SEISMIC RESPONSE PREDICTION OF STEEL FRAMES UTILIZING PLASTIC STRAIN ENERGY OBTAINED FROM PUSHOVER ANALYSIS

T. Hasegawa[1] and H. Kamura[2]

[1] *Senior Researcher, Dept. of Structural Engineering, Building Research Institute, Tsukuba, Japan*
[2] *Senior Researcher, Civil Engineering Research Dept., JFE R&D Corp., Kawasaki, Japan*
Email: hase@kenken.go.jp, h-kamura@jfe-rd.co.jp

ABSTRACT:

A seismic response prediction method for building structures presented in this paper is based on the energy balance concept, which can predict maximum inter-story drift and damage of each member of buildings. In this paper, the procedure of seismic response prediction for steel moment-resisting frames is illustrated, which is utilized inelastic strain energy obtained from pushover analysis. In order to examine the validity of the proposed method for practical application, thirteen kinds of example moment-resisting steel frame were selected. A series of earthquake response analyses of these example frames was carried out, and was compared to the results of the proposed method. From the results of the earthquake response analysis, it was found that the maximum inter-story drift and the cumulative ductility demands of members obtained from the proposed method could approximately catch the tendency of results of the earthquake response analysis.

KEYWORDS: Seismic response prediction, Pushover analysis, Energy balance concept,

1. INTRODUCTION

In Japan, seismic response prediction methods for building structures based on the balance between input energy and dissipation energy of structure have been presented by some researchers (Akiyama 1985, Ogawa and Hirano 2002). Akiyama proposed the energy spectrum (V_e) and the damage distribution law. Akiyama's proposed method could predict the plastic energy distribution along the height of the building and the maximum inter-story drift. Ogawa showed a seismic response prediction method for steel building structures with hysteretic dampers by using equivalent one degree of freedom system based on the above energy balance concept. In U.S., a new seismic design procedure for steel moment frames considering the input energy, a pre-selected yield mechanism and a target drift was presented (Leelataviwat and Goel 1999).

A new method proposed in this paper can predict maximum inter-story drift and damage of each member of building, which is also based on above mentioned energy balance concept. If a structural analysis program considering inelastic behavior of joint panel zones is used, damage of every member of the frame can be obtained considering an effect of energy absorption of panel zones. In the calculation procedure of the proposed method, the elastic strain energy of frame and the plastic strain energy of each member obtained from static incremental analysis (pushover analysis) are used. The proposed method in this paper is based on the following assumption that the tendency of damage distribution in low- and medium-rise building structures under earthquake ground motion is approximately same to the tendency of damage distribution obtained from pushover analysis. In order to examine the validity of this assumption for practical applications, some example moment-resisting steel frames are selected, and earthquake response analysis is carried out. The results of the earthquake response analysis of these example frames are compared to the results of the proposed method.

2. PROCEDURE OF SEISMIC RESPONSE PREDICTION FOR MOMENT RESISTING FRAMES

2.1. Calculation of Energy Input into a Frame

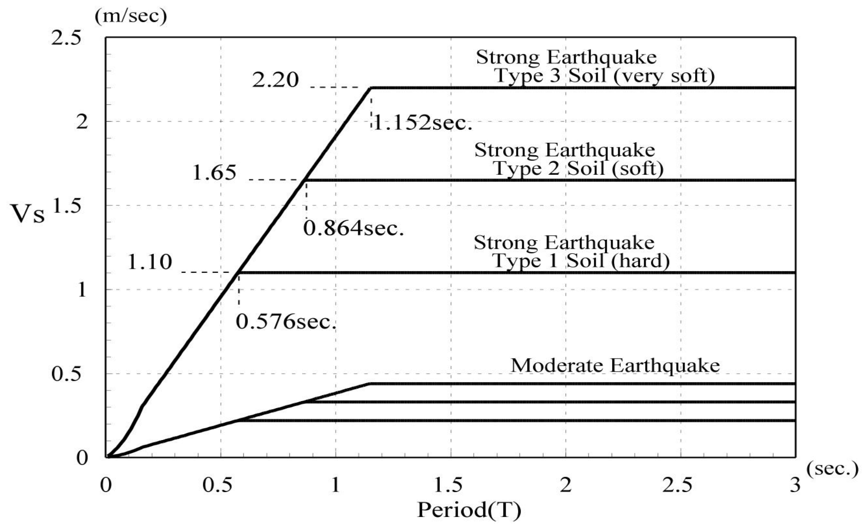


Figure 1 Design pseudo-velocity spectrum prescribed in Japanese building code

In the proposed method of this paper, the energy input into a structure is calculated as the damage causing energy (E_d), which is equal to the sum of the vibration strain energy and the cumulative plastic energy of the structure. The damage causing energy (E_d) of the proposed method can be calculated as:

$$E_d = \frac{1}{2} M \cdot V_s^2 = W_e + W_p \tag{2.1}$$

where M is total mass of the system. V_s is the design pseudo-velocity spectrum as shown in Figure 1, which is stipulated in the Notification No.631 (Seismic calculation method for building structures based on the balance of energy) of Japanese building code, W_e is the elastic vibration energy of the structure and W_p is the cumulative plastic energy of the structure.

The V_s value for practical design applications is needed to consider the elongation (steel moment frame 1.2T, RC frame 1.4T) of natural period (T) due to the plasticity of structure. The validity of Equation 2.1 has been verified by Housner (Housner 1956), Akiyama (Akiyama 1985) and Ogawa (Ogawa, Inoue and Nakashima 2000).

2.2. Calculation of Dissipation Energy of a Structure

During earthquake, members composing a building structure have to dissipate the design input energy calculated by Equation 2.1. In the proposed method of this paper, the vibration strain energy of the structure and the cumulative plastic energy of each member are computed by the pushover analysis. In each incremental load step of the pushover analysis, the sum of the vibration strain energy of the structure and the cumulative plastic energy dissipated by plastic hinges in the structure is calculated, and is compared to the design input energy calculated by Equation 2.1. When the sum of the vibration strain energy of the structure and the cumulative plastic energy of hinges become larger than the input energy as shown in Equation 2.2, the pushover analysis is finish at this step.

$$E_d < W_{ei} + \sum (4 \times {}_m W_p^s) \tag{2.2}$$

Where W_{ei} is vibration strain energy of the structure, ${}_m W_p^s$ is plastic energy dissipated by each hinge.

In Equation 2.2, coefficient 4 means equivalent cyclic member for a plastic hinge to determine the cumulative plastic energy dissipated by a hinge during earthquake excitation. The validity of coefficient 4 has been verified by some researchers (Akiyama 1985, Hasegawa and Yamanouchi 1994).

2.3. Prediction of Maximum Inter-Story Drift and Damage of a Structure

In the proposed methods of this paper, the maximum inter-story drift of the structure under the energy input calculated by the design spectrum (V_s) is directly obtained by the inter-story drift at the final step of the pushover analysis. The cumulative plastic energy (${}_mW_p$) of each plastic hinge in the structure is calculated by following Equation:

$$ {}_mW_p = 2 \times ({}^{+}_{m}W_p^{\max} + {}^{-}_{m}W_p^{\max}) \tag{2.3}$$

where ${}^{+}_{m}W_p^{\max}$ is plastic energy of each hinge in the structure at the final step in positive loading pass of the pushover analysis, ${}^{-}_{m}W_p^{\max}$ is plastic energy of each hinge in the structure at the final step in negative loading pass of the pushover analysis.

3. EARTHQUAKE RESPONSE ANALYSIS OF MOMENT-RESISTING STEEL FRAMES

In order to examine the validity and applicability of the proposed seismic response prediction method for practical applications, some example moment-resisting steel frames are selected, and earthquake response analysis is carried out. The results of the earthquake response analysis are compared to the results of the proposed method.

3.1. Outline of Example Moment-Resisting Steel Frames for Analysis

In this study, four different configuration frames (AR-frame, BR-frame, CR-frame, DR-frame) as shown in Figure 2 were selected. Four kinds of story (2-story, 4-story, 8-story, 12-story) are designed for AR-frame and BR-frame, respectively. Three kinds of story (2-story, 4-story, 8-story) are designed for CR-frame, and two kinds of story (2-story, 4-story) are designed for DR-frame. The collapse mechanism of AR-frame, BR-frame and CR-frame is designed to be strong-column weak-beam mechanism. On the other hand, DR-frame is designed to be a soft story mechanism. These thirteen kinds of example frame were selected for this study, which were designed according to the current Japanese building codes (Hasegawa et al. 1996). Earthquake response analysis of these frames as well as pushover analysis by using the proposed method was performed.

3.2. Method of Earthquake Response Analysis

A nonlinear analysis program club.f developed by Ogawa at University of Kumamoto was used to perform the analyses. In this analysis, the hysteretic rule of columns, beams and joint panel zones of the model frames was assumed to be bi-linear type. For the earthquake response analysis, three earthquake records (the 1940 El Centro NS, the 1968 Hachinohe EW, the 1995 JMA Kobe NS) were selected. These records were chosen because of different characteristics of shaking. These three actual earthquake records were scaled so that damage causing energy of analysis frames are approximately the same as the design input energy calculated by Equation 2.1. The

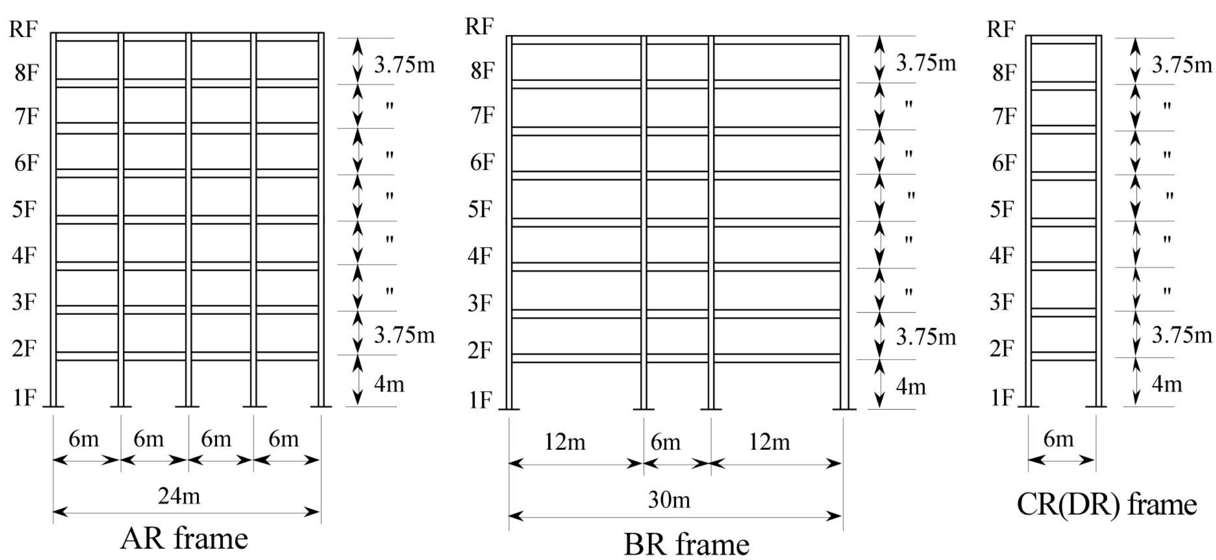


Figure 2 Example moment-resisting steel frames

floor masses were lumped at the beam-to-column connection nodes. The damping was taken as 2% of the critical damping value and was taken proportionally to the elastic stiffness matrix only.

3.3. Results of the Earthquake Response Analysis and the Proposed Method (pushover analysis)

Some results of the earthquake response analysis and the prediction methods (pushover analysis) for the thirteen frames are presented in Figures 3, 4 and 5. Figure 3 shows maximum inter-story drift of the thirteen frames obtained from the earthquake response analysis and the prediction methods. In Figure 3, three kinds of line show results of the earthquake response analysis, and marks of ○ show results of the proposed methods (pushover analysis) in this paper, and marks of ● show results of prediction by using the damage distribution law proposed by Akiyama (Akiyama 1985). From Figure 3, it was found that the proposed method could approximately catch the results of the earthquake response analysis. Akiyama's prediction method also could approximately catch the results of the earthquake response analysis.

Figure 4 shows cumulative ductility demands at plastic hinges in AR-02 frame, which was obtained from the proposed method (pushover analysis) and the earthquake response analysis against the JMA Kobe, respectively. Figure 5 shows the results of AR-04 frame. The cumulative ductility demands ($\bar{\eta}$) used in Figure 4 and 5 are defined as:

$$\bar{\eta} = \frac{{}_{m}W_{p}}{2(M_{p} \times \theta_{p})} \tag{3.1}$$

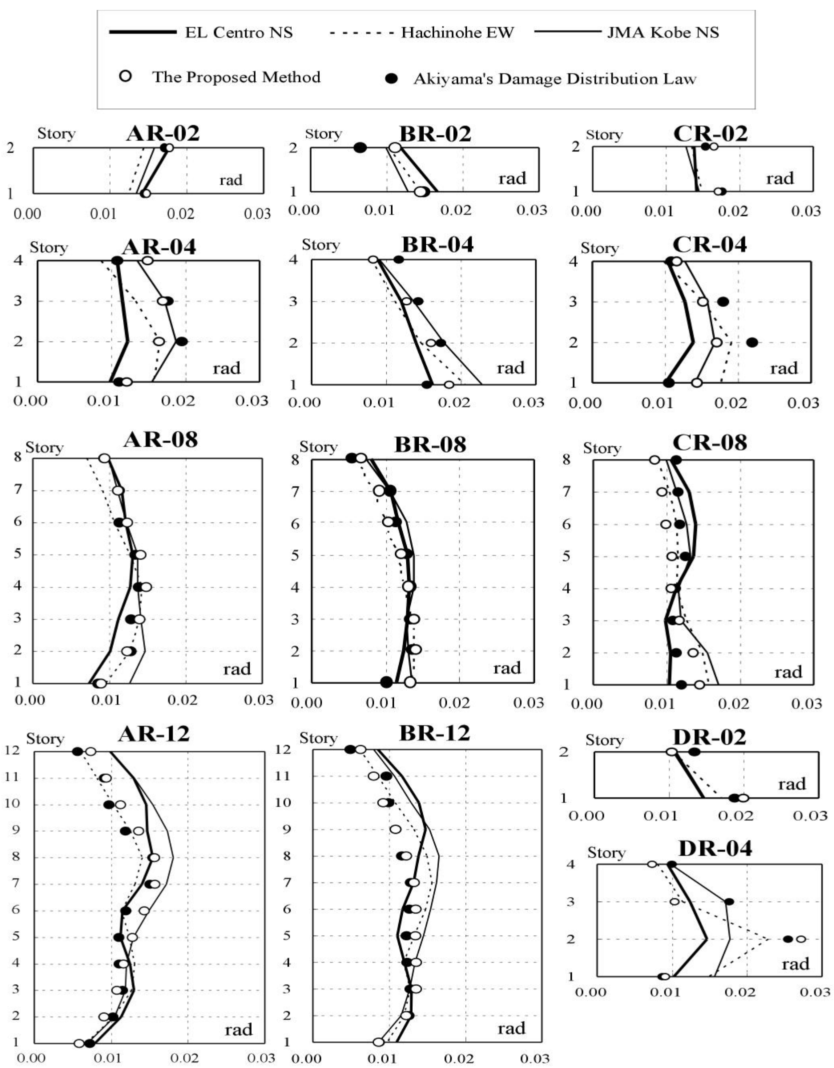
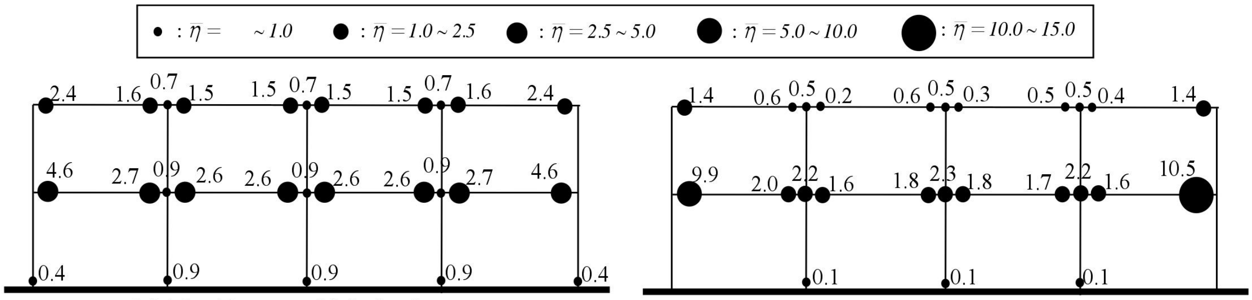
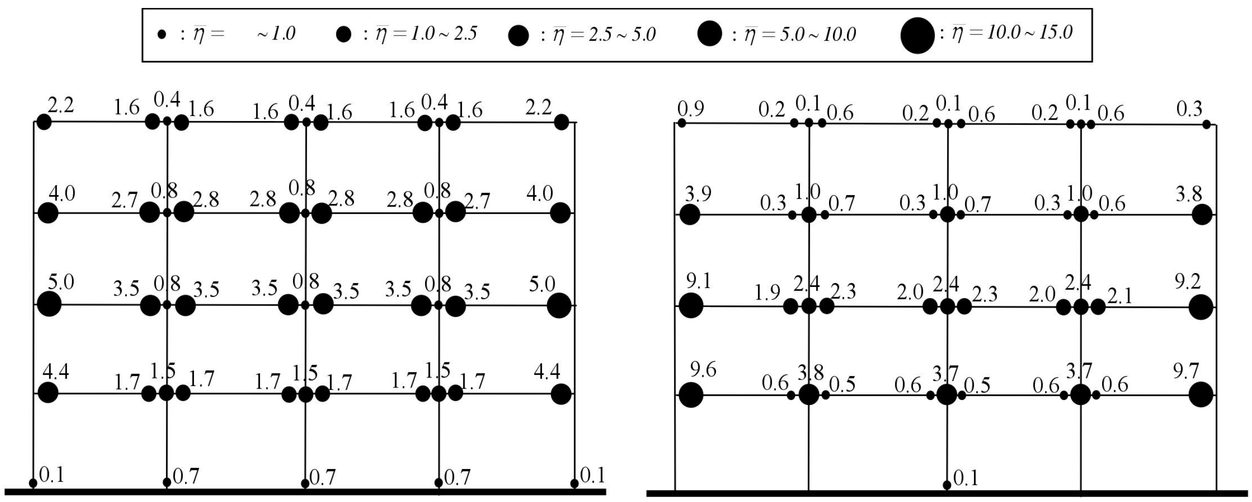


Figure 3 Maximum inter-story drift of example frames



(a) The Proposed Method (b)Earthquake Response Analysis (JMA Kobe NS)

Figure 4 Cumulative ductility demands in AR-02 frame



(a) The Proposed Method (b)Earthquake Response Analysis (El Centro NS)

Figure 5 Cumulative ductility demands in AR-04 frame

where ${}_mW_p$ is cumulative plastic energy of each hinge, M_p is full plastic moment of each member, θ_p is the end rotation at the elastic limit assuming anti-symmetric deformation of the member.

In this analysis, the analysis program club.f can compute inelastic deformation of joint panel zones. From the result of analysis using such a program, the cumulative ductility demands ($\bar{\eta}$) of beams, columns and panel zones composing the structure can be obtained.

From Figure 4 and 5, it was found that the cumulative ductility demands ($\bar{\eta}$) of members obtained from the proposed method could approximately catch the tendency of results of earthquake response analysis. But the prediction values at panel zones in the frame, and the prediction values at ends of beam connecting to outside columns became smaller than those of the earthquake response analysis. Generally, joint panel of steel moment frames have very large ductility. On the other hand, in terms of ends of beam connecting to outside columns in the frame, larger ductility demands than the prediction values should be considered for safety prediction.

4. SUMMARY AND CONCLUSIONS

A seismic response prediction method for building structures presented in this paper is based on the energy balance concept, which can predict maximum inter-story drift and damage of each member of buildings. In this paper, the procedure of seismic response prediction for steel moment-resisting frames is illustrated, which is utilized inelastic strain energy obtained from pushover analysis. In order to examine the validity of the proposed method for practical application, thirteen kinds of example moment-resisting steel frame were selected. A series of earthquake response analyses of these example frames was carried out, and was compared to the results of the proposed method.

From the results of the earthquake response analysis, maximum inter-story drift of the proposed method could approximately catch the results of the earthquake response analysis, and the cumulative ductility demands ($\overline{\eta}$) of members obtained from the proposed method could approximately catch the tendency of results of the earthquake response analysis. But the prediction values ($\overline{\eta}$) of panel zones in the frames, and the prediction values ($\overline{\eta}$) of ends of beam connecting to outside columns became smaller than those of the earthquake response analysis. In terms of ends of beam connecting to outside columns in the frame, larger ductility demands than the prediction values by the proposed method should be considered for safety prediction.

REFERENCES

Akiyama, H. (1985). Earthquake-Resistant Limit-State Design for Buildings. University of Tokyo Press, Japan.

Hasegawa, T. and Yamanouchi, H. (1994). Required deformation capacity of steel structural members based on damage distribution in steel frames under strong earthquake ground motions. Journal of Structural and Construction Engineering, AIJ, No.**460**, 169-177. (in Japanese)

Hasegawa, T. et al. (1996). Earthquake response analysis of rigid frames with RHS columns allowing for deformation of joint panels. AIJ Journal of Technology and Design, No.**2**, 43-48. (in Japanese)

Housner, G. W. (1956). Limit design of structures to resist earthquake. Proceeding of the World Conference on Earthquake Engineering, **5**, 1-11.

Leelataviwat, S., Goel, S. C. and Stojadinovic, B. (1999). Toward performance-based seismic design of structures. Earthquake Spectra, Vol.**15**, No.**3**, 435-461.

Ogawa, K. and Hirano, T. (2002). Ductility demanded of hysteretic dampers. Journal of Structural and Construction Engineering, AIJ, No.**558**, 197-204. (in Japanese)

Ogawa, K., Inoue, K. and Nakashima, M. (2000). A study on earthquake input energy causing damages in structures. Journal of Structural and Construction Engineering, AIJ, No.**530**, 177-184. (in Japanese)