論文 Seismic Evaluation of Reinforced Concrete Frame and Wall Structures Predicting Response Displacement

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ABSTRACT: A method based on the energy concept is proposed in order to predict the maximum story response of reinforced concrete (RC) frame and wall structures when subjected to earthquake ground motions. In the proposed method, the input earthquake energy on the building is expressed in terms of elastic and plastic energies. The elastic energy is determined based on the story shear force-displacement relationship obtained from nonlinear static push-over analysis. The plastic energy is assumed to be composed of two parts associated with mechanism deformation of the structure in total-collapse and story-collapse modes. Two types of RC frame and wall structures having various story strengths are analyzed in order to verify the validity of the proposed method under several earthquake motions.

KEYWORDS: Reinforced concrete structure, maximum story response, elastic energy, plastic energy, story shear strength factor, total-collapse mode, story-collapse mode.

1. INTRODUCTION

In recent years, severe earthquakes, such as the 1995 Kobe earthquake and the 1999 Turkey and Taiwan earthquakes, have caused significant damage to old buildings. Thus, seismic evaluation of existing old buildings is considered to be important and urgent in seismic affected countries. In seismic evaluation, one of the most important procedures is to predict the maximum interstory drift under any level of future earthquake ground motion. Some studies have taken this factor into account. For example, the capacity spectrum method proposed by Kuramoto and Teshigawara [1] evaluates the seismic response displacement of multistory buildings using an equivalent single degree of freedom (SDOF) system. However, a structure may deform in several collapse modes and have energy dissipation concentration under earthquake motions other than the mode caused by the static lateral seismic force corresponding to the first mode of vibration. In the present paper, a method based on the energy concept is proposed in order to predict the maximum story response of reinforced concrete frame and wall structures when subjected to earthquake ground motions. In order to verify the validity of the proposed method, frame and wall structures with various story strengths are analyzed under several earthquake motions.

2. RC FRAME MODEL AND STORY RESPONSE DISPLACEMENT

2.1 FRAME MODEL

Two frame structures of 3, 9 and 15 stories with a span of 5 m and a uniform height of 3 m are analyzed, as shown in **Fig. 1**. The dimension and concrete strengths are given in **Table 1**. The weight of each story is assumed to be 500 kN uniformly distributed on each floor level. The degrading trilinear model (Takeda model) is used for flexural deformation of beams and columns. The model for shear deformation is considered to be linear. The stiffness degradation factor at the yield point and the post-yield stiffness for all members are assumed 0.3 and 0.01 times the initial elastic stiffness, respectively. The damping factor is assumed to be 0.05 and is proportional to the tangential stiffness.

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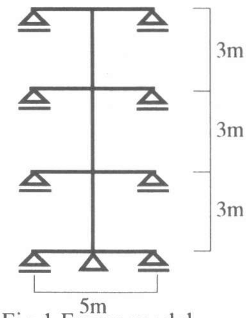


Fig.1 Frame model

Table 1 Model dimensions and concrete strengths

Model	Story	Beam (cm)		Column	Concrete strength
		Width	Depth	(cm)	(kg/cm²)
3-story	1-3	45	65	65 x 65	300
9-story	1-3	55	90	90 x 90	300
	4-6	50	85	85 x 85	300
	7-9	45	80	80 x 80	300
15-story	1-5	60	100	100 x 100	300
	6-10	55	95	95 x 95	300
	11-15	50	90	90 x 90	300

The yield moment of the column at the i-th story is calculated by

$$M_{cyi} = \psi \cdot {}_0Q_i \cdot h/2 \qquad (1)$$

where ψ is a factor equal to 0.8, 1.2, or 1.5, as described later. ${}_0Q_i$ is the i-th story shear force due to lateral seismic forces with respect to the vertical distribution factor, A_i, of the Japanese Building Standard Law. The structural characteristics factor D_s is assumed to be 0.3, and the standard shear coefficient C_0 is 1.0 for the second phase seismic design in Japan.

Under the assumption that the structure is formed in total-collapse mode under this force, the yield moment of the beam at the i-th story is determined based on the principle of virtual work as follows

$$M_{byi} = \frac{M_{bi}}{\sum_{j=2}^{n} M_{bj}} \cdot \left(h \sum_{j=1}^{n} {}_0Q_j - M_{cy1} - M_{cyn} \right) \qquad (2)$$

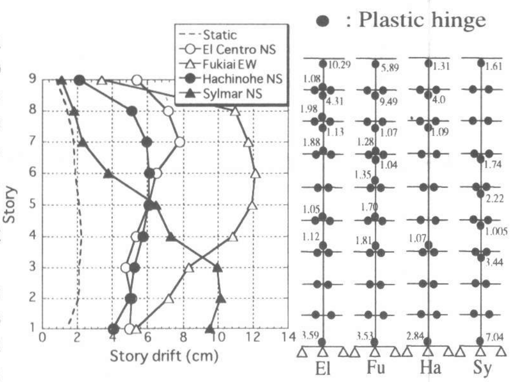
where n is the total number of stories and M_{bi} is the beam moment at the i-th story obtained from the results of elastic analyses of the structure when subjected to the seismic static force.

The foundation beams and roof beams are intended to remain in the elastic region so that their yield moments are assumed to be 3 and 1.5 times those calculated from **Eq. 2**, respectively. The cracking strengths for all members can be calculated based on section 3 of [2]: clause 3.2. However, in order to simplify the caculation, they are approximately assumed to be one-third the yield strengths.

2.2 STORY RESPONSE DISPLACEMENT

The input earthquake waves are taken from the Fukiai EW (1995), Sylmar NS (1994), El Centro NS (1940), and Hachinohe NS (1968) records. The El Centro NS and Hachinohe NS records are multiplied by three. The story response displacements of the structure with $\psi = 1.2$ in **Eq. 1** under these wave motions are illustrated in **Fig. 2**, in which the values are the ductility factors at the ends of column members.

This figure reveals that the story response varies along the height of the structure with various earthquake motions. For instance, the maximum response is located at mid-level for Fukiai EW, but at the upper and lower levels for El Centro NS and Sylmar NS, respectively. As a result, the position of plastic hinges , which may occur at two ends of beams and columns, is complicated.



a) Story response b) Ductility Factor

Fig.2 Story response and ductility factor ($\psi = 1.2$)

3. RC WALL MODEL AND STORY RESPONSE DISPLACEMENT

3.1 WALL MODEL

Two wall structures of 9 and 15 stories with a span of 10 m and a uniform height of 3 m are examined. The dimensions and concrete strengths are given in **Table 2**. Story weight is assumed to be 1500 kN distributed uniformly on each floor level. The model for analyses is shown in **Fig. 3**, in which two boundary columns and a wall plate at each story are modeled as an equivalent column member with a plastic rotational spring at the bottom, where a plastic hinge may occur. The Takeda model is also used for flexural deformation, but the origin-oriented degrading stiffness model is used for shear deformation. The stiffness degradation factor and the damping factor are assumed to be identical to those of the frame model.

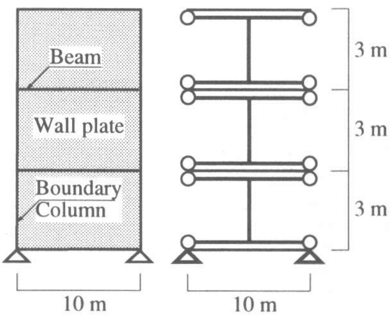


Fig. 3 Wall structure

Table 2 Model dimensions and concrete strengths

Model	Story	Boundary column (cm)	Wall thickness (cm)	Concrete strength (kg/cm²)
9-story	1-3	70 x 70	20	300
	4-6	65 x 65	20	300
	7-9	60 x 60	20	300
15-story	1-3	85 x 85	20	300
	4-6	80 x 80	20	300
	7-9	75 x 75	20	300
	10-12	70 x 70	20	300
	13-15	65 x 65	20	300

Analysis to determine the bending moment and shear strengths of the structure is performed as follows.

(1) Perform a linearly elastic analysis for the structure subjected to lateral seismic forces at each floor level in accordance with the vertical distribution factor of A_i. The structural characteristics factor D_s is assumed to be 0.6 and the standard shear coefficient C_0 is 1.0.

(2) Calculate the minimum ultimate bending moment and shear strengths of wall based on the data given in **Table 2** and the minimum percentages of reinforcement required in the AIJ standard [2], [3]. The minimum percentages of total reinforcement are 0.8% for columns and 0.25% for walls.

(3) Determine the flexural strengths and shear strengths of wall from the results of the elastic analyses multiplied by 1.5; with the exception that the flexural strength at the bottom of the first story is determined according to the elastic analyses and the weak-story shear strength is factored by ψ, as described in the cases given below. In all of these cases, the selected strength should be no less than the minimum strengths.

3.2 STORY RESPONSE DISPLACEMENT

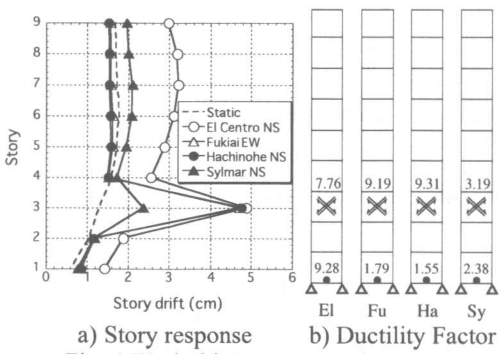


Fig. 4 Weak third-story model, $\psi=1.0$

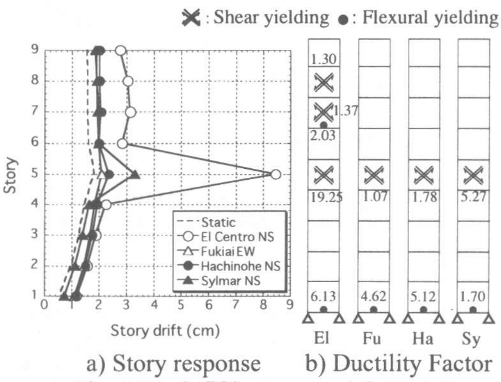


Fig. 5 Weak fifth-story model, $\psi=1.0$

The story response displacement for the structure with a weak third-story under wave motions similar to those of the frame model are shown in **Fig. 4**. For the cases of El centro and Sylmar records, the shear ductilities at the third floor are approximately the same as the flexural ductilities at the first floor. But for the Fukiai and Hachinohe records, they dominate over the flexural ductilities. The results for the structure with a weak fifth-story are shown in **Fig. 5**, in which the flexural ductilities, but not the shear ductilities as in **Fig. 4**, are dominant in the Fukiai and Hachinohe records. Thus, the results of the frame and wall models show differential collapse modes and energy dissipation concentration of the structure under earthquake motions and, consequently, indicate a drawback of the method based on the equivalent SDOF system where only one deformation mode is assumed.

4. PREDICTION OF STORY RESPONSE DISPLACEMENT

4.1 STORY FORCE-DISPLACEMENT RELATIONSHIP AND ELASTIC ENERGY

Nonlinear static push-over analysis is performed assuming the lateral seismic force to be distributed in form of a reverse triangle relating to the first mode of vibration of the structure. The story force Q_{ui} and the associated story displacement δ_{ei} are taken at the loading step when mechanism collapse occurs, as shown by the circles in **Fig. 6**. The elastic energy of each story E_{ei} is defined by the shaded area and the total elastic energy E_e is defined as

$$E_e = \sum_{i=1}^{n} E_{ei} \tag{3}$$

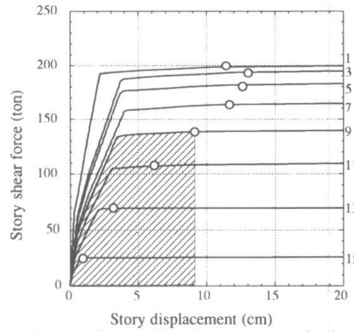


Fig.6 Story force-displacement relationship

4.2 STORY SHEAR STRENGTH FACTOR

Since the provided yield strength of the structure often exceeds the required strength as determined by analyses, the story shear strength factor α_i is defined as follows

$$\alpha_i = \frac{Q_{si}}{{}_0Q_i} \tag{4}$$

where Q_{si} is the story shear force, which is assumed to induce the collapse shown in **Fig. 7** and ${}_0Q_i$ is defined in **Eq. 1**.

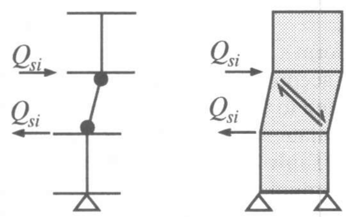


Fig.7 Story collapse

4.3 TOTAL INPUT EARTHQUAKE ENERGY.

The total input earthquake energy E_{total} over the structure can be expressed in terms of an equation of relation between equivalent velocity V_{total} and the total mass M of the building [4].

$$E_{total} = \frac{1}{2} M . V_{total}{}^2 \tag{5}$$

The equivalent velocity can be estimated depending on the magnitude of an expected earthquake.

4.4 PLASTIC ENERGY AND STORY DRIFT

The total energy is assumed to be subdivided into two components, elastic energy E_e and plastic energy E_p. Hence,

$$E_p = E_{total} - E_e \tag{6}$$

The plastic component E_p is also assumed to be composed of two parts, E_{ps} and E_{pt}, which form the structure in story-collapse and total-collapse modes, respectively. **Figure 8** shows the relationship between the minimum story shear factor α_{min} and the ratio of E_{ps} to E_p, which are calculated based on the ductility factors from the time-history nonlinear dynamic analyses described above. Then, the upper bound can be estimated as the curved lines shown in **Fig. 8** or the **Eq. 7**.

$$E_{ps} = \max\left[\left(\frac{2}{\alpha_{\min}} - 1\right)^3 . E_p, \quad 0\right] \tag{7}$$

Also, **Figure 9** shows the relationship between E_{psi} and E_{ps} corresponding to the $\alpha_i / \alpha_{\min}$ ratio, where E_{psi} is the distribution of E_{ps} to the i-th story. Then, the plastic energy distribution E_{psi} can be estimated as the linear line shown in **Fig. 9** or the **Eq. 8**.

$$E_{psi} = \max\left[\left(2 - \frac{\alpha_i}{\alpha_{\min}}\right). E_{ps}, \quad 0\right] \tag{8}$$

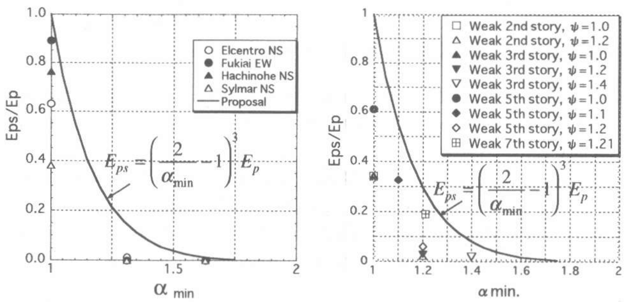
The energy corresponding to the total-collapse mode, E_{pt}, is given by

$$E_{pt} = E_p - E_{ps} \tag{9}$$

Using the energies given above, the maximum story response displacement can be predicted by

$$\delta_i = \frac{E_{psi}}{Q_{si}} + \frac{E_{pt}}{\sum_{j=1}^{n} Q_{uj}} + \kappa . \delta_{ei} \tag{10}$$

where k is a modification factor that takes into account differences in lateral seismic loading patterns in the elastic deformation range and is tentatively assumed to be 1.2.



a) 9-story frame model

b) 9-story wall model (El Centro NS)

Fig. 8 Relationship between E_{ps}/E_p and $\alpha_{\min}$

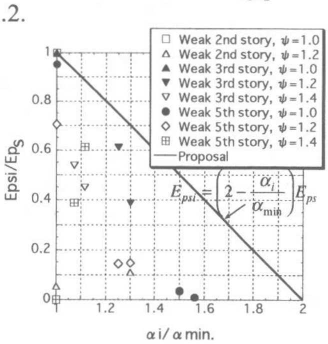


Fig. 9 Relationship between E_{psi}/E_{ps} and $\alpha_i/\alpha_{\min}$ for the 9-story wall (El Centro NS)

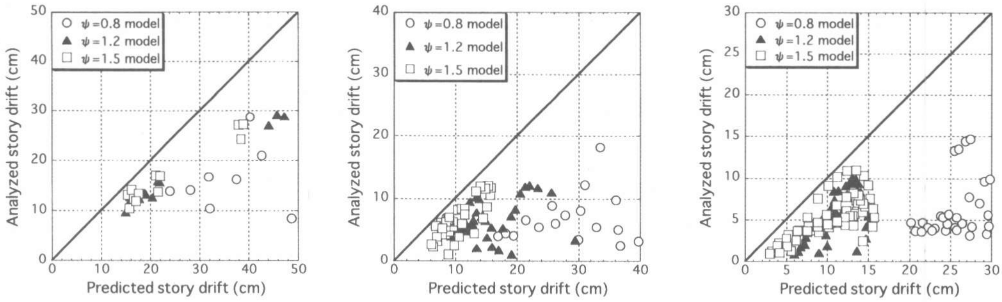
In addition, total-collapse modes may be dominant even in a structure having small $\alpha_{\min}$ values, as indicated in **Figs. 2, 4**, and **5**. Thereby, the value of E_{pt} can reach the maximum bound of E_p and the drift at the i-th story δ_i may be determined as follows:

$$\delta_i = \frac{E_p}{\sum_{j=1}^{n} Q_{uj}} + \kappa . \delta_{ei} \tag{11}$$

The upper limit of the story drift is taken as the larger of the values obtained from **Eqs. 10** and **11** above.

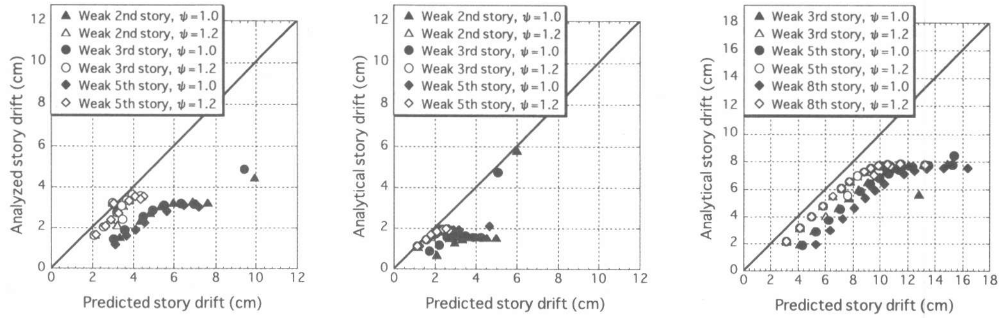
4.5. ANALYZED AND PREDICTED STORY RESPONSE DISPLACEMENT

Figure 10 shows a comparison of the predicted maximum story drift and that computed by time-history nonlinear dynamic analyses under the four earthquake motions given above for the 3-, 9-



a) 3-story model b) 9-story model c) 15-story model

Fig.10 Analyzed and predicted story drift for frame model



El Centro NS Fukiai EW Fukiai EW

a) 9-story model b) 9-story model c) 15-story model

Fig. 11 Analyzed and predicted story drift for wall model

, and 15- story frame structures. For the ψ=1.5 models, the predicted values agree with the computed ones. But for the models with smaller ψ factors of 1.2 and 0.8, or for those having more numerous stories, the results tend to allow higher safety.

In addition, **Figure 11** shows a comparison of the predicted maximum story drift and that computed by the time-history nonlinear dynamic analyses under El Centro and Fukiai records for the 9- and 15- story wall structures with various weak story models. The results are likely to be effective in the weak story models with $\psi=1.2$, but tend to allow higher safety in those with $\psi=1.0$.

5. CONCLUSIONS

The maximum story response of RC frame and wall structures under future earthquakes can be conservatively predicted using **Eqs. 7** through **11** based on the considerations of collapse mechanism of the structure, which is essentially uncertain. The proposed method is effective in structures that respond primarily in form of total-collapse modes and tends to allow higher safety for structures that respond in a variety of collapse modes because of the complicated story response under various earthquake motions.

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