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Paper No. 1107. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

INELASTIC SEISMIC DESIGN PROCEDURE BASED ON ENERGY RESPONSE BEHAVIOR OF RC STRUCTURES

N. HORI, N. INOUE and A. SHIBATA

Department of Architecture, Faculty of Engineering, Tohoku University
Aoba Aramaki Aoba-ku Sendai Miyagi, 980-77, JAPAN

ABSTRACT

Damage of structures by earthquake is generally estimated by indices based on maximum response. During earthquakes, however, damage of structures will be accumulated by effect of cyclic response. It is necessary to evaluate damaging potential of earthquakes not only by maximum response, but also by cyclic response.
In this study, damaging potential of earthquakes to structures is estimated by total input energy and damage of RC structures is evaluated by dissipated hysteretic energy. Based on inelastic response analyses using several observed ground motions, a procedure is presented to find yield force of RC structures corresponding to given ductility factor considering energy dissipation during earthquakes. This design concept permits a designer to choose acceptable level of structural damage explicitly.

KEYWORDS

reinforced concrete structure; single degree of freedom; inelastic response; energy response; cyclic response; damage parameter

INTRODUCTION

In the earthquake resistant design of buildings, it is necessary to evaluate damaging potential of earthquakes not only by maximum value such as maximum ground acceleration, but also by cyclic load effect to structures.

In this study, damage assessment of RC structures is carried out based on energy response. The damaging potential of earthquakes to structures is estimated by total input energy, which is considered to depend primarily on the earthquake property. It is considered that earthquake input energy can be used as the basic value in the earthquake resistant design of buildings.

Structures will dissipate the input energy of earthquakes as hysteretic energy and viscous damping energy. The dissipated hysteretic energy can be suitable index for evaluating the seismic damage of structures. In this study, energy response behaviors of several observed strong ground motions are studied, and a design concept considering both maximum response and cyclic response of structures is proposed.

ENERGY RESPONSE

Models for Analyses and Input Ground Motions

Inelastic models with single degree of freedom having various initial periods are analyzed for studying the damage characteristics of RC structures. As for a force-displacement relation, modified Takeda model (degrading trilinear type) in Figure 1 was used.

Initial period T_0 and yield point period T_y are given as follows.

$$T_0=\frac{2\pi}{\sqrt{K_0/m}} \quad , \quad T_y=\frac{2\pi}{\sqrt{K_y/m}}=\frac{2\pi}{\sqrt{0.3K_0/m}}=\frac{T_0}{\sqrt{0.3}} \simeq 1.83T_0 \tag{1}$$

where m is the mass of the system, K_0 is initial stiffness and K_y is yield point stiffness. The rigidity degrading ratio at yield point K_y/K_0 is assumed to be 0.3. In this study, the yield point period T_y is considered as an important parameter as well as the initial period T_0. Viscous damping coefficient which is proportional to tangential stiffness is assumed, and viscous damping ratio h is taken as 0.05.

For input ground motions, four observed strong ground motions are used. These ground motions are records of El Centro NS(1940 Imperial Valley), Japan Meteorological Agency(JMA) at Kushiro N63E(1993 Off Kushiro), Sylmar County Hospital NS(1994 Northridge) and JMA Kobe NS(1995 Hyogoken-Nanbu). Acceleration time histories are shown in Figure 2 and maximum values are shown in Table 1.

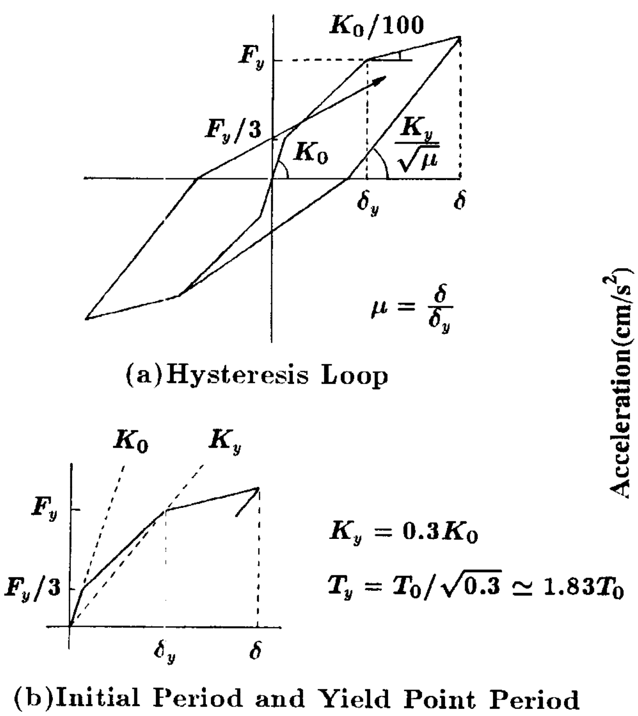


Fig.1. Model for Force-Displacement Relation

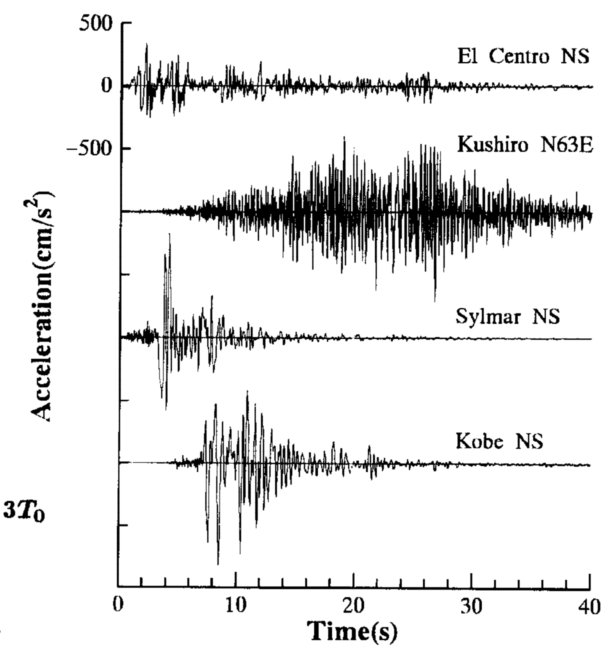


Fig.2. Observed Ground Motions

Table 1. Maximum Values of Input Ground Motions

	A_{max}(cm/s²)	V_{max}(cm/s)
El Centro NS	342	34
Kushiro N63E	711	33
Sylmar NS	827	122
Kobe NS	818	83

Input Energy

Damaging potential of earthquakes to structures is evaluated by input energy E_I given by equation(2), and damage of structures by energy dissipation is evaluated by E_H given by equation(3).

$$E_I = \int_0^T (-m\ddot{x}_0)\dot{x}dt = \frac{1}{2}mV_I{}^2 \tag{2}$$

$$E_H = \int_0^T F(x)\dot{x}dt \quad = \frac{1}{2}mV_H{}^2 \tag{3}$$

where $F(x)$, x, $\dot{x}$, $\ddot{x}_0$, T are restoring force of the system, relative displacement, relative velocity to the ground, ground acceleration, duration time, respectively. In many cases, these two energy values, E_I and E_H are presented by equivalent velocity V_I and V_H, respectively, as shown in equation(2) and (3).

Inelastic responses are represented by specified levels of ductility factor μ given by equation(4).

$$\mu = \frac{\delta}{\delta_y} \tag{4}$$

where δ is maximum displacement and δ_y is yield displacement. It should be noted that ductility factor μ is defined using yield displacement, and plastic deformation is observed for μ >1.0. And because trilinear type force-displacement relation considering cracking point is used, μ=1.0 does not mean elastic behavior.

Elastic response velocity S_V spectra and elastic input energy V_I spectra are shown in Figure 3 and Figure 4, respectively. Because input energy is relatively stable for various damping ratios, input energy for h=0.10 is taken as a representative one to be used for design purpose(Akiyama, 1985). Sylmar NS and Kobe NS have large input energy for relatively wide period range of structures. In case of Kushiro N63E, input energy of short period range is very large, while velocity response is not so much large at the same period range.

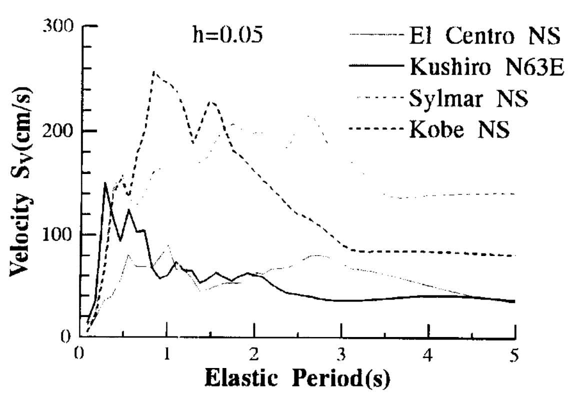


Fig.3. Elastic Response Velocity

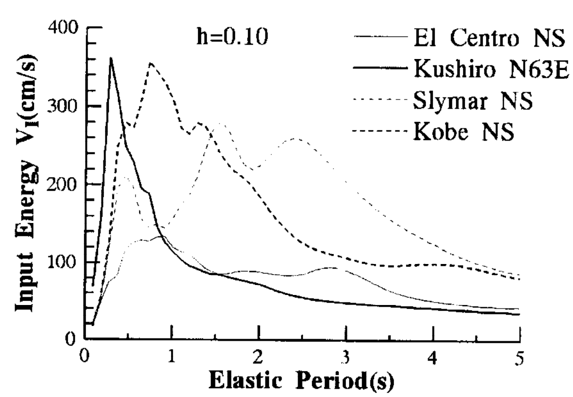


Fig.4. Elastic Input Energy

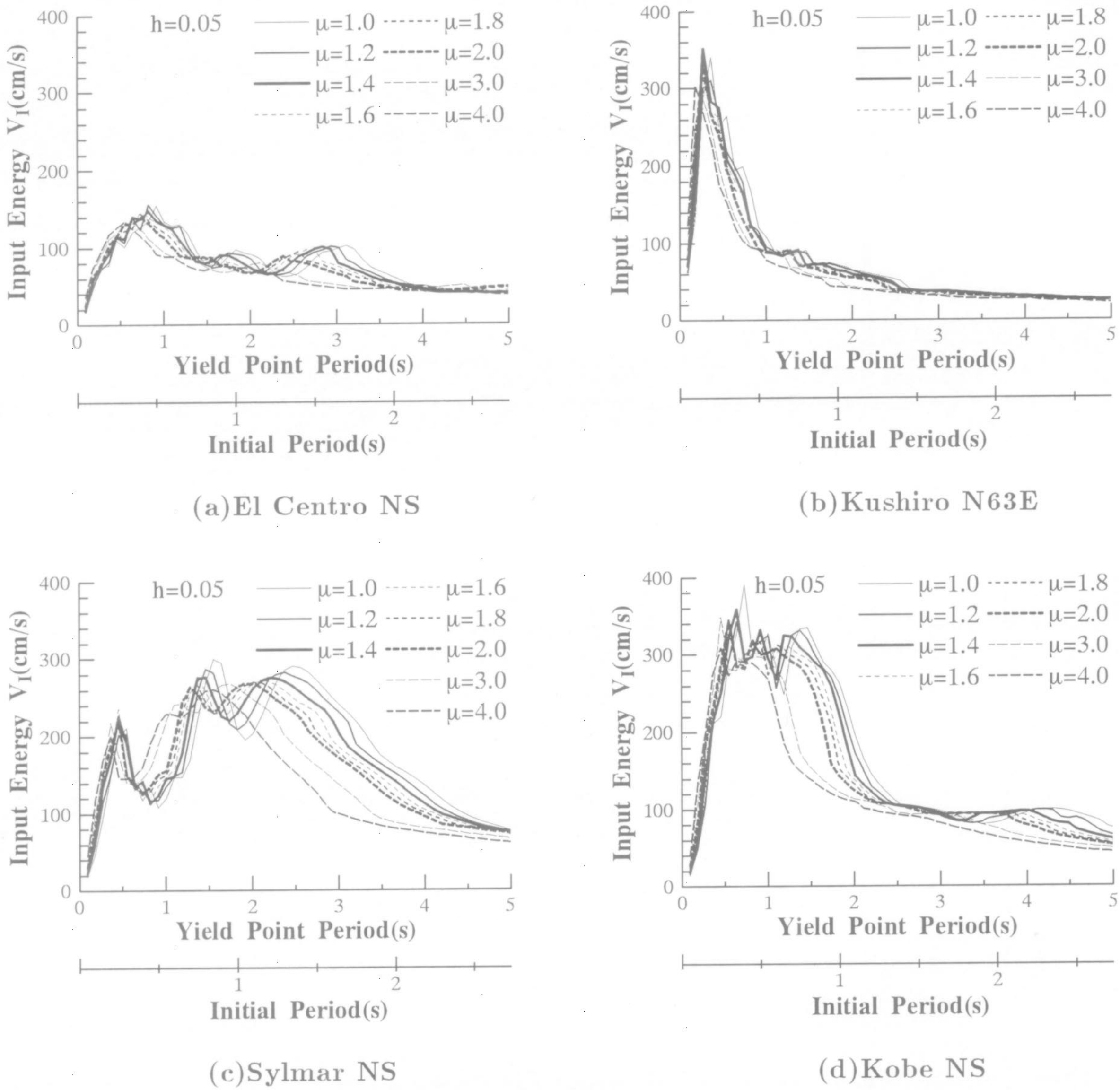


Fig.5. Inelastic Input Energy for Various Ductility Factor

Inelastic input energy V_I spectra for specified various ductility factor μ are shown in Figure 5. These spectra are computed for constant target ductility factor μ, and are presented both with initial period and corresponding yield point period in the horizontal axis. Input energy V_I seems to be independent of ductility factor μ. It is seen that elastic input energy spectra with elastic period in Figure 4 and inelastic input energy spectra with yield point period in Figure 5 are similar for each ground motion.

Energy Dissipation

Input energy is relatively stable with respect to ductility factor μ for each ground motion, but behavior of energy dissipation by structures is considered to change with structural properties. Ratio of dissipated hysteretic energy V_H to input energy V_I is shown in Figure 6. The larger the ductility factor μ is, the larger the dissipated hysteretic energy V_H becomes. El Centro NS and Sylmar NS seem to be not affected largely by period. But Kushiro N63E and Kobe NS are smaller comparatively in long period range. In the long period range, viscous damping is considered to dissipate much input energy of these ground motions.

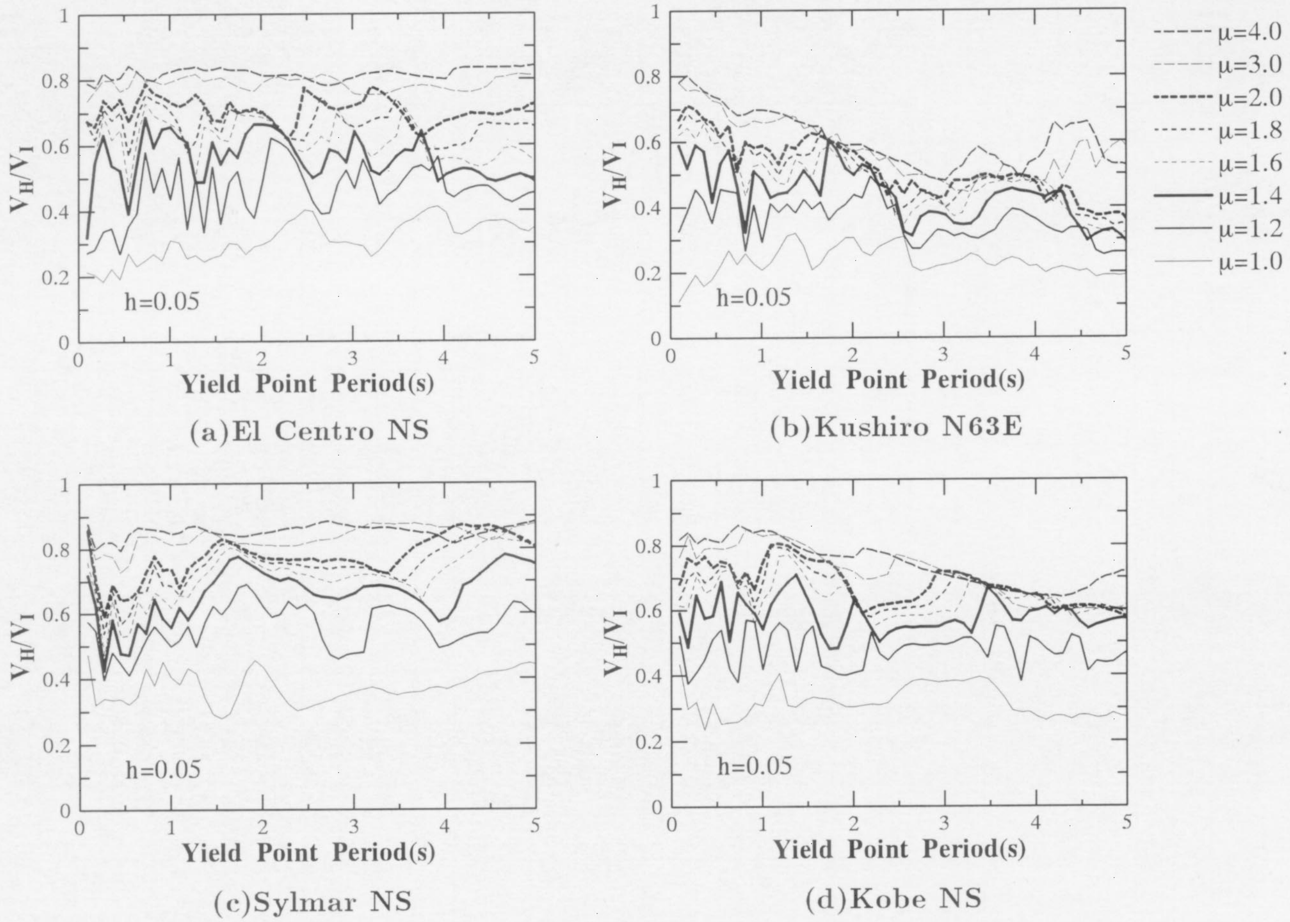


Fig.6. Ratio of Energy Dissipation for Various Ductility Factor

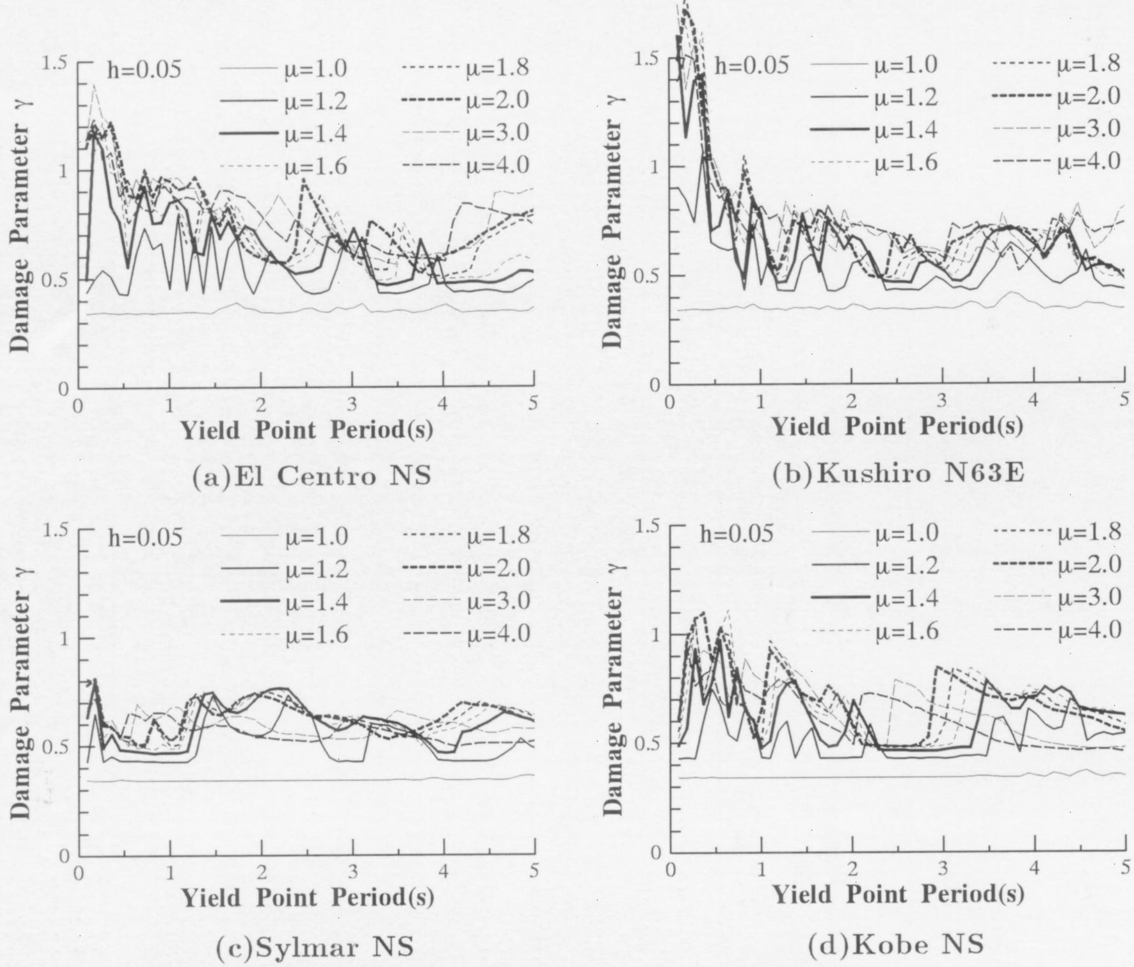


Fig.7. Damage Parameter for Various Ductility Factor

Fajfar studied equivalent single degree of freedom systems of buildings, and proposed damage parameter γ in equation(5), where F_y is yield force(Fajfar, 1992).

$$\gamma^2 \mu^2 = \frac{E_H}{F_y \delta_y} = \mu_e \tag{5}$$

In this study energy factor μ_e defined by equation(5) is used. The energy factor μ_e is dissipated hysteretic energy E_H normalized by unit energy $F_y\delta_y$, which is considered to represent characteristic of cyclic response. It is considered that maximum response or ductility factor μ, and cyclic response or energy factor μ_e, are related by the damage parameter γ, which may be called a response pattern parameter.

Damage parameter γ spectra for various values of ductility factor μ are shown in Figure 7. Damage parameter γ is considered to be affected largely by neither ground motions nor period of structures, except for very large values in the short period range of Kushiro N63E. By the above property of γ, energy factor μ_e tends to increase in proportion to μ^2 for medium and long periods as ductility factor μ increases.

INELASTIC DESIGN PROCEDURE

In the earthquake resistant design procedure of structures, it is necessary to define design limit and to find yield force F_y corresponding to the design limit. In the following, an inelastic design procedure for finding yield force F_y by considering energy dissipation during earthquakes is shown. As an example, a case of μ=2 is shown.

Input Energy

As mentioned above, input energy is considered to depend primarily on earthquake property, and inelastic input energy with yield point period is similar to elastic input energy with elastic period. In this study, elastic input energy spectrum for damping ratio h=0.10 is assumed to represent a model for inelastic input energy spectrum of each ground motion.

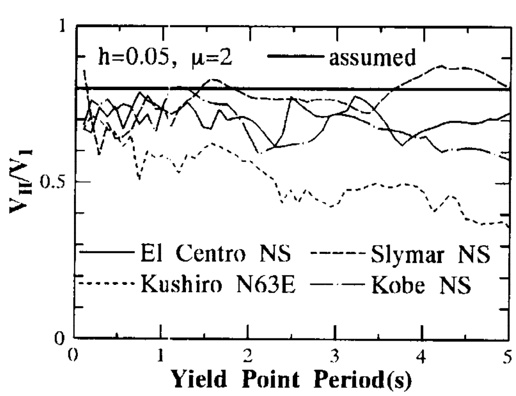


Fig.8. Ratio of Energy Dissipation for μ=2

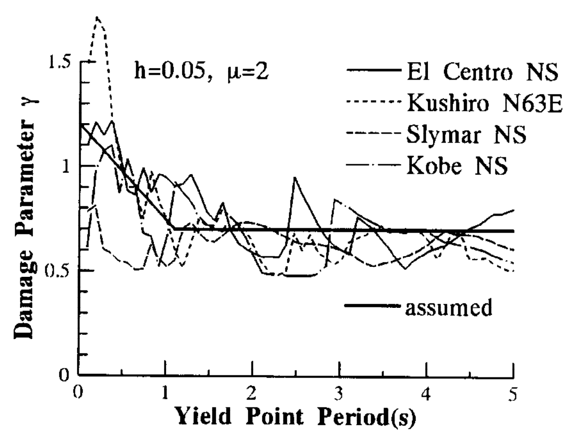


Fig.9. Damage Parameter for μ=2

Energy Dissipation

The input energy of ground motions is considered to be dissipated by structures with hysteretic energy and viscous damping energy. As shown in Figure 6, the ratio V_H/V_I varies with ground motion, ductility factor μ and period of structures, but upper limit seems to be about 0.8. Because larger V_H means larger damage, in this study $V_H = 0.8V_I$ is assumed as a limit value that structures can dissipate as hysteretic energy. Figure 8 shows the assumed V_H/V_I and the obtained V_H/V_I from actual responses corresponding to μ=2. It is to be noted that the above relation is for h=0.05 and that the effect of damping ratio h has to be studied separately.

Because damage parameter γ tends to become large in the period range shorter than predominant period of ground motion, Fajfar et al. defined the transition period assuming that the response spectra consist of the period ranges with constant response acceleration and constant velocity(Vidic et al., 1994, Fajfar et al., 1994). In this study, for simplification, γ is assumed to have linear relation in short period range($T_0 \leq$ 0.6sec) and constant value 0.7 in long period range($T_0 \geq$0.6sec), irrespective of ground motions(Shibata et al., 1995). Figure 9 shows the assumed γ and the obtained γ from actual responses corresponding to μ=2.

Yield Force

The equation(5) for the definition of damage parameter γ can be rewritten as follows.

$$\gamma^2\mu^2 = \mu_e = \frac{E_H}{F_y\delta_y} = \frac{\frac{1}{2}m{V_H}^2}{F_y \times \dfrac{F_y}{m\left(\frac{2\pi}{T_y}\right)^2}}$$

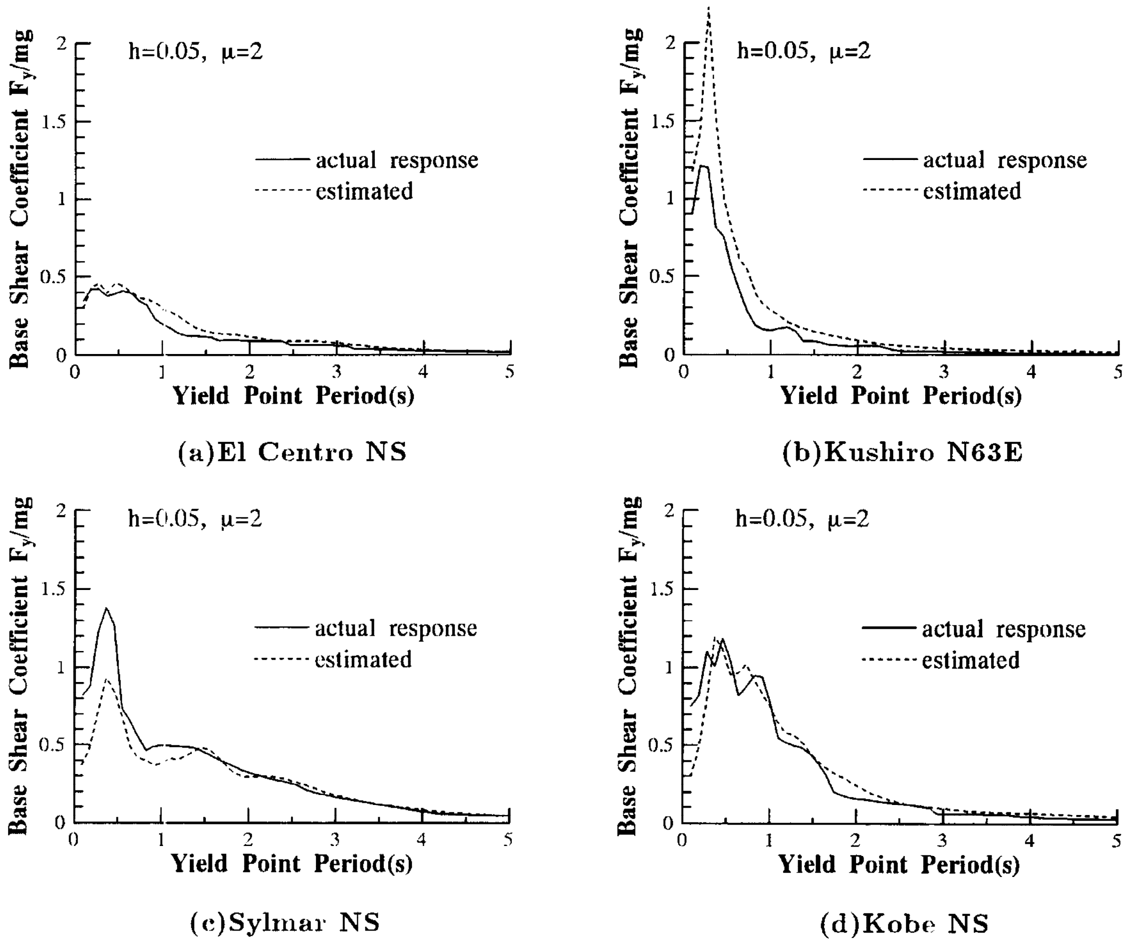
$$F_y = \sqrt{\frac{\frac{1}{2}m^2{V_H}^2\left(\frac{2\pi}{T_y}\right)^2}{\gamma^2\mu^2}} = \frac{\sqrt{2}\pi m V_H}{\gamma\mu T_y} \qquad (6)$$

Estimated F_y by equation(6) and necessary F_y obtained from actual responses corresponding to μ=2 are shown in Figure 10 in terms of base shear coefficient F_y/mg, where g is the gravity acceleration. There are some differences in the period range where modeling of V_H/V_I or γ is not suitable, but estimated F_y can evaluate the necessary yield force spectra approximately.

CONCLUSION

In this study damaging potential of earthquakes was evaluated by input energy, and difference of input energy properties and its influence to structures were investigated. Using this results, inelastic seismic design procedure based on energy response behavior of RC structures was proposed.

Necessary yield force corresponding to expected damage(μ=2 in case of this paper) can be estimated by using input energy spectrum of considering input ground motion. And it is considered that this inelastic seismic design procedure utilizing input energy spectra can be applied to the earthquake resistant design of RC structures.



(a)El Centro NS

(b)Kushiro N63E

(c)Sylmar NS

(d)Kobe NS

Fig.10. Yield Force for μ=2

REFERENCES

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

Bertero,R.D. and Bertero,V.V.(1992). Tall Reinforced Concrete Buildings: Conceptual Earthquake-Resistant Design Methodology, Report No. UCB/EERC-92/16, Earthquake Engineering Research Center, College of Engineering, University of California at Berkeley.

Fajfar,P.(1992). Equivalent Ductility Factors, Taking into Account Low-Cycle Fatigue, Earthquake Engineering and Structural Dynamics, Vol.21, No.10, pp.837-848.

Fajfar,P. and Vidic,T.(1994). Consistent Inelastic Design Spectra: Hysteretic and Input Energy, Earthquake Engineering and Structural Dynamics, Vol.23, No.5, pp.523-537.

Shibata,A., Inoue,N. and Hori,N.(1995). Inelastic Design of Earthquake Resistant R/C Buildings Considering Displacement and Energy Limits, Proc. Mete A.Sozen Symposium, Part III, ACI, Tapan Springs, Florida.

Vidic,T., Fajfar,P. and Fischinger,M.(1994). Consistent Inelastic Design Spectra: Strength and Displacement, Earthquake Engineering and Structural Dynamics, Vol.23, No.5, pp.507-521.