpha'/\alpha \tag{2.1}$$

$$E_r = D_r/\Sigma D_r \tag{2.2}$$

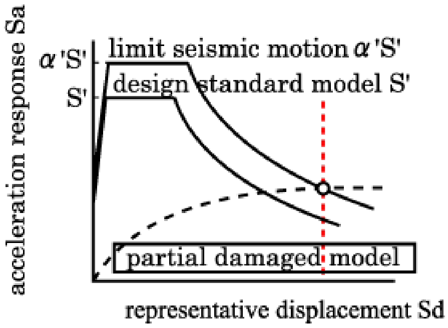


(a) undamaged model (b) partial damaged model

Figure 2.1. Story shear capacity at ultimate limit state



(a) Undamaged model



(b) Partial damaged model

Figure 2.2. Seismic capacity index α for undamaged and partial damaged models

3. PRACTICAL EVALUATION OF CONTRIBUTION FACTOR

3.1 Evaluation Method

As describe above, evaluation of seismic capacity index, α, for all the plastic hinges is required to evaluate contribution factor, E_r, of each structural element. However, push-over analyses of partial damage model for all the plastic hinge locations are complex and troublesome for the purpose of practical damage evaluation. Therefore, a simplified evaluation method is proposed in this chapter.

Generally, seismic capacity index, α, increases as base shear (acceleration response, Sa, in Figure 2.2), representative displacement, Sd, of an equivalent SDOF system, and damping factor, h, increase. Acceleration response, Sa, can be obtained by Eqn. 3.1. Base shear decreasing ratio $\overline{Q}$ for partial damaged model and three modification factors κ_b, κ_s, and κ_h are introduced and contribution factor, E_r, is assumed to be calculated by Eqn. 3.2

$$Sa = \sum Q_1 / M_e \tag{3.1}$$

$$D_r = \overline{Q} \cdot \kappa_b \cdot \kappa_s \cdot \kappa_h \tag{3.2}$$

Where, ΣQ_1: base shear, M_e: effective mass of equivalent SDOF system, κ_b: modification factor for variation of representative displacement, Sd, κ_s: modification factor for variation of effective mass, M_e, κ_h: modification factor for energy dissipation capacity.

3.1.1 *Base shear decreasing ratio* $\overline{Q}$

Firstly base shear for undamaged model ΣQ_1, and for partial damaged model ΣQ_1' are calculated by joint distribution method or other proper method (Figure 2.1). Lateral force degradation for a brittle shear member is idealized by a model as shown in Figure 3.1 and lateral force Q_s at story drift angle of 2% was used. Then base shear decreasing ratio $\overline{Q}$ is calculated by Eqn. 3.3. Note that base shear decreasing ratio $\overline{Q}$ is equivalent to $Q_{ui}/\ \Sigma Q_{ui}$ and $M_{ui}/\ \Sigma M_{ui}$ in Figure 1.1 which can be considered as a contribution factor in the current Damage Evaluation Guideline and previous paper, respectively.

$$\overline{Q} = 1 - \sum Q_1' / \sum Q_1 = \Delta Q / \sum Q_1 \tag{3.3}$$

3.1.2 *Modification factor for variation of representative displacement,* κ_b

Seismic capacity index α tends to decrease when representative displacement Sd of partial damaged model decrease comparing to undamaged model. Then κ_b is modification factor by which the effect was taken into calculation. General concept of κ_b is shown in Figure 3.2 and 3.3. κ_b is assumed to be given by Eqn. 3.4.

$$\kappa_b = 1 + \overline{\delta} / 0.1 \tag{3.4}$$

Where, $\overline{\delta}$ is decreasing ratio of representative displacement of partial damaged model. Refer to ref.(Miura et al. 2012) for detail.

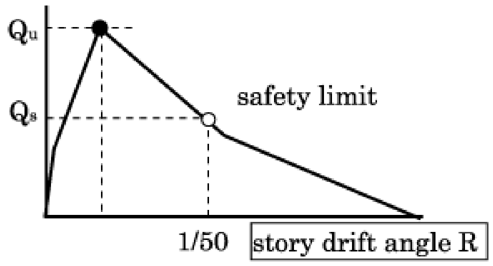


Figure 3.1. Assumed shear capacity for brittle members

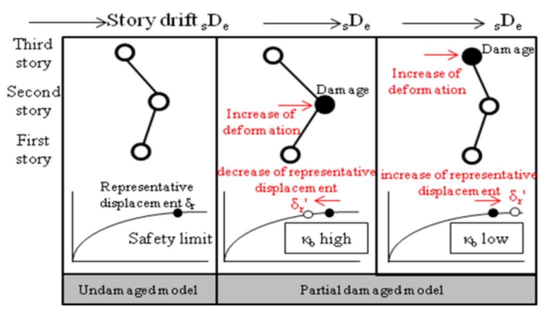


Figure 3.2. General concept of κ_b

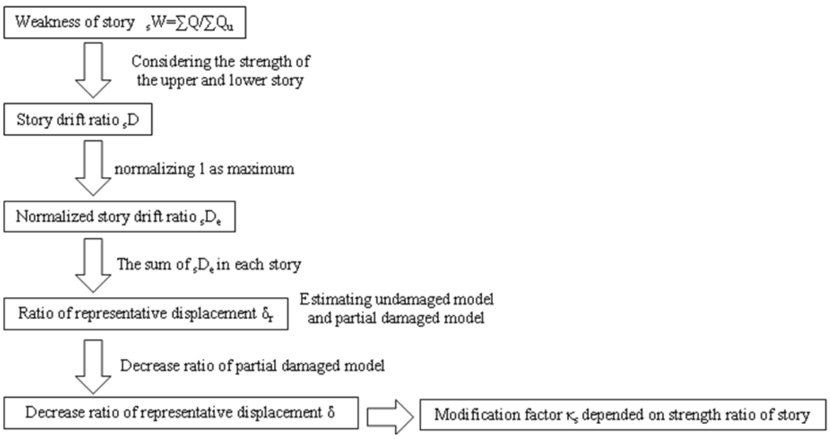


Figure 3.3. Flow of evaluation of modification factor κ_b

3.1.3 *Modification factor for variation of* effective mass, κ_s

It is obvious from Eqn. 3.1 that acceleration response, *Sa*, is inverse proportion to effective mass, M_e. Generally, effective mass, M_e, tends to increase in case of larger story drift occur in lower stories such as soft first story mechanism. As a result of increase in M_e, acceleration response, *Sa*, decrease. κ_s is a modification factor to consider the location of a structural element along the building height. κ_s is assumed by quite simple Eqn. 3.5.

$$\kappa_s = 1.4 - 0.7(i/n) \tag{3.5}$$

Where, *i*: story number for considered element, *n*: total number of stories of the buildings.

3.1.4 *Modification factor for energy dissipation capacity*, κ_h

κ_h is a modification factor to consider energy dissipation capacity of each structural element. In this paper, energy dissipation capacity is assumed to be proportion to ductility factor of the element. If the ratio of flexural moment M_R in elastic state to flexural strength M_u increases, larger ductility factor may be expected. Therefore, κ_s was assumed to be given by Eqn. 3.6.

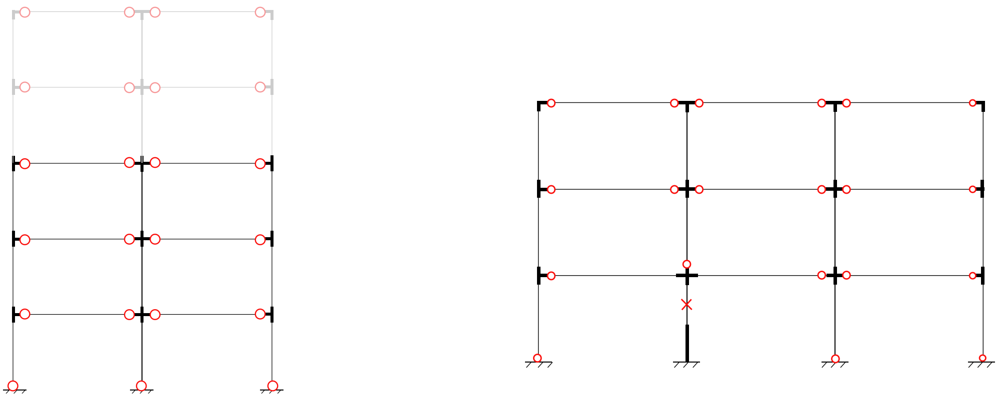
$$\kappa_s = \sqrt{M_R/M_u} \tag{3.6}$$

Note that κ_s should be normalized so that the maximum value in the target structure is 1.0, and 0.66 is employed for brittle shear members considering poor energy dissipation capacity.

3.2 Verification of Evaluation Method through Prototype Frame Model Structures

3.2.1 *Outline of prototype frame model*

Three frame models with different number of stories (3 or 5) and collapse mechanism (total collapse and mixed failure mode) as shown in Figure 3.4 were employed in the study. The name of the models shown in Figure 3.4 indicates number of the stories, type of collapse mechanism and number of bays of analytical models. Distribution of story drift obtained by the method mentioned above (Eqn.3.4) is compared with those from push-over analysis described in chapter 2 in Figure 3.5.



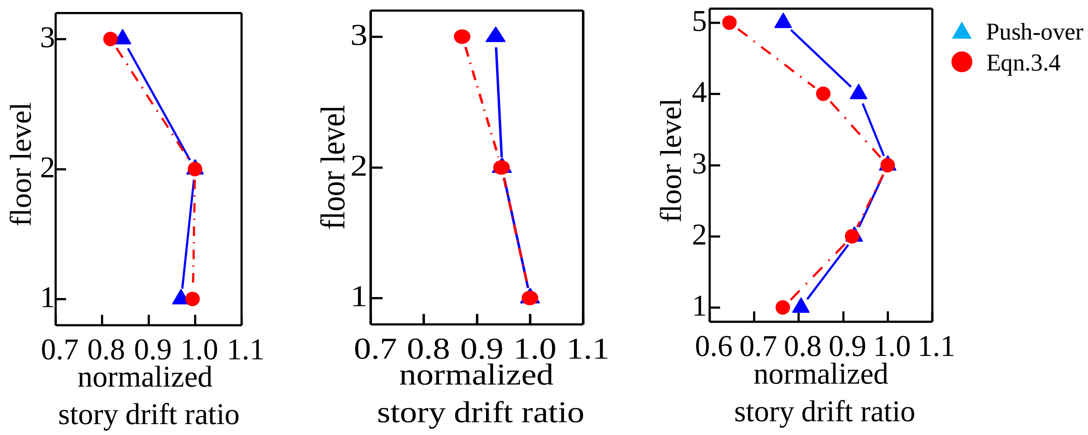
(a) 3T-2 (c) 5T-2

(b) 3M-3

T: beam yielding total collapse mechanism

M: mixed failure mode collapse

Figure 3.4. Prototype frame models used in verification



(a) 3T-2 (b) 3M-3 (c) 5T-2

Figure 3.5. Distribution of story drift of undamaged models

3.2.2 *Result of evaluated contribution factor E_r*

Contribution factor E_r calculated by the method proposed in this chapter was shown in Figure 3.6 together with $M_u/\Sigma M_u$ which was proposed in previous paper (Bao et al. 2010). As can be seen from the figure, $M_u/\Sigma M_u$ overestimates contribution factor E_r by precise evaluation based on push-over analyses for the stories with smaller drift angle (Figure 3.5), whereas underestimate for stories with larger drift angle. On the other hand, contribution factor E_r by practical method agrees with those by precise evaluation.

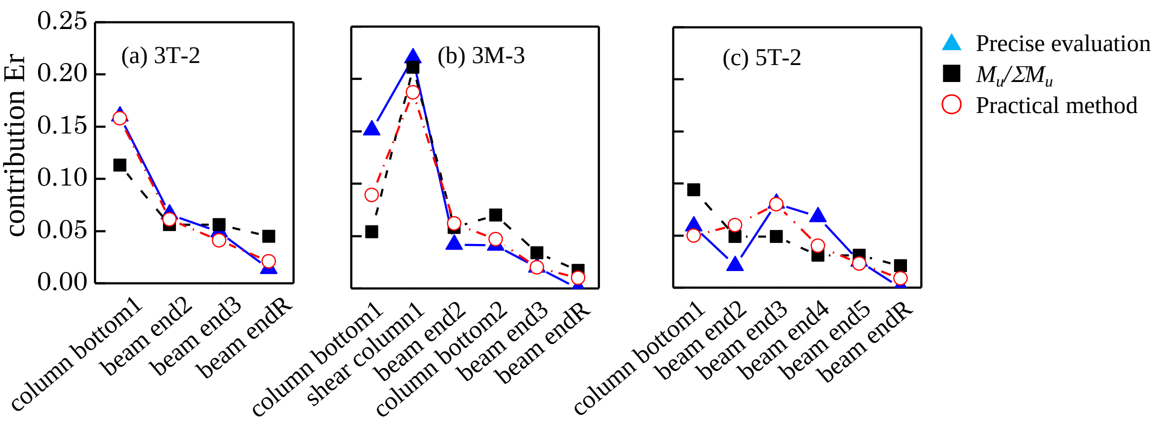


Figure 3.6. Evaluated contribution factor E_r

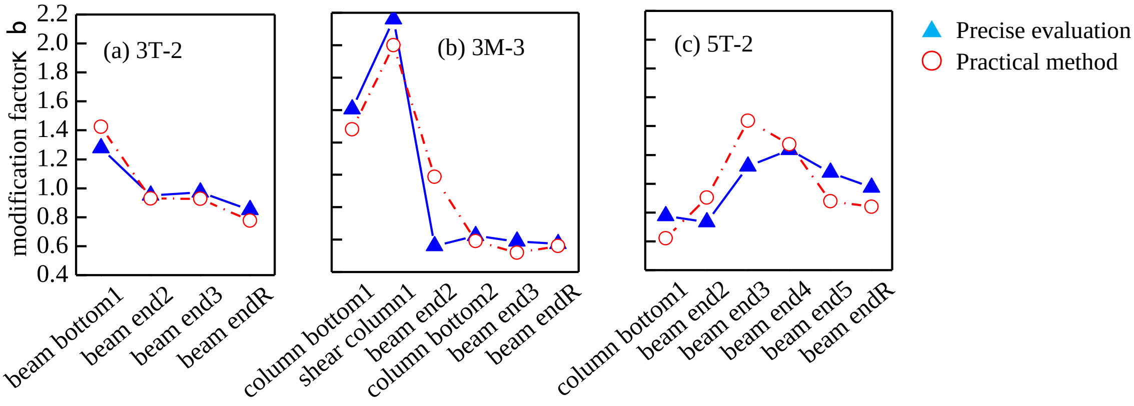


Figure 3.7. Modification factor κ_b

Figure 3.7 shows evaluated modification factor κ_b for all the models. Values of modification factor κ_b are larger for elements in the story with larger drift angle and the distribution of modification factor κ_b is similar with distribution of contribution factor E_r shown in Figure 3.4. This suggests the main reason of relatively good agreement in contribution factor E_r may be modification factor κ_b.

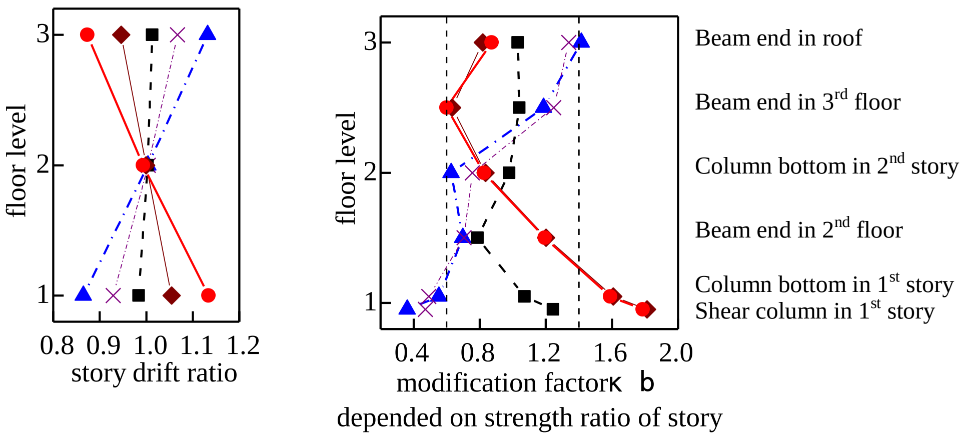
4. APPROXIMATED EVALUATION OF CONTRIBUTION FACTOR

Although the evaluation method proposed in chapter 3 gives good prediction of contribution factor for structural members, it is too complicated for the purpose of damage evaluation associated with field survey. Therefore, an approximated evaluation method was developed in this chapter.

4.1 Approximation of modification factors

4.1.1 *Modification factor for variation of representative displacement*, κ_b

Modification factors κ_b for models with various story drift distribution as shown in Figure 4.1(a) were calculated by the method proposed in chapter 3 and the tendency was investigated. Figure 4.1(b) shows example of calculated results of modification factors κ_b for 3T-3 model. From the figure, there are no big differences in κ_b values for the model with uniform story drift distribution (■). In other models, κ_b values are larger for the story with relatively large story drift. The ratio of story drift along the height seems to affect the κ_b values which range from about 0.6 to 1.4.



(a) Story drift distribution ratio (b) modification factors κ_b

Figure 4.1. Distribution of story drift of undamaged models

From the analytical results mentioned above, story drift angle were classified into three groups, i.e., “large”, “middle” and “small” as shown in Table 4.1. Story drift is predicted by average ductility factors, which is assumed based on damaged class observed in damage survey, of all the structural elements in a story (Table 4.2).

Table 4.1. Approximation of modification factors κ_b

Group of story drift	modification factors κ_b
Large	1.4
Middle	1.0
Small	0.6

Table 4.2. Assumption of ductility factor

Damage class	Assumed ductility factor
O	0.05
I	0.5
II	1.5
III	2.5
IV	4
V	5.5

4.1.2 *Modification factor for energy dissipation capacity*, κ_h

Modification factors are given according to Table 4.3 based on length and failure mode of structural members considering that larger inelastic deformation and, as a result, larger energy dissipation can be expected in short and stiff structural members.

Table 4.3. Approximation of modification factors κ_h

Failure mode	Length L		Damping	modification factors κ_h
Flexural	Short	$L < 0.66Le$	Large	1.0
	General	$1.5Le > L > 0.66Le$	Middle	0.8
	Long	$L > 1.5Le$	Small	0.66
Shear				

Le: length of most popular structural members

4.2 Verification of Evaluation Method through Prototype Frame Model Structures

Parametric study of prototype frame models used in chpter3 and, in addition, models with changing beam stiffness in the right bay were carried out. Comparison between the approximated and the practical evaluation was shown in Figure 4.2. As can be seen from the figure, approximation gives good prediction of contribution factor E_r. General error range is less than 30 percent and average ratio of the approximation to practical evaluation is almost 1.0 with coefficient of variation of 10 percent or less.

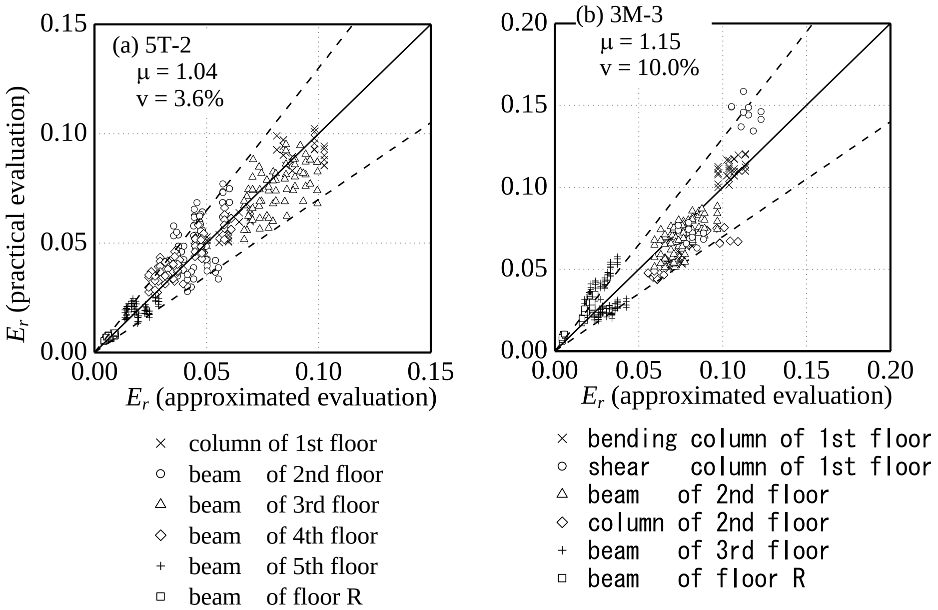


Figure 4.2. Comparison of contribution factor E_r between approximated and practical evaliation

5. VERIFICATION BY EXPERIMENT ON A SINGLE STORY FRAME SPECIMEN

5.1 Outline of Experiment

Objective specimen is a single story and two bay reinforced concrete frame, as shown in Figure 5.1, which consists of a brittle shear column at the center of frame and ductile flexural beams and other columns. Behavior, especially after shear failure of the center column, was investigated under constant axial load on all the columns and reversed cyclic horizontal forces at the both end of beams. Load cells were installed at the middle height of the both side columns.

5.2 Experimental Result

Shear force in center column reached to the maximum at the story drift angle of 0.7% and then the center column failed in shear. Story shear reached to the maximum at the drift angle of 0.9% and then gradually decreased as shown in Figure 5.2. The frame specimen sustained axial loads and escaped collapse until drift angle of 3%, although the center column totally lost lateral and axial load carrying capacity with crush of core concrete.

5.3 Estimation of Contribution Factor

Contribution factors , E_r, were calculated from experimental lateral force – displacement curve of the specimen and were compared with values evaluated by previous method, $M_u/\Sigma M_u$, and the proposed method in Figure 5.3. As can be seen from the figure, $M_u/\Sigma M_u$, tends to overestimate the contribution for brittle center column. It is because only maximum strength of structural elements was considered in the previous method, and poor energy dissipation capacity and deterioration in shear force of brittle center column at ultimate limit state were not taken into consideration.
On the other hand, proposed method gives relatively good estimation for Contribution factors , E_r.

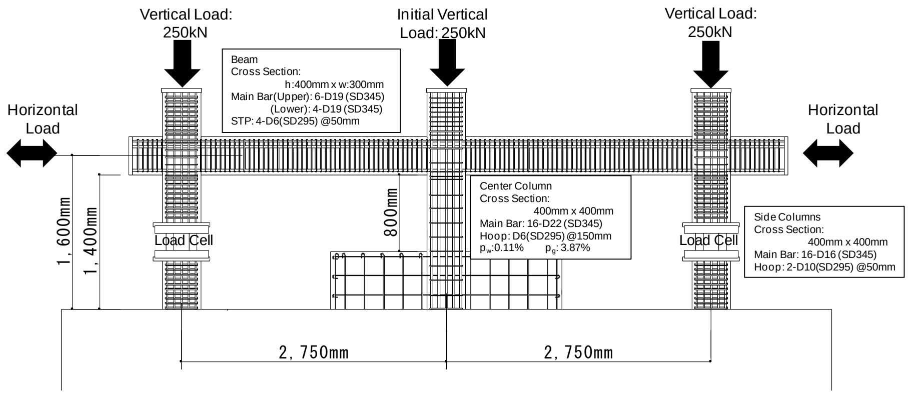


Figure 5.1. Side view of single-story and two-bay frame specimen

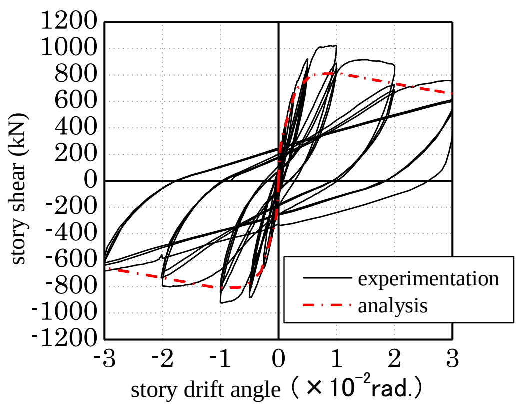


Figure 5.2. Story shear – drift angle of frame specimen

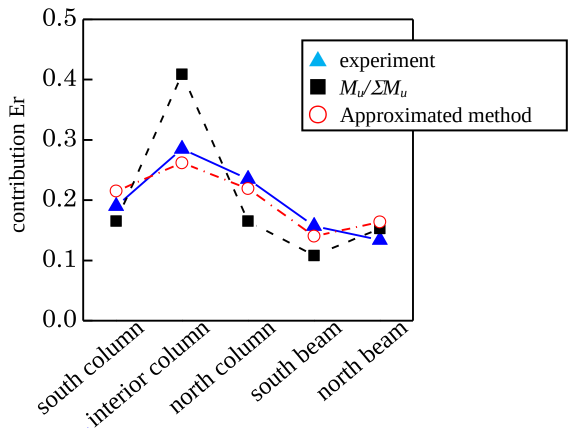


Figure 5.3. Comparison of contribution factor, E_r, in experiment with calculation

6. APPLICATION OF PROPOSED METHOD IN DAMAGE EVALUATION OF RC SCHOOL BUILDING DAMAGED BY THE 2011 EAST JAPAN EARTHQUAKE

6.1 Outline of Objective Building and Damage due to 2011 East Japan Earthquake

The proposed method was applied to post-earthquake damage evaluation for a RC building suffered from the 2011 East Japan Earthquake. Objective building is a three-storied RC school building located in Sendai city, Miyagi prefecture. The building includes short columns, long columns and wing walls. According to the seismic evaluation (JBDPA 2001b), the building was evaluated to have enough seismic capacity and no retrofitting was needed. Figure 6.1 shows damage classes of columns in the first story after the 2011 East Japan Earthquake (Maeda et al. 2012). The numbers indicates damage class classified base on the Japanese “Damage Evaluation Guideline” (JBDPA 2001a). In the guideline, Damage class I corresponds to “slight damage”, whereas damage class V corresponds to “collapse”. Although shear failure in short columns and wing walls, as shown in Photo 6.1, were observed, damage to most columns was quite limited and damage level was judged as “moderate damage”. Shear failure of those short columns was allowed in the Japanese seismic evaluation in case that axial loads could be redistributed to surrounding columns and the building didn’t collapse.

6.2 Evaluation of Residual Seismic Capacity Ratio *R*-index

Contribution factor, E_r, and residual seismic capacity ratio, R, were evaluated by current Guideline (JBDPA 2001a) and the approximated method proposed in Chapter 4. Evaluated contribution factor, E_r, and residual seismic capacity ratio, R, were shown in Figure 6.2 and Table 6.1. The current Guideline gives larger contribution factor, E_r, for wing wall and smaller R-index. As a result, damage level of “severe” did not agree with the expert judgment. On the other hand, damage level by the proposed method agrees with “moderate”. From this, proposed method can be applied to damage evaluation of RC buildings with brittle shear members. Moreover, proposed method gives better estimation of damage level for building in which shear failure in partial brittle columns did not induce total collapse of the structure.

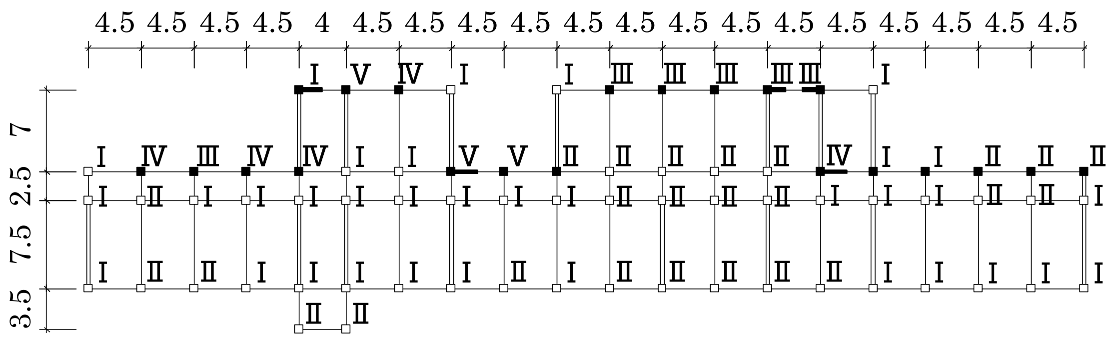


Figure 6.1. Damage distribution in the first story of the damaged RC school building

(a) Short column (b) Long column (c) Wing wall

Photo 6.1. Damage to structural members

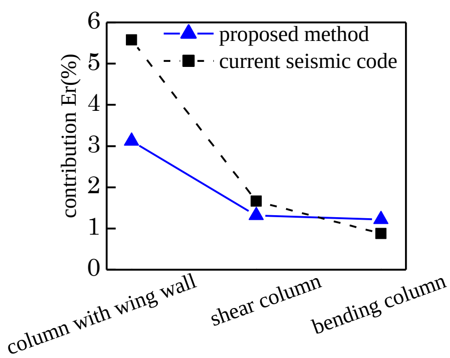


Figure 6.2. Contribution factor, E_r

Table 6.1. Comparison of damage evaluation results between current guidelines and proposed method

	Residual seismic capacity ratio, *R*	Damage level
Current guidelines	66.2	Severe
Proposed method	54.2	Moderate

7. CONCLUSION

An evaluation method of residual seismic capacity, *R*-index for buildings with various collapse mechanism was studied in this paper. Especially, evaluation method contribution factor, E_r, of structural element to residual seismic capacity was developed.

It was shown that the proposed method gives good prediction of contribution of each structural element comparing to both of the current Damage Evaluation Guideline and author's previous paper through analyses on prototype frame models with various collapse mechanism, story drift distribution and so on. Contribution factor, E_r, evaluated by proposed method agreed with those from experiment on a single-story RC frame structure. Finally, the proposed method was applied to a RC school building damaged due to the 2011 East Japan Earthquake, and it was confirmed that the proposed method gives more appropriate estimation of damage level for building with combination of brittle and ductile structural members.

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