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A METHODOLOGY FOR SEISMIC DAMAGE ASSESSMENT OF SIMPLE DEGRADING STRUCTURES

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ABSTRACT

In the aseismic design of structures, it is generally necessary to allow for some level of damage for economic reasons. In order to implement this philosophy properly, models for assessing structural damage within the context of a random earthquake environment are required. Two seismic damage indexes for simple degrading structures are proposed herein. The first index is strictly defined by a linear function of the monotonic plastic displacement and energy ductilities. The second index is derived from the results of the numerical energy response analysis for SDOF systems subjected to strong earthquake motions as a more practical one.

KEYWORDS

Seismic damage index; degrading structure; energy response; displacement ductility; energy ductility; stiffness degradation; strength deterioration; strong earthquake motion.

INTRODUCTION

In the aseismic design of structures, some level of damage would be expected and permitted against a moderate earthquake that can be expected over the life of a structure. In order to implement this philosophy properly, models for assessing structural damage within the context of a random earthquake environment are required and a large number of damage indexes were suggested (Park *et al.*,1985, Hirao *et al.*, 1987, Nariyuki *et al.*,1994). Y.J.Park et al. proposed a practical seismic damage model definedby a linear function of the maximum deformation and the effect of cyclic loadings based on the analytical results of the static and dynamic test data for reinforced concrete members.

The objective of this study is to theoretically develop an exact model for evaluating the seismic damage of simple degrading structures, like T-shaped R/C bridge piers, and also examine its practical application based on numerical analytical results. The stiffness degradation and the strength deterioration are considered in the hysteretic model used in this study and also this model has the trilinear skeleton curve where the slope of the third segment is negative. For evaluating the degree of the seismic structural damage exactly, it is necessary to clarify the ultimate state of structures subjected to strong earthquake motions. In this study, the collapse of structures is defined as when the strength of these structures drops to *80%* of the initial one and the seismic damage index is precisely defined as the ratio of the plastic displacement at the target point on the skeleton curve to that at the collapse point.

In order to examine the damage index proposed herein for its validity and elucidate the relation between the monotonic plastic displacement and the general plastic displacement, numerical energy response analyses for single-degree-of-freedom (SDOF) systems were carried out using seven earthquake records.

EQUATIONS OF MOTION AND ENERGY EQUILIBRIUM

Equation of Motion

Simple degrading structures, like T-shaped R/C bridge piers, can be modeled as single-degree-of-freedom (SDOF) systems. The equation of motion for a SDOF system subjected to an earthquake ground excitation can be written as follows:

$$m\ddot{x} + c\dot{x} + Q(x) = -m\ddot{x}_G \tag{1}$$

in which m = mass of the structure; c = viscous damping coefficient; x = relative displacement at time t of the mass with respect to the ground; $\ddot{x}_G$ = ground acceleration. The dots represent differentiation with respect to time. $Q(x)$ is the restoring force for structures.

Energy Equilibrium Equation

The energy absorbed in the structure by the various behavioral mechanisms must be equal to the energy imparted to it. Integration of the differential equation of motion, Eq.1, with respect to the time t yields

$$\int_0^t m\ddot{x}\,\dot{x}\,dt + \int_0^t c\dot{x}^2 dt + \int_0^t Q(x)\,\dot{x}\,dt = \int_0^t -m\ddot{x}_G\,\dot{x}\,dt \tag{2}$$

The first term on the left-hand side of Eq.2 represents the kinetic energy of the structure considered. The second term represents the energy dissipated by viscous damping and the third term represents the sum of the hysteretic energy (W_H) plus the strain energy. The term on the right-hand side represents the energy input to the structure. At the end of the response of structures subjected to earthquake excitations, both kinetic energy and strain energy become zero. The hysteretic energy (W_H) is closely connected with the cumulative damage of structures under severe earthquakes (Kato *et al.*,1975, Zahrah *et al.*,1984, Hirao *et al.*,1986).

PLASTIC DISPLACEMENT AND ENERGY DUCTILITIES, μ_{DP} AND μ_H

The maximum plastic displacement ($|x|_{max}$ - x_y) and hysteretic energy (W_H) can be normalized as follows:

$$\mu_{DP} = (|x|_{max} - x_y)/x_y \tag{3}$$

$$\mu_H = W_H/(Q_y x_y) \tag{4}$$

in which x_y and Q_y represent the yield displacement and restoring force. μ_{DP} and μ_H can be very important parameters for assessing the structural damage and in this paper they are called "plastic displacement ductility and energy ductility" respectively.

HYSTERETIC MODEL

The hysteretic model used in this study is illustrated in Fig.1. A variety of hysteretic properties are obtained through the combination of the trilinear skeleton curve and the two parameters, α and β , whose values determine the properties of stiffness degradation and strength deterioration respectively. Though this model is similar to the 3-parameter model (Park *et al.*, 1985), the effect of pinching behavior is neglected and the slope of the third segment of the skeleton curve is negative.

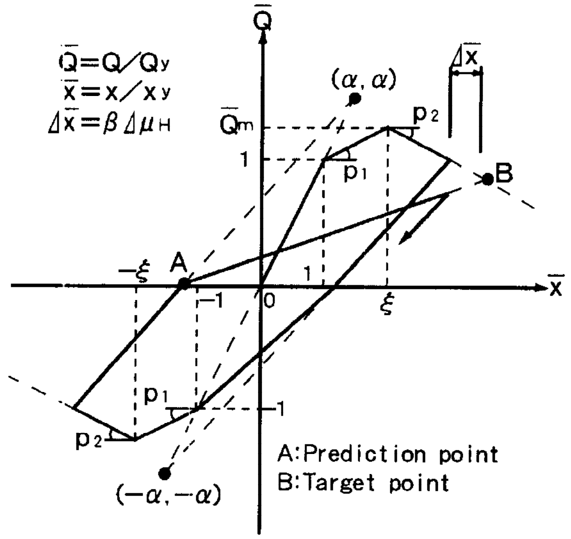


Fig.1. Hysteretic model.

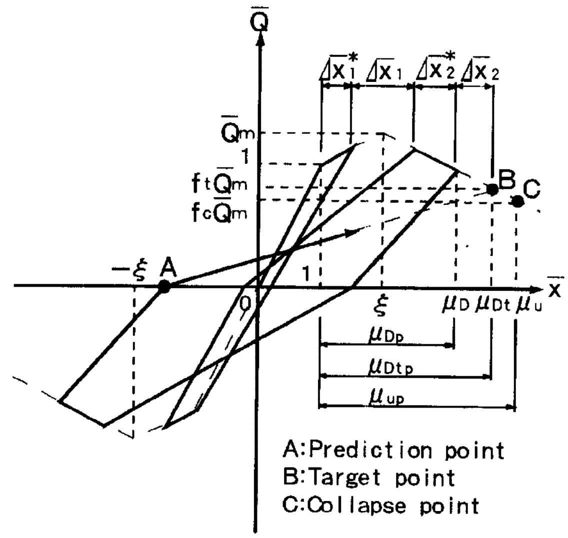


Fig.2. Definition of ultimate state.

As shown in Fig.1, the stiffness degradation is introduced by setting a common point (α,α) or $(-\alpha,-\alpha)$ on the extrapolated initial skeleton curve line, and assumes that the unloading lines aim at this point until they reach the x-axis. $\Delta\bar{x}$ represents the normalized displacement increment at the target point on the skeleton curve due to the dissipated hysteretic energy and is expressed as follows:

$$\Delta\bar{x}=\beta\Delta\mu_H \tag{5}$$

in which $\Delta\mu_H$ is the energy ductility increment per cycle. β is a non-negative constant which emphasizes the strength deterioration per cycle.

DEFINITION OF ULTIMATE STATE

In order to rationally evaluate the degree of the structural damage caused by strong earthquake motions, the first priority must be given to the definition of the ultimate state. In this study, the collapse of structures is defined as when the ratio of the strength of these structures to the initial one drops to the prescribed ratio f_c shown in Fig.2. f_c may be called "degraded strength ratio" and its value is assumed to be *0.8* in this study. μ_U is the ultimate displacement ductility under monotonic loading.

As a result of the increment or alternation of inelastic deformation, the target point *B* on the skeleton curve moves toward the collapse point $C(\mu_U, f_c\bar{Q}_m)$. When the displacement ductility, μ_{Dt}, on the target point *B* agrees with or exceeds μ_U on the collapse point *C*, structures collapse.

DAMAGE INDEX , D_I^*

In this study , we defined the seismic damage index D_I^* for measuring the structural damage as follows:

$$D_I^* = \frac{\mu_{Dtp}}{\mu_{Up}} \tag{6}$$

in which $\mu_{Dtp}=\mu_{Dt}-1$ and $\mu_{Up}=\mu_U-1$ as shown in Fig.2. The damage index D_I^* was normalized to produce values between *0* and *1*. Under elastic response, the value of D_I^* is less than or equal to zero. $D_I^*\geqq 1$ signifies the structural collapse. μ_{Dtp} is based on a linear combination of monotonic increased deformation and energy absorption as follows:

Table 1. List of earthquake records used in this study.

Earthquake record component	$\ddot{x}_{Gmax}$ (gal)	T_p (sec)
El Centro, S00E, Imperial Valley Earthquake, USA(1940)	314.7	0.68
Ferndale, N44E, Eureka Earthquake, USA(1954)	155.7	1.58
Los Angeles, N00W, San Fernando Earthquake, USA(1971)	250.0	0.32
Muroran, S-241, N-S, Tokachioki Earthquake, Japan(1968)	117.4	0.42
Hachinohe, S-252, N-S, Tokachioki Earthquake, Japan(1968)	264.1	2.73
Kushiro, S-733, N-S, Nemurohantouoki Earthquake, Japan(1973)	186.8	1.41
Kobe, N-S, Hyougoken Nambu Earthquake, Japan(1995)	818.0	0.69

$$\mu_{Dtp} = \mu_{Dp}^{*} + \beta\mu_{H} \tag{7}$$

in which $\mu_{Dp}^{*} = \Delta\bar{x}_1^{*} + \Delta\bar{x}_2^{*} + \cdots$ and $\beta\mu_H = \Delta\bar{x}_1 + \Delta\bar{x}_2 + \cdots$ as shown in Fig.2. On referring to Eqs.6 and 7, the damage index D_I^{*} may be rewritten as

$$D_I^{*} = \frac{1}{\mu_{Up}}(\mu_{Dp}^{*} + \beta\mu_H) = D_{ID}^{*} + D_{IH} \tag{8}$$

in which μ_{Dp}^{*} is called "monotonic plastic displacement ductility" here. D_{ID}^{*} and D_{IH} represent the damages due to the monotonic and alternating plastic deformations respectively.

INPUT GROUND MOTIONS AND SEISMIC STRENGTH RATIO , R_I

We selected seven earthquake records shown in Table 1 as input ground motion. In this Table, $\ddot{x}_{Gmax}$ and T_p represent the absolute maximum acceleration and the predominant period respectively. These records considerably differ from each other in the periodic characteristics.

It is convenient to divide Eq.1 by the product of m and x_y and rewrite it as

$$\ddot{\bar{x}} + 2h\omega_0\dot{\bar{x}} + \omega_0^2\bar{Q}(\bar{x}) = -\omega_0^2 R_I \ddot{z}_G \tag{9}$$

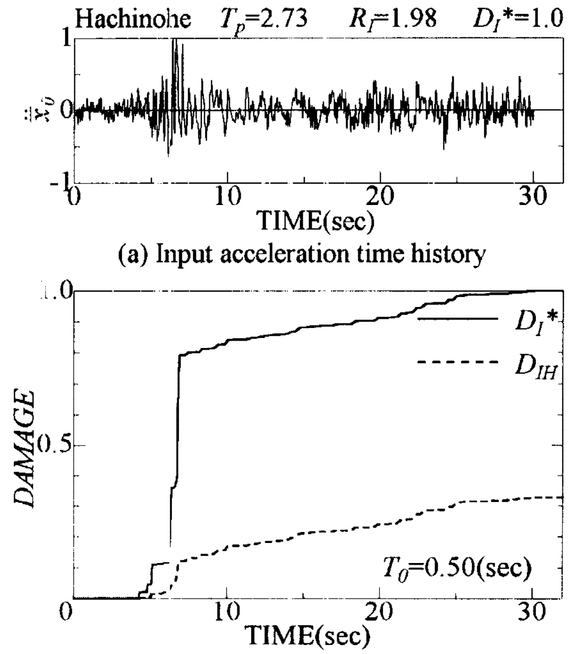
in which $\bar{x} = x/x_y$, $\dot{\bar{x}} = \dot{x}/x_y$, $\ddot{\bar{x}} = \ddot{x}/x_y$, $\bar{Q}(\bar{x}) = Q(x)/Q_y$, ω_0 = undamped circular frequency, h = viscous damping factor, $\ddot{z}_G = \ddot{x}_G/\ddot{x}_{Gmax}$ and R_I is the seismic strength ratio defined as follows:

$$R_I = \frac{m\ddot{x}_{Gmax}}{Q_y} \tag{10}$$

In order to calculate the seismic response of nonlinear SDOF systems, we solved Eq.9 by using the linear acceleration method. Therefore, the amplitude of each input acceleration wave was normalized to correspond to the prescribed value of R_I.

TIME HISTORY OF SEISMIC STRUCTURAL DAMAGE

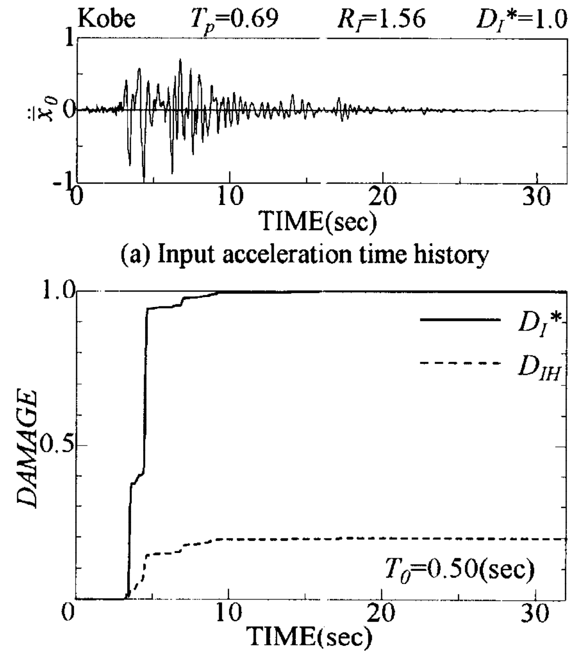
Using the damage index, D_I^{*}, given by Eq.8, the damage for structures subjected to Hachinohe and Kobe ground motions is evaluated as shown in Figs.3 and 4. The values of the structural parameters except natural period, T_0 , are established to be standard data given in Table 2. T_0 is equal to *0.5*(sec) as shown in these figures. By using the method of trial and error, the seismic strength ratio, R_I , was determined as D_I^{*} became equal to *1.0* at the end of the structural response. In these figures, the difference at any time between the curves for D_I^{*} and D_{IH} represents D_{ID}^{*} shown in Eq.8.



(a) Input acceleration time history

(b) Time history of damage D_I*, D_{IH}

Fig.3. Time history of damage D_I* for Hachinohe record.



(a) Input acceleration time history

(b) Time history of damage D_I*, D_{IH}

Fig.4. Time history of damage D_I* for Kobe record.

From these figures, it is shown that the damage, especially D_{ID}*, rapidly increases during the strong motion and after that, only the D_{IH} damage gradually increases. The latter tendency may be remarkable in the case that the predominant period of input acceleration wave, T_p, is much longer than the natural period, T_0, and in that case, the ratio of D_{IH} to D_I* at the end of response is relatively large as for example, that represented by the result shown in Fig.3.

The facts as described above show that the damage index, D_I*, proposed here can be very reasonable.

RELATION BETWEEN μ_{DP}* and μ_{DP}

We defined the seismic damage index D_I* (Eq.8) based on a linear combination of μ_{Dp}* and μ_H and showed that this index was relatively rational in the preceding chapter. On the other hand, the combination of the plastic displacement and energy ductilities, μ_{DP} and μ_H, has been employed to evaluate the seismic structural damage (Nariyuki *et al.*,1994).

The relation between μ_{Dp}*/μ_{Up} and μ_{Dp}/μ_{Up} in the five kinds of degrees of damage is shown in Fig.5. The values of the structural parameters are given in Table 2 and the seven earthquake records shown in Table 1 were used as input ground motions.

As shown in Fig.5, the plots exist in the part bordered by two strait lines which intersect the origin and the upper border line is close enough to the diagonal. This diagonal naturally represents the case of μ_{Dp}*$=\mu_{Up}$, which corresponds to the relation between μ_{Dp}* and μ_{Dp} for static repeated loading with the symmetric displacement amplitude.

In order to make the relation between μ_{Dp}* and μ_{Dp} more clear, Fig.5 was rearranged as Fig.6(a). Fig.6 (b) shows the coefficient of variation (*COV*) of *a* which is the ratio of μ_{Dp}* to μ_{Dp} defined by Eq.11 and can range between *0.0* to *1.0*.

Table 2. Standard value of each parameter.

parameter	standard value
p_1	0.1
p_2	-0.1
ξ	5.0
α	2.0
β	0.1
$T_{0(sec)}$	0.1, 0.25, 0.5 0.75, 1.0
h	0.05
f_c	0.8

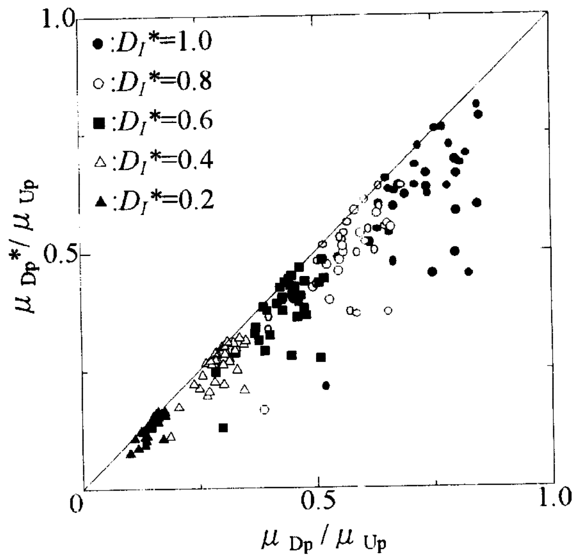


Fig.5. $\mu_{Dp}-\mu_{Dp}^*$ relationship.

$$a = \frac{\mu_{DP}^*}{\mu_{DP}} \tag{11}$$

As can be seen from Fig.6, the values of a (= μ_{Dp}^*/μ_{Dp}) are distributed in the region of $0.4\sim1.0$ and as the degree of the structural damage becomes higher, the mean value of the ratio, a_M, decreases slightly and almost linearly. The coefficient of variation (COV) shows the tendency contrary to a_M and is within the region of $0.1\sim0.2$.

In this study, changing the values of the structural parameters systematically, the energy response analyses were carried out. Fig.7 shows an example to see the effect of each parameter on a_M and COV. We can see that while the structural parameters except β have a small effect on a_M and COV, β greatly influence them.

Fig.8 shows the relation between a_M and T_0 in the case of $D_I^* = 1.0$ shown in Fig.7. As can be seen from Fig.8, as T_0 becomes longer, a_M increases and COV decreases generally. The effect of β on a_M is relatively large when T_0 is short. In the case of $T_0 \geqq 0.5$(sec), the effects of T_0 on a_M and COV are relatively small and the values of a_M and COV are about 0.9 and 0.1 respectively. On the other hand, in the case of $T_0 < 0.5$(sec), a_M is about 0.7 while COV is varying in the region of about $0.1 \sim 0.3$.

By using the ratio, a , defined by Eq.11, Eq.8 can be written as

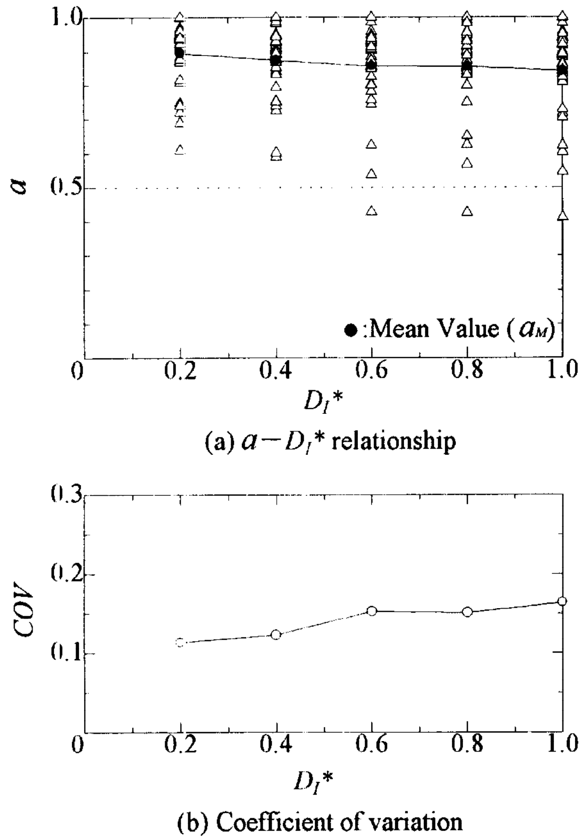
$$D_I^* = \frac{1}{\mu_{UP}}(a\mu_{DP} + \beta\mu_H) \tag{12}$$

In practice it is necessary to use some representative value (a_r), for instance, the mean value, etc. in place of the exact value (a) . The damage index, D_I, which includes a_r may be redefined, from Eq.12, by

$$D_I = \frac{1}{\mu_{UP}}(a_r\mu_{DP} + \beta\mu_H) \tag{13}$$

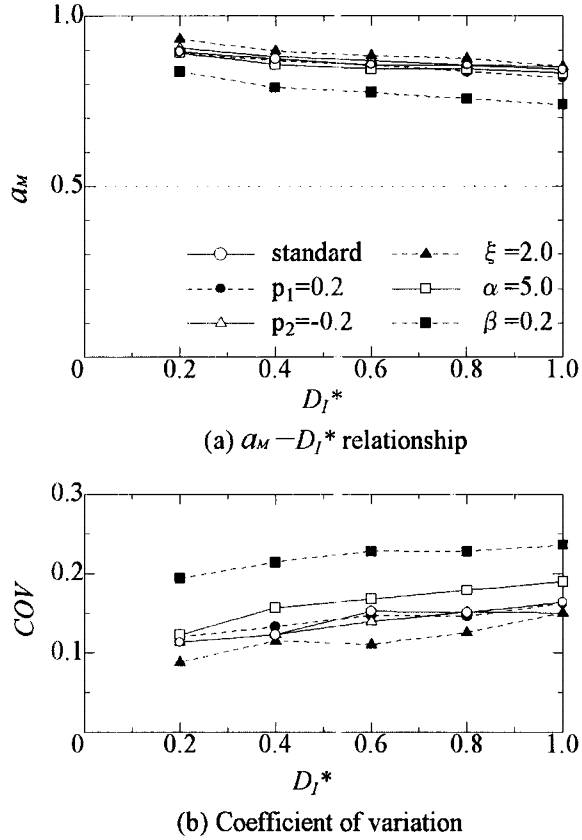
AN EXAMPLE OF SEISMIC DAMAGE ASSESSMENT USING D_I

As an application of the damage index, D_I , defined by Eq.13, the time history of D_I for El Centro record is shown in Fig.9. The values of the structural parameters are the standard values as shown in Table 1 and



(a) $a-D_I$* relationship
(b) Coefficient of variation

Fig.6. $a-D_I$* relationship (standard case).



(a) a_M-D_I* relationship
(b) Coefficient of variation

Fig.7. Comparison of a_M of 6 cases.

the input strength ratio, R_I, is established as the structure has just collapsed at the end of its response (D_I*= *1.0*). As to the value of a_r, *1.0* and *0.88* signify the least upper bound and the mean (a_M) respectively.

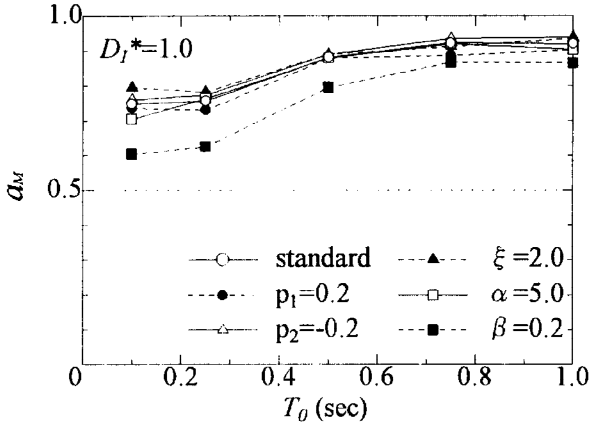
The damage curves obtained by using the damage index , D_I , with a_r = *1.0* and a_r = a_M for El Centro and Kushiro records are shown in Figs.9(a) and 9(b) respectively. As can be seen from these figures, by using D_I with a_r = *1.0*, the seismic damage is just overvalued. This suggests that the index D_I with a_r= *1.0* may be the good index for relatively accurately evaluating the seismic damage of structures.

CONCLUSIONS

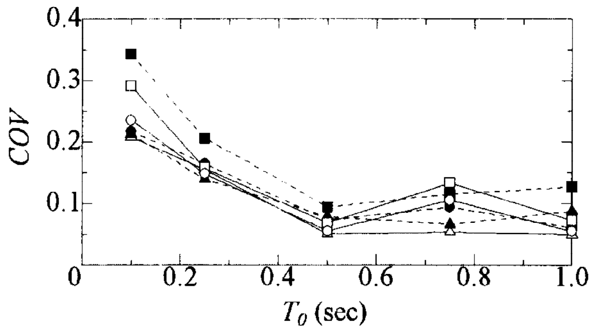
Two indexes, D_I* and D_I, for evaluating the degree of the seismic damage of simple degrading structures are presented herein. The first index D_I* (see Eq.8), is strictly defined by a liner function of the monotonic plastic displacement and energy ductilities. By using the index D_I*, the seismic structural damage can be rationally assessed as follows :

(1) $D_I^* \leqq 0$: nondamaged, (2) $0 < D_I^* < 1$: damaged, (3) $D_I^* \geqq 1$: collapse

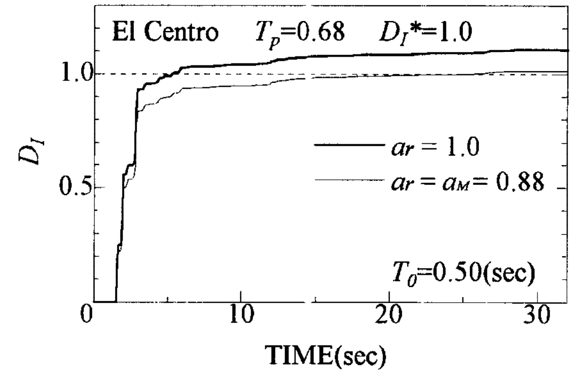
The second index, D_I (see Eq.13), is obtained by introducing the coefficient, a_r , which is the representative value of the ratio of the monotonic plastic displacement to the general plastic displacement into the index D_I*. By using the index D_I with a_r = *1.0*, the damage of structures subjected to strong earthquake motion can be always slightly overestimated. The index D_I seems to be a practical index for evaluating the seismic damage of degrading structures.



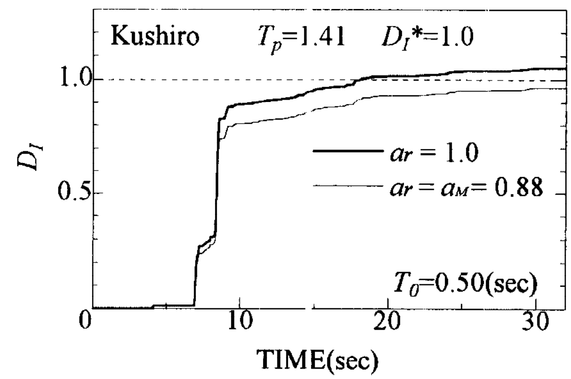
(a) $a_M - T_0$ relationship



(b) Coefficient of variation



(a) Damage D_I for El Centro record



(b) Damage D_I for Kushiro record

Fig.8. Effect of T_0 on a_M.

Fig.9. Time history of damage D_I for El Centro and Kushiro records.

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