コンクリート工学年次論文集，Vol. 23，No. 3，2001

# 論文 Inelastic Seismic Response of Exisiting Reinforced Cocrete Wall Buildings

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**ABSTRACT**: The response of existing RC wall buildings to future earthquake ground shaking is studied in terms of dissipating energies associated with collapse mechanism. For this purpose, reinforced concrete (RC) wall structures with various story strengths are analyzed by nonlinear time-history analyses under three ground motion records and a number of their phase-variation-based generations by wavelet transform. A story-shear-safety factor is introduced to distinguish between total-collapse and story-collapse mechanisms of structures and to investigate height-wise distribution of plastic energy. In addition, an equation is developed to estimate story response displacement under any level of future earthquake ground motion.

**KEYWORDS:** Reinforced concrete wall building, plastic energy, story-shear-safety factor, total-collapse, story-collapse, and story response displacement.

## 1. INTRODUCTION

In recent years, a great effort has been made to enable seismic design of RC buildings toward the performance-based seismic design such as the capacity spectrum approach introduced by Freeman [1] and the direct displacement-based seismic design by Priestley et al. [2]. These methods simply characterize a multistory building as an equivalent single-degree-of-freedom (SDF) system, and utilize approaches of nonlinear static pushover analysis and substitute structure [3] on seismic structural performances. However, an existing multistory building or even a currently constructed building may collapse in different ways during severe earthquakes (so-called total-collapse, story-collapse, or mixed -collapse types). Consequently, energy dissipation in the plastic hinge zones of structural components is concentrated on various stories over height of the building, depending significantly on characteristics of the earthquake ground motion and properties of the structure. Thus, an effectively simple method developed on the basis of the collapse mechanism (or energy-dissipating mechanism) of structure instead of its equivalent SDF systems is needed for the seismic evaluation of existing buildings under future earthquakes. The objective of this paper is to study the seismic response of existing RC wall buildings in terms of dissipating energies with emphasis on story strengths. The results indicate that story-shear-safety factor must be considered as the basis for performance procedures in the seismic evaluation of existing RC buildings. In addition, this study may be extended toward the performance-based seismic design of new buildings.

## 2. STRUCTURAL WALL MODELS ANALYZED

All wall models analyzed have 9 stories, spans of 10 m, and constant story heights of 3 m as shown in **Fig. 1**. The dimensions are given in **Table 1** and the constant story weight is assumed to be 1500 kN (resulting in fundamental period $T_1 = 0.42$ sec). The concrete strength is taken as 30 N/mm$^2$. Two boundary columns and a wall plate at each story are modeled as an equivalent column member with two plastic rotational springs at the top and bottom and a shear spring in the middle, where plastic deformations may occur. The degrading trilinear model (Takeda model) is used for flexural deforma-

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tion and the origin-oriented degrading stiffness model is used for shear deformation. Secant stiffness and post-yield stiffness are assumed to be 0.3 and 0.01 times initial elastic stiffness, respectively. Damping factor is set equal to 0.05. These models are organized in three groups according to their heightwise variations in story yield shear strengths (as will be shown below). Analyses to determine the yield moment and yield shear strengths of the wall columns are performed as follows.

Table 1 Model dimensions (cm)

| Story | Column | Plate thickness | Beam |
|---|---|---|---|
| 7 ~ 9 | 60 x 60 | 20 | 35 x 55 |
| 4 ~ 6 | 65 x 65 | 20 | 40 x 60 |
| 1 ~ 3 | 70 x 70 | 20 | 45 x 65 |

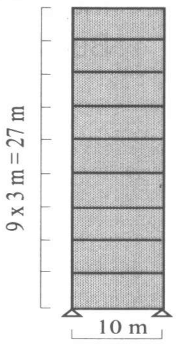


Fig. 1 Wall model

1. Perform a linearly elastic analysis for the structure subjected to lateral static forces distributed in accordance with the vertical distribution factor $A_i$ specified by the Japanese Building Code [4]. The base shear coefficient $C_B$ is taken as 0.6. The bending moments and shear forces at the $i$th story are then denoted by $M_{wi}$ and $Q_{wi}$, respectively.
2. Increase both values of $M_{wi}$ and $Q_{wi}$ by a factor of $\psi$ for each group while keeping the moment at the bottom of the first story and the shear force at a selected weak story in the case of weak-first-story or weak-fifth-story models unchanged as follows

   Group 1 (uniform-shear-increase models)

   $$M_1 = M_{w1},\ Q_1 = \psi Q_{w1},\ M_i = \psi M_{wi} \text{ and } Q_i = \psi Q_{wi} \quad (i = 2, 3, \dots n \text{ and } \psi = 1, 1.1, \dots \text{ or } 1.4) \tag{1}$$

   Group 2 (weak-first-story models)

   The same as **Eq. 1** except $Q_1 = Q_{w1}$ and $\psi > 1$ $\quad (\psi = 1.1, 1.2, 1.3, \text{ or } 1.4)$ (2)

   Group 3 (weak-fifth-story models)

   The same as **Eq. 1** except $Q_5 = Q_{w5}$ and $\psi > 1$ $\quad (\psi = 1.1, 1.2, 1.3, \text{ or } 1.4)$ (3)

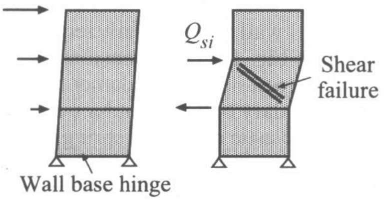
   where $n$ is the number of stories.
3. Calculate the required minimum moment and shear strengths of the structure according to the data given above and minimum percentages of reinforcement required in the code [4].
4. Determine the yield moment and yield shear strengths at each story for each model as the larger of the corresponding values calculated on the above steps 2 and 3. The cracking strengths for all members of the model are calculated in accordance with the code [4].

## 3. INPUT EARTHQUAKE GROUND MOTIONS

Three earthquake ground motion records, 1940 El Centro NS, 1994 Sylmar NS, and 1995 Fukiai NS, are taken into account. El Centro NS record is multiplied by 2.6 times to make its peak velocity equal to 100 cm/sec. To consider uncertainties in characteristics of earthquake motions that may occur at the site of an existing building in the future and their effects on the response of structure, each of them is then generated based on the phase-variation technique using the wavelet transform to produce twenty other motions [5].

## 4. STORY-SHEAR-SAFETY FACTOR

For a given existing building subject to severe future earthquakes, a question being widely considered is whether it will fail in total-collapse type as expected in seismic design or in undesirable story-collapse type (**Fig. 2**). If it fails in story-collapse type, how the plastic energy is distributed over its height? To consider the probability of storv-collapse



a) Total-collapse b) Story-collapse

Fig. 2 Energy-dissipating mechanisms

and plastic energy concentration of a building with emphasis on the story strength, the story-shear-safety factor for the $i$th story, $f_i$, is defined as the story-collapse-resisting shear strength redundancy, $\Delta Q_i$, divided by the story shear force, $Q_{ui}$, for ultimate state:

$$f_i = \Delta Q_i / Q_{ui}, \quad \Delta Q_i = Q_{si} - Q_{ui} \quad \left(f_i \geq 0\right) \tag{4}$$

where $Q_{si}$ is the $i$th story shear strength with the assumption of the story-collapse mechanism shown in **Fig. 2b** (shear failure develops in wall). The value of $Q_{ui}$ in **Eq. 4** can be obtained based on the nonlinear static pushover analysis under the lateral static force distributed in inverted triangular form (refer to **Fig. 2a**). The minimum story-shear-safety factor, $f_{min}$, for each model is defined by

$$f_{\min} = \min\left\{f_i\right\}, \quad i = 1, 2, \ldots n \tag{5}$$

## 5. DISSIPATED PLASTIC ENERGY

### 5.1. Definition of Plastic Energies

The plastic energy dissipated in a story is defined as the shaded area shown in **Fig. 3** for both flexural yielding and shear yielding. Thus in a given plastic region, the plastic energy is determined based on the corresponding value of ductility factor and the associated story yield strength and deformation. Summing up plastic energies of all the stories of the building gives the total plastic energy ($E_p$). Considering a mixed-collapse type building, the value of $E_p$ is thus composed of two components, say $E_{pt}$ and $E_{ps}$, corresponding to the contribution of total-collapse and story-collapse modes, respectively ($E_p = E_{pt} + E_{ps}$). Note that for particular cases, the value of $E_{ps}$ can reach $E_p$ or zero if the building is either collapsed in a story-collapse type or a total-collapse type, respectively. The value of $E_{pt}$ is defined as the plastic energy dissipated by flexural yielding at the bottom of the first story wall for each model. The value of $E_{ps}$ is then derived from summing the plastic energies by both shear yielding and flexural yielding, if available, of other plastic regions for each model.

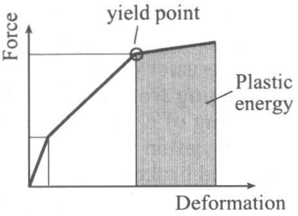


Fig. 3 Plastic energy

### 5.2. Effects of Minimum Story-Shear-Safety Factor $f_{min}$ on Collapse Modes

This section will show an understanding of how the minimum story-shear-safety factor, $f_{min}$, affects the relative contributions of the collapse modes in a building during earthquake motions in terms of dissipating energies. For this purpose, the ratio $E_{ps}/E_p$ is established to indicate how much the structure may behave in an undesirable story-collapse mode during an expected level of future earthquakes. **Fig. 4** shows the relationship between the ratio $E_{ps}/E_p$ and the minimum story-shear-safety factor $f_{min}$ for all the models under all given earthquake motions (three earthquake records with each having twenty generations). From this figure, it can be seen that for buildings having the value of $f_{min}$ greater than about 0.3, no plastic energy due to story-collapse is dissipated ($E_{ps} = 0$). In other words, the structure fails only in total-collapse type. A value of $f_{min}$ less than 0.3 and greater than zero then represents a structure that either fails in a mixed-collapse type ($E_{ps}$ and $E_{pt} \neq 0$) or a total-collapse type ($E_{ps} = 0$ and $E_{pt} = E_p$). For $f_{min} = 0$, the values of $E_{ps}/E_p$ are resulted ranging from zero to unity which a structure fails in total-collapse type ($E_{ps} = 0$ and $E_{pt} = E_p$), story-collapse type ($E_{ps} = E_p$ and $E_{pt} = 0$), or mixed-collapse type ($E_{ps}$ and $E_{pt} \neq 0$). This is because of the uncertainty in the seismic response of the structure. Thus it can be concluded that, the contribution of the story-collapse mode to the seismic response of a building tends to be lower as the factor $f_{min}$ is larger, although it scatters depending on the characteristics of earthquake motions and structures. The mean and mean-plus-one-standard-deviation values of the ratio $E_{ps}/E_p$, as shown by the solid and broken lines, also have a tendency to decrease with increasing the

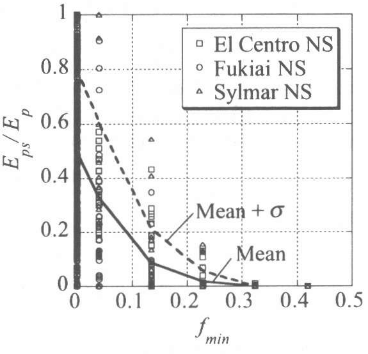


Fig. 4 $E_{ps}/E_p$ and $f_{min}$ relation (all Groups) factor $f_{min}$ of the building. For convenience, we propose the following equation to estimate the mean values of $E_{ps}/E_p$:

$$E_{ps}/E_p = (1-5f_{\min})/2 \quad (\geqq 0) \tag{6}$$

### 5.3. Effects of $f_i$ - $f_{min}$ on Plastic Energy Distribution

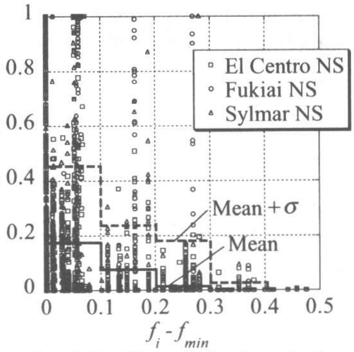


Fig. 5 $E_{psi}/E_{ps}$ and $f_i$ - $f_{min}$ relation (all Groups)

The plastic energy component due to story-collapse mode $E_{ps}$ is distributed (or concentrated) along the height of a building depends on the story-shear-safety factor during severe earthquake motions. **Fig. 5** shows a plot of the ratio of $E_{psi}/E_{ps}$ versus the difference of $f_i$-$f_{min}$ where $E_{psi}$ is the distribution of $E_{ps}$ to the $i$th story. From this figure, it can be found that the plastic energy component due to story-collapse can be partly concentrated on some stories even where the story strengths are relatively strong ($f_i$-$f_{min}$ greater than zero), depending on characteristics of the earthquake motions. Hence, an inevitable scatter is observed at the values of $f_i$-$f_{min}$ ranging from zero to 0.5 for the models in Groups 2 and 3 ($f_{min}$ = 0). However, in general, the scattering of $E_{psi}/E_{ps}$ decreases when $f_i$-$f_{min}$ increases. In addition, the mean and mean-plus-one-standard-deviation values of $E_{psi}/E_{ps}$ computed for every ten percent difference of $f_i$-$f_{min}$ (as shown by the solid and broken lines) have a tendency to decrease as the value of $f_i$-$f_{min}$ increases. We propose the following equation to estimate the mean values of $E_{psi}/E_{ps}$:

$$E_{psi}/E_{ps} = [1-2(f_i - f_{\min})]/n \qquad (n = \text{number of stories}) \tag{7}$$

For a building with story strengths corresponding to the inverted triangular forces, $f_i$-$f_{min}$ becomes zero and the above equation gives the uniform energy distribution. Frame models with 6 and 9 stories have been also carried out to investigate height-wise distributions of plastic energies and similar results have been obtained [5].

## 6. ESTIMATE OF STORY RESPONSE DISPLACEMENT

### 6.1. Equation of Estimating Story Response Displacement

The story drift in each story, $\delta_i$, imposed by seismic response is estimated depending on the contributions of three components:

$$\delta_i = \delta_{psi} + \delta_{pti} + \delta_{ei} \tag{8}$$

where $\delta_{psi}$, $\delta_{pti}$, and $\delta_{ei}$ are the components of the story drift corresponding to the contribution of story-collapse, total-collapse, and elastic response modes, respectively. The component $\delta_{psi}$ is estimated as the energy $E_{psi}$ due to story-collapse mode divided by the story strength $Q_{si}$:

$$\delta_{psi} = E_{psi}/Q_{si} \tag{9}$$

Assuming that the total-collapse mode causes uniform interstory drift angle $\phi$ over the height of the building, the component $\delta_{pti}$ in **Eq. 8** is determined as

$$\delta_{pti} = \phi \cdot h_i \tag{10}$$

where

$$\phi = E_{pt} \Big/ \sum_{j=1}^{n} (h_j \cdot Q_{uj}) \tag{11}$$

$Q_{uj}$ is the $j$th story shear force at the first yield, or the mechanism collapse in the case of simple wall structures, shown by the solid circles in **Fig. 6,** and $h_i$ is the height of the $i$th story.

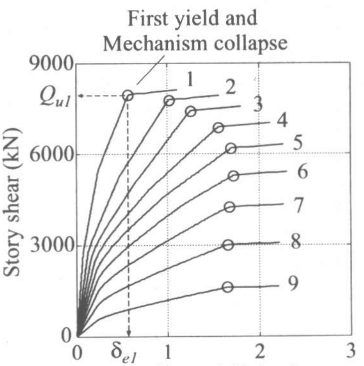


Fig. 6 Story shear-drift relation for $\psi$ = 1.2 wall model in Group 1

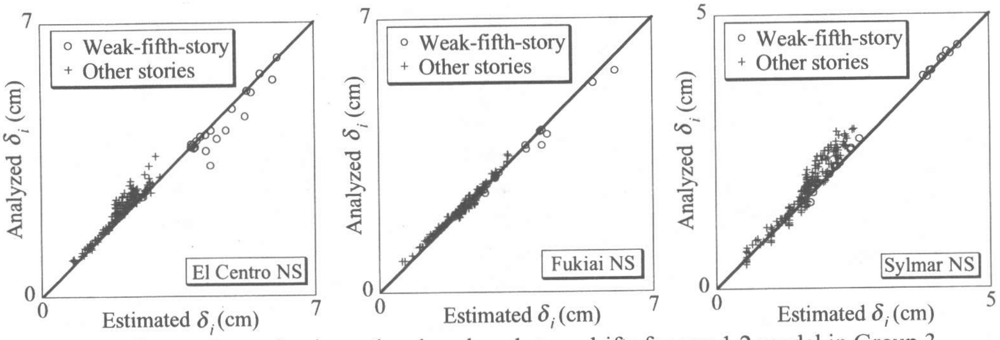


Fig. 7 Comparison of estimated and analyzed story drifts for $\psi = 1.2$ model in Group 3

Thus, **Eq. 6** is written as

$$\delta_i = \frac{E_{psi}}{Q_{si}} + \frac{E_{pt}}{\sum_{j=1}^{n}\left(h_j \cdot Q_{uj}\right)} \cdot h_i + \delta_{ei} \qquad (12)$$

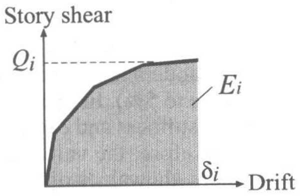


Fig. 8 Story dissipating energy

## 6.2 Verification of the Proposed Equation

For the purpose of verifying the validity of **Eq. 12**, the values of $E_{pt}$ and $E_{psi}$ in this equation are taken as those obtained from nonlinear dynamic time-history analyses corresponding to each model and each earthquake motion. Note that the values of $Q_{ui}$ and $\delta_{ui}$ are indicated in section 6.1, which are considered independent of seismic actions. **Fig. 7**, as an example, shows a comparison of the peak values of story drifts estimated by **Eq. 12** and those analyzed by dynamic analyses under the given earthquake motions for $\psi = 1.2$ models in Group 3. Recall that each earthquake record has 21 motions including its original and 20 generations. The results indicate that a relatively high degree of accuracy is generally observed for the model under the earthquake motions. In some cases, the estimate in the weak-story tends to be somewhat larger than the analysis, which gives a safety margin. We, furthermore, have done similar verifications for all other models considered under all given earthquake motions and obtained similar results.

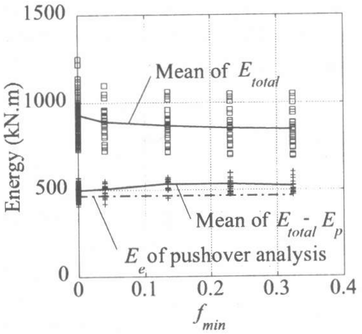


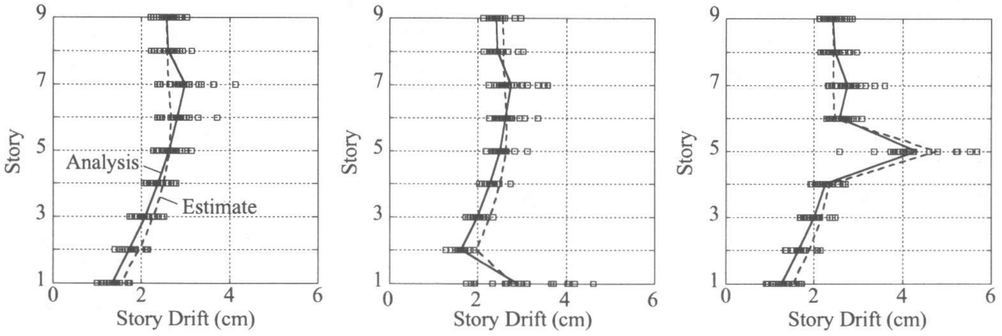
Fig. 9 $E_{total}$ for all models under El Centro NS

## 6.3 Estimate of Mean Story Drifts

To estimate the value of $\delta_i$ by using **Eq. 12**, the associated values of dissipating plastic energies in this equation should be first addressed as follows. Assuming that the total plastic energy $E_p$ is estimated as the difference between the total input earthquake energy, $E_{total}$, and the total elastic energy, $E_e$, in a building:

$$E_p = E_{total} - E_e \qquad (13)$$

The value of $E_{total}$ is determined based on the story shear force-drift relation that is assumed to be obtained from the nonlinear pushover analyses of the structure. Shown in **Fig. 8** is the total energy dissipated in the ith story $E_i$, which is defined by the shaded area based on the relationship between the story drift $\delta_i$ and the story shear force $Q_i$ over the earthquake-induced response of structure. Thus summing over all the stories of the building gives the value of $E_{total}$. **Fig. 9**, as an example, shows the values of $E_{total}$ and $E_e$ against the factor $f_{min}$ for all the models imposed by El Centro NS record (21 motions). In this figure, the values of $E_{total}$ are resulted in a likely constant range of 700 to 1050 kNm with the various values of $f_{min}$ ranging from zero to 0.32. Thus, it is found that the mean values of $E_{total}$



a) Group 1 b) Group 2 c) Group 3

Fig. 10 Estimate of mean story drifts for $\psi = 1.2$ models under El Centro NS record

does not depend much on the story strength distributions. Also, in this figure, the scattering of $E_{total}$-$E_p$ for all the models is generally small with a standard deviation value of approximately 2.5 (or COV approximate to 5%). In other words, for a considered yielding model the value of $E_e$ is most sensitive to its initial stiffness and can be estimated by the pushover analysis as shown by the chained line in this figure. Therefore, the value of $E_p$ in **Eq. 13** is determined depending on the selected value of $E_{total}$. Furthermore, the values of the plastic energy components and their distributions ($E_{pt}$, $E_{ps}$, and $E_{psi}$) are then estimated with reference to section 5. An example of estimating the mean value of story drifts is presented in **Fig. 10** for $\psi = 1.2$ models in all Groups 1, 2, and 3 under El Centro NS record. The solid lines in this figure indicate the mean values of analyses from the 21 motions and the broken lines indicate the estimate using **Eqs. 12**, **6**, and **7**. The results are likely good for all the models considered, including those under Sylmar NS and Fukiai NS records.

## 7. CONCLUSIONS

1. The story-shear-safety factor is proposed as the basis for performance procedures in the seismic evaluation of old existing RC buildings.
2. The contribution of the story-collapse mode in a building during earthquake motions is reduced with increasing the minimum story-shear-safety factor, although it scatters depending on the characteristics of earthquake motions and structures.
3. The part of the plastic energy due to story-collapse mode that may be concentrated on a story of a building increases when its story-shear-safety factor decreases.
4. The story response displacement of a building to a selected level of future earthquake motions can be estimated based on the story-shear-safety factor considering the energy concept and collapse mechanism of structure, as expressed by **Eq. 12**.

## REFERENCES

[1] Freeman, S. A., Prediction of Response of Concrete Buildings to Severe Earthquake Motion, SP-55, ACI, Detroit, USA, pp. 589-605, 1978.

[2] Priestley, M. J. N. and Kowalsky, M. J., Direct Displacement-Based Seismic Design of Concrete Buildings, Bullentin of the New Zealand Society for Earthquake Engineering, Vol. 33, No. 4, pp. 421-444, 2000.

[3] Shibata, A. and Sozen, M., Substitute Structure Method for Seismic Design of Reinforced Concrete, Journal of the Structural Division, ASCE, Vol. 102, No. 6, pp. 1-18, 1976.

[4] Architectural Institute of Japan, Design Guidelines for Earthquake Resistant Reinforced Concrete Buildings Based on Inelastic Displacement Concept, 1999. (in Japanese)

[5] Ichinose, T., Umemura, H., Kanbayashi, H., Kagohasi, H., and Thuat, D. V., Seismic Evaluation of Reinforced Concrete Buildings, Proceedings of the Tokai Region, Architectural Institute of Japan, Japan, Parts 1-5, 2001. (in Japanese)