CORRELATION OF STRUCTURAL DAMAGE INDEXES WITH STRONG GROUND MOTION PARAMETERS

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ABSTRACT

Comprehensive studies have been carried out to investigate the correlation between structural damage indexes (SDIs) and a number of widely used ground motion intensity (GMI) parameters. To this, Nonlinear time–history analyses of steel and concrete frames are performed under a set of many ground motion records. The frames reflect the features of typical low- to medium-rise structures. The records used in nonlinear time history analyses have intensities to represent a wide range of seismic forces that impose various degrees of elastic as well as inelastic response of the frames. The SDIs were compared with the GMI parameters and correlations between them were investigated through coefficients of correlation and determination.

The results revealed that spectrum intensity parameters, having the strongest correlation, are superior to other parameters such as peak ground velocity, peak ground acceleration, and spectral acceleration. It was concluded that both peak ground acceleration/peak ground velocity (A/V) ratio and effective duration significantly influence the damage potential of ground motions, although they are not represented appropriately by the spectral definitions of earthquake excitations in seismic design codes. The ground motion A/V range had a significant effect not only on peak inelastic response but also on hysteretic energy dissipation and stiffness deterioration of stiffness degrading systems. Also, improved damage spectra were proposed to quantify the damage potential of recorded earthquake ground motion. The improved damage spectra are promising for assessment of the performance-based seismic vulnerability of existing structures.

INTRODUCTION

One of the most important steps in the earthquake-resistant design of buildings is the proper representation of earthquake effects. A common approach in current seismic design practice is to characterize the earthquake effects by simple intensity measure. This measure may not be able to completely consider damage potential of ground motions. Therefore quantification of the potential for damage of earthquake ground motion is one of the fundamental issues in earthquake engineering. A reliable measure of the damage potential of ground shaking has a wide range of applications for analysis and design of new structures as well as for seismic evaluation of existing facilities.

Consequently, reliable and simple intensity measures are required to estimate the damage potential of ground motions. several simple to elaborate intensity measures were proposed, each depending on either ground motion parameters only, namely, peak ground acceleration (PGA), peak ground velocity (PGV), and cumulative absolute velocity (CAV) [Electric Power Research Institute (EPRI), 1988], or on both ground motion and structural characteristics, namely, spectral acceleration (S_a), spectral velocity (S_v), and acceleration spectrum intensity (ASI) (Von Thun et al., 1988). Other common intensity parameters that may be calculated from the ground motion trace are Arias intensity (AI), and characteristic intensity (I_c) (Kadas et al., 2011).

In recent years, poor correlation of structural damage, especially with PGA, has been illustrated by many researchers (Akkar and Ozen, 2005; Yakut and Yilmaz, 2008). Spectral intensity measures are preferred over other measures because they are simple, needing no detailed analysis, and they incorporate the knowledge of the structure.

Spectral acceleration at the fundamental period of the structure, S_a, is a widely employed parameter obtained from the pseudo acceleration response spectrum (Luco and Cornell, 2007). Other most common parameters that are computed from the response spectra of the ground motion record are Housner intensity (HI) (Housner , 1952), effective peak acceleration (EPA), acceleration spectrum intensity (ASI), and velocity spectrum intensity (VSI) (Von Thun et al., 1988). The EPA is computed as the average of the spectral acceleration values of the elastic pseudo acceleration spectrum (5% damped) in the period range of 0.1–0.5 s divided by a constant value of 2.5. The HI and VSI are similar parameters calculated as the area under the velocity spectrum (5% damped) of the ground motion between the period range of 0.1–2.5 s. The only difference being that HI is calculated from the pseudo velocity spectrum, whereas VSI is based on the absolute velocity spectrum. These parameters capture important aspects of the amplitude and frequency content in a single parameter. ASI is defined as the area under the elastic pseudo acceleration spectrum (5% damped) between the periods of 0.1–0.5 s (Von Thun et al., 1988). This parameter was introduced to characterize strong ground motion for analysis of concrete dams, which generally have fundamental periods of less than 0.5 s; however, it is believed to correlate better with the response of other structures if their period range (i.e., 0.1–2.0 s for buildings) is employed.

Evaluation of some of mentioned GMI parameters to determine their correlation with structural response has been performed by several researchers. Akkar and Özen (2005) investigated the correlation of PGV and PGA with inelastic spectral displacement based on analyses of single-degree-of freedom (SDOF) systems. Their observations revealed a better correlation of PGV than PGA for the short-to-medium period range. Zhu et al. (1988) used three sets of real earthquake records to represent seismic ground motions in the low, normal, and high A/V (peak ground acceleration/peak ground velocity) ranges. They showed that the systems subjected to ground motions in the low A/V range can sustain much more significant peak inelastic deformation than those subjected to ground motions in the high A/V range. Multi-degree-of-freedom based evaluation of some energy and acceleration-related parameters have been carried out by Elenas and Meskouris (2001) based on limited analyses. They observed that spectral acceleration, AI, and seismic input energy correlate well with damage. Riddell (2007) investigated the efficiency of 23 ground motion intensity measures that have been proposed over the years. The correlation of these GMI parameters with SDIs were studied for different period ranges. The results indicated that none of the ground motion intensity parameters were satisfactory over the entire frequency range.

As inferred from the earlier research discussed above, a comprehensive evaluation of the most widely employed GMI parameters, recommended as indicators of the damage potential of ground motions, is needed. In view of this, many concrete and steel frames are employed to study the relationship between seismic response and GMI parameters. These frames were analyzed under many ground motion records to determine the maximum structural demands from nonlinear time–history analyses. These results were then examined with respect to GMI parameters to evaluate their correlation. PGA, PGV, S_a, ASI, VSI, I_c, I_F, CAV, AI, HI, EPA, A/V or (V/A) and D_c are the most commonly used GMI parameters.

DEFINITION of THE SPECTURAL INTENSITY MEASURES

This section is based on research by Kadas et al. (2011). Spectral acceleration at the fundamental period of the structure is a widely used demand parameter in the assessment of damage potential of the ground excitations. However, the same structure subjected to different ground motions that have the same linear deformation potential considering the spectral acceleration of the ground motion calculated at the fundamental period of the structure can yield different levels of inelastic deformation. This outcome proves that the applied ground motion intensity and the capacity of the structure determine the response behavior and also that the frequency characteristics of the ground motion have a significant effect on the dynamic response. It is proposed that the shape of the response spectrum along the period elongation path (an increasing or a decreasing trend in the spectral acceleration with respect to spectral acceleration corresponding to T_i (Fig. 1)) reveals the damage potential or severity of the seismic demand in view of seismic capacity of the structure. The area below an ascending spectrum will be larger than the area below a descending spectrum, indicating a larger seismic demand.

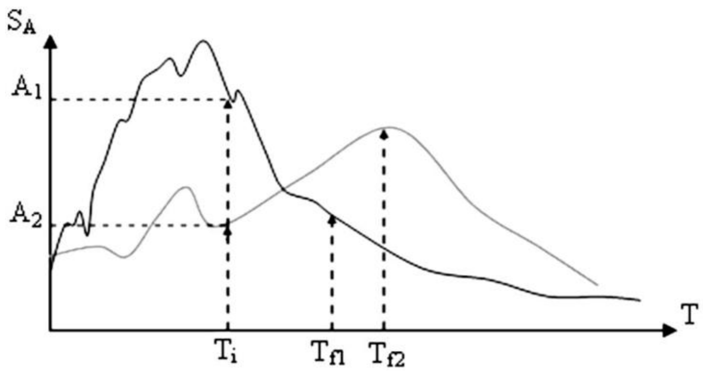

Figure 1. Ascending and descending spectra (Kadas et al., 2011)

At this point, we refer to the works of Housner (1952) and Von Thun et al. (1988) to establish a basis for a new spectral intensity measure. There exist several spectral intensity measures that quantify the damage potential of ground motions. Von Thun et al. (1988) proposed a equation that calculates the area below the acceleration response spectrum between the periods 0.1 and 0.5 s. For short-to-medium period range of the spectrum using the same analogy, this intensity measure is modified by introducing new period ranges as shown in Eq. (1), which relies on the elastic acceleration response spectrum plot illustrated in Fig. 2:

$$I_H = \int_{T_i}^{T_f} S_A(T,\xi)dT \tag{1}$$

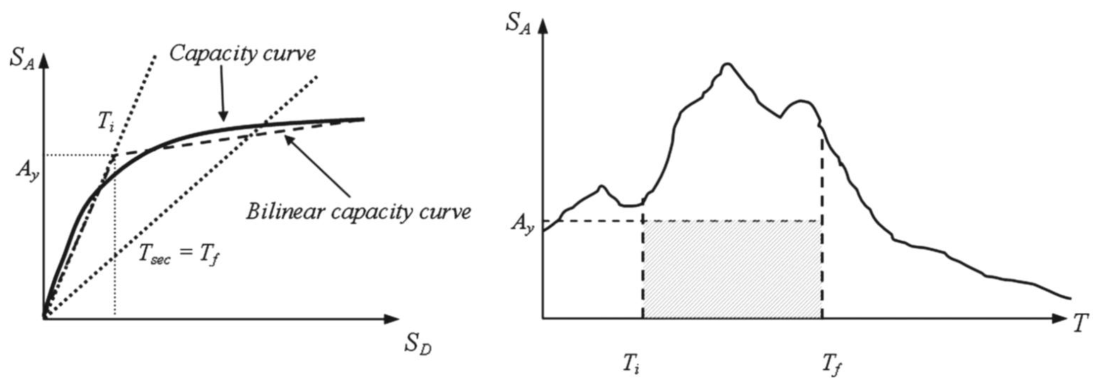

Figure 2. Pictorial description of the intensity measure (Kadas et al., 2011)

Eq. (1) calculates the area below the elastic acceleration response spectrum between the fundamental period (T_i) and calculated softened period (T_f). By normalizing the calculated area by dividing to the area below the yield base acceleration level (A_y), a dimensionless intensity measure can be obtained, which is given by Eq. (2). This intensity measure incorporates the capacity of the structure as well:

$$I_a = \frac{1}{(T_f - T_i)A_y} \int_{T_i}^{T_f} S_A(T,\xi)dT \tag{2}$$

The value calculated from Eq. (2) can also be used to determine whether a ground motion will cause an elastic or inelastic response on structural system, depending on capacity of the structure (A_y).

To differentiate between an ascending and a descending spectrum more accurately, the expression given in Eq. (2) is modified by weighing the area enclosed by the initial and final periods about the initial period. The new equation takes the following form:

$$I_{am} = \frac{1}{(T_f - T_i)A_y} \int_{T_i}^{T_f} S_A(T,\xi)(T - T_i)dT \tag{3}$$

The terms in front of the integral sign take into account the capacity of the structure, which is related to the damage experienced by the structure under a given ground motion. This intensity measure accounts for the approximate capacity of the structure that may be obtained through approximate analyses, such as the ones reported by Applied Technology Council (ATC, 2005). It can also be obtained from pushover analysis prior to the comprehensive nonlinear time-history analyses. The intensity measures given in Eqs. (1)–(3) rely on the area under the acceleration spectrum, which is an indication of the force imparted on the structure. An additional modification in Eq. (3) incorporates the capacity of the structure and the shape of the spectrum, through the term T- T_i, beyond the initial period. For a given spectrum, a structure with low capacity leads to a larger intensity. Similarly, a structure with ascending spectrum yields a larger intensity that would result in larger nonlinear response.

The proposed intensity measure strongly depends on the values selected for initial (T_i) and softened (T_f) periods to compute the integral given in the previous equations. Eq. (4), obtained by the curve fitting through the results of analyses carried out by Kadas et al. (2011), is recommended for the approximate calculation of the elongated period (T_f). As can be seen, the period elongation starts when the structure responds in the inelastic range [$Sa(T_i) > A_y$], saturating at the value of nearly $T_f = 2.0T_i$:

$$T_f = 1.07 \times T_i \times \left[\frac{S_a(T_i)}{A_y}\right]^{0.45} \leq 2.0T_i \tag{4}$$

The frame employed is two bays two stories reinforced concrete frame (story height = 3^m) that has dynamic properties including the first mode period of 0.3 sec, corresponding effective period of 0.36 sec, first modal participation ratio of 1.339, and modal mass contribution factor of 0.815. These values suggest that the response of the selected frames is dominated by the first mode behavior.

Analyses results displayed that the best correlation between the intensity and maximum interstory drift ratio (MIDR), with the least dispersion in data, was obtained with the intensity measure calculated using Eqs. (1) and (3). A typical case is shown in Fig. 3.

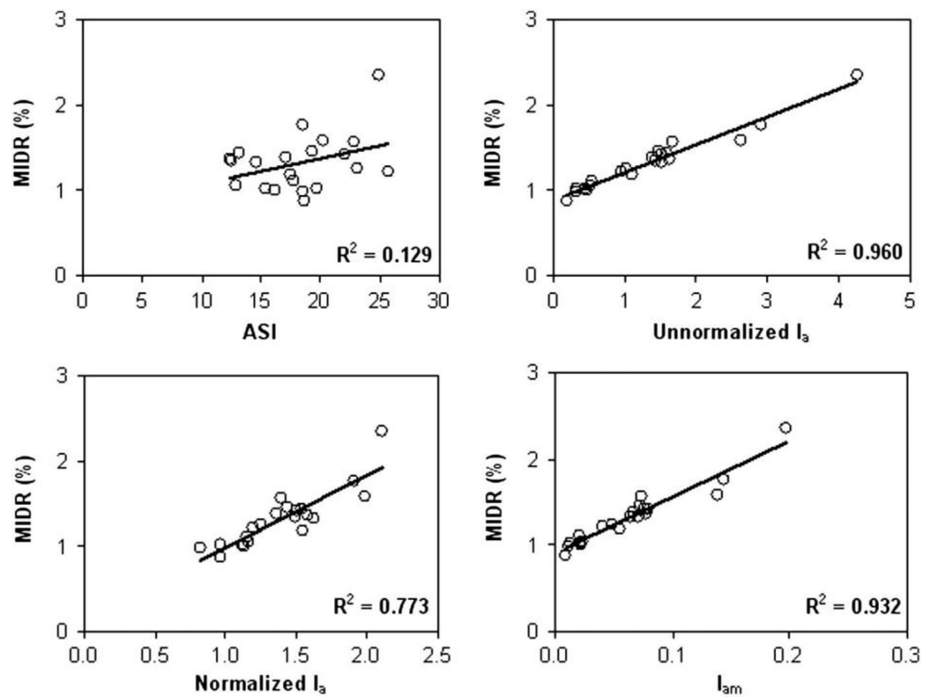

Figure 3. Correlation between the intensity measures and MIDR for the frame F2S2B2 (Kadas et al., 2011)

To evaluate the correlation between the proposed intensity measure and the MIDR, the coefficient of determination (R^2) and Pearson's correlation coefficient (r) values are computed. R^2 value is between 0 and 1, and reveals how closely the estimated values for the trend line correspond to actual data. As the value of R^2 becomes closer to 1, the trend line becomes more reliable. Pearson's correlation coefficient represents the extent of a linear relationship between the two data sets (T_f /T_i and I_a, I_{am}). The value of r ranges from -1 to 1 and is equal to the square root of the R^2 value computed for the linear fit. The dispersion in data is much less in the cases of unnormalized I_a and I_{am}. Despite Eqs. (1) and (3) giving similar results for the correlation, the intensity measure given in Eq. (3) is superior because it accounts for the shape of the spectrum and the yield capacity of the structure, which are important parameters affecting the response of the structure.

EVALUATION of SELECTED INTENSITY PAPAMETERS

This section is based on research by Yakut and Yilmaz (2008). As mentioned above, AI was proposed by Arias (1970) as a GMI related to the energy content of the ground motion and is calculated using Eq. (5), where t_d indicates the total duration of the ground motion and *a(t)* represents the acceleration time history. CAV, the absolute area under the ground motion trace [Eq. (6)], was introduced by EPRI (1998). Kramer and Mitchell (2006) stated that the cumulative absolute velocity shows a good correlation with structural damage :

$$AI = \frac{\pi}{2g}\int_0^{t_d} a(t)^2\,dt \tag{5}$$

$$CAV = \int_0^{t_d} |a(t)|\,dt \tag{6}$$

The characteristic intensity (I_c) *(*Ang, 1990) takes into account both the amplitude and duration-related parameters and is expressed by Eq. (7). Fajfar et al. (1990) proposed an intensity measure, given in Eq. (8), which considers two basic ground motion parameters; PGV and the significant duration of strong motion (t_e), defined as the time interval between 5 and 95% AI accumulation (Bommer and Martinez-Pereira, 1999). They stated that this intensity measure can adequately represent the damaging potential of the ground motions for the structures in the medium-period range

$$I_c = (a_{rms})^{3/2}\sqrt{t_d} \qquad\qquad a_{rms} = \sqrt{\frac{1}{t_d}\int_0^{t_d} a(t)^2\,dt} \tag{7}$$

$$I_F = PGV.t_e^{0.25} \tag{8}$$

As it has been indicated by many researchers, some of GMIs are closely related so they have a strong correlation. Since AI, CAV, and I_c are computed from the acceleration trace of the ground motion, a strong correlation between them was observed (with correlation coefficient greater than 0.90). Among the spectral parameters, ASI, HI, and VSI are indications of the force imparted on the structure, however, only a very strong correlation was observed between HI and VSI (correlation coefficient nearly 1.0). The moderate correlation with respect to ASI is due to the difference in the period range considered. PGA is observed to be strongly correlated with EPA and ASI, whereas PGV is highly correlated with HI and I_F.

The dependencies of MIDR on each one of the intensity parameters are evaluated based on best-fitted curves of two types: linear and exponential, as shown in Fig. 4. As is well known, the general trend of structural response with seismic intensity follows a nonlinear relation especially in the nonlinear response range. This dependency may be assumed to show a linear trend at small MIDR’s indicating elastic response. In order to approximately determine the elastic limits for the MIDR of frame, pushover analyses were carried out and the yield points were identified using the approach proposed in FEMA 356 (ASCE, 2000) for bilinearizing the capacity curve. The limit for frame has been marked on the plots given in Fig. 4. It is worth mentioning that the largest value of MIDR yield is 0.6%, indicating that there are many cases where the employed frame responded in elastic as well as inelastic ranges.

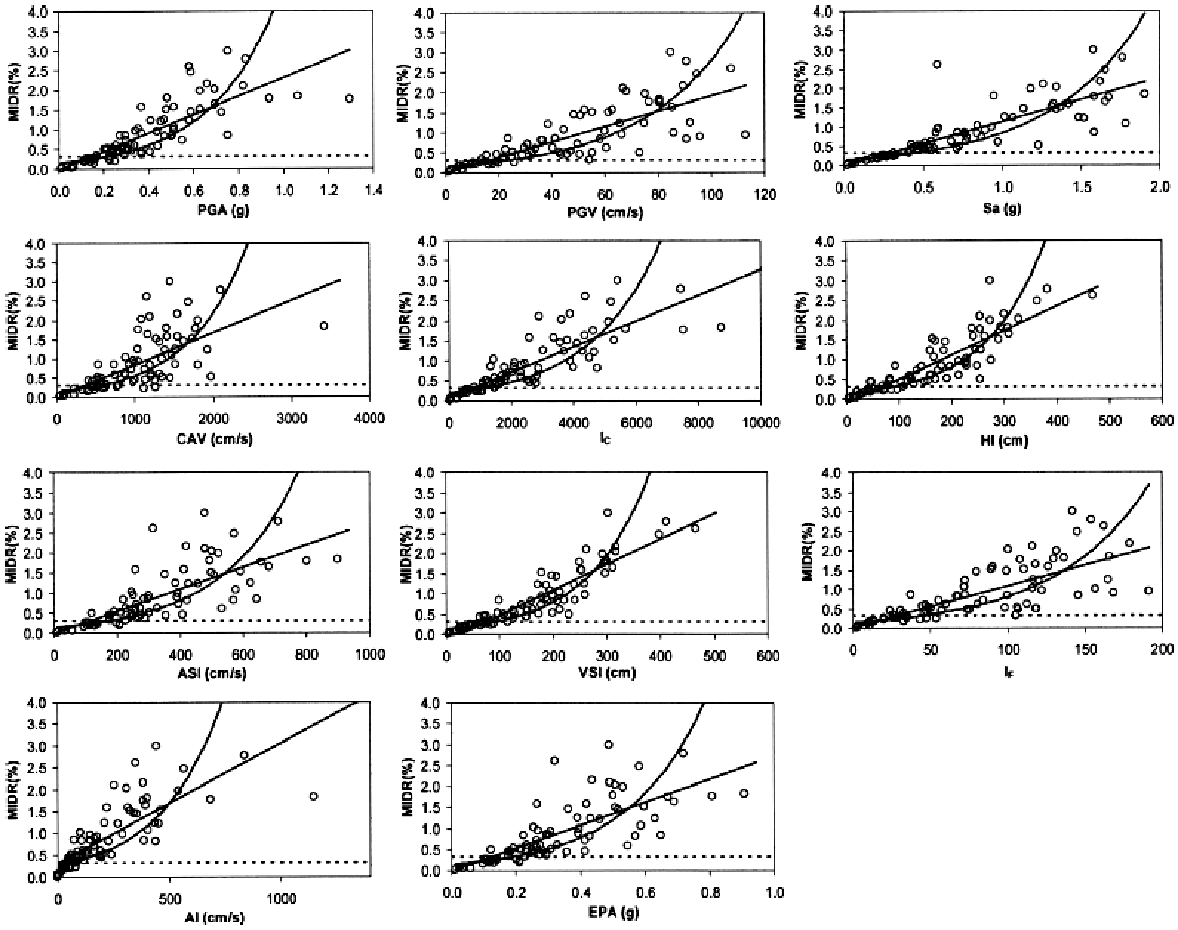

Figure 4. Relationship between the selected GMI's and MIDR for special frame (Yakut and Yilmaz, 2008)

CUMULATIVE DAMAGE INDEX (D_c)

This section is based on research by Sucuoglu et al. (1998). Seismic damage accumulates with repeated inelastic deformation cycles during an earthquake. If the damage experienced during each cycle of response is Δd_i, therefore the total damage associated with n cycles will be given by :

$$D_c = \sum_{i=1}^{n} \Delta d_i \tag{9}$$

Thus, cumulative index D_c always takes positive values in which those values exceeding one imply collapse.

The largest acceleration pulse, or peak ground velocity, and the effective duration of ground excitation are employed as the characteristic intensity parameters of ground motions in study of Sucuoglu et al. (1998) for evaluating their damage potential. The ratio of the synchronized peak ground velocity and dominant ground acceleration (V/A ratio) indicates the average duration of the dominant acceleration pulse. V/A ratio is used here for identifying the impulsive character of accelerograms. Long acceleration pulses producing high ground velocities are usually observed in near-fault accelerograms as a result of rupture directivity effects. Damage potential of these ground motions are mainly attributed to seismic energy concentrated in such pulses.

Effective excitation duration (t_{eff}) is the duration of ground motion during which significant structural response develops. The method proposed by Tifunac and Brady (1975) is employed here to evaluate the effective duration. This procedure defines the effective duration of a ground motion as the time interval during which accelerogram intensity increases from 5% to 95% of its final value. Accelerogram intensity is the time integral of the square of ground acceleration from the beginning of record to time t.

Normalized accelerograms in the ground motion database are divided into four groups according to their V/A ratios. Then, mean values of D_c are calculated for each group and for each SDOF system. The mean spectra of D_c are presented in Fig. 5. This figure indicates strong dependence of the ground motion damage potential on the V/A ratio.

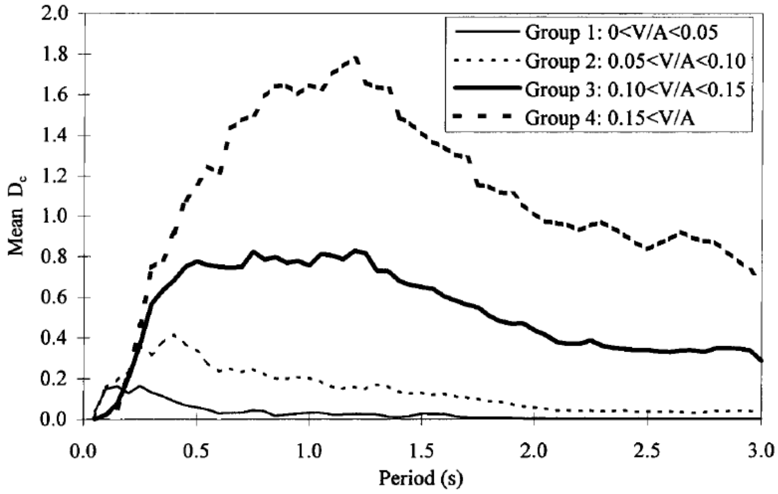

Figure 5. Mean spectra of D_c with bi-linear reduction factor for ground motions grouped according to V/A ratio. (Sucuoglu et al., 1998)

The ground motion database is again divided into four groups, but according to their effective durations. Mean spectra of D_c for each group are shown in Fig. 6. It may be observed that spectral variations of the damage index clearly exhibit sensitivity to the effective duration of strong motion.

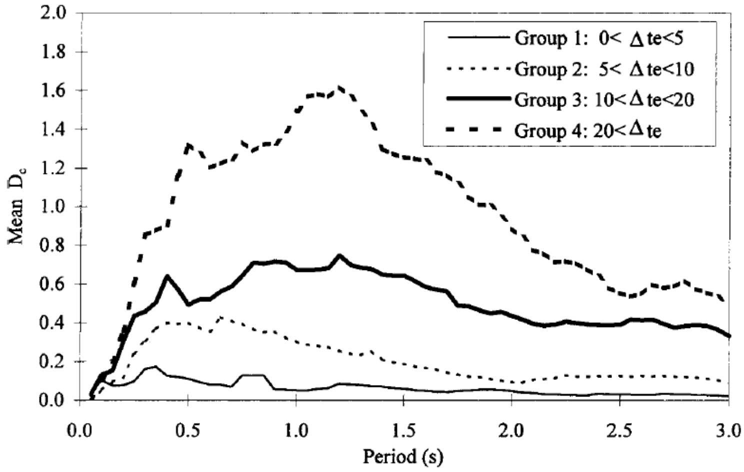

Figure 6. Mean spectra of D_c with bi-linear reduction factor for ground motions grouped according to effective duration. (Sucuoglu et al., 1998)

DAMAGE SPECTRA

Bozorgnia and Bertero (2003) proposed improved damage spectra to quantify the damage potential of recorded earthquake ground motion. Their damage spectra were based on a combination of normalized hysteretic energy and deformation ductility of a series of inelastic SDF systems. Using the definition of hysteretic ductility μ_H (Mahin and Bertero, 1976) given in Eq. (10) for both earthquake and monotonic excitations, the improved damage indices can be rewritten as DI_1 and DI_2 :

$$\mu_H = [E_H / (F_y u_y)] + 1 \tag{10}$$

$$DI_1 = [(1-\alpha_1)(\mu - \mu_e)/(\mu_{mon} - 1)] + \alpha_1(\mu_H - 1)/(\mu_{Hmon} - 1) \tag{11}$$

$$DI_2 = [(1-\alpha_2)(\mu - \mu_e)/(\mu_{mon} - 1)] + \alpha_2[(\mu_H - 1)/(\mu_{Hmon} - 1)]^{1/2} \tag{12}$$

where F_y and u_y = yield strength and yield deformation of the system, respectively. $\mu=\mu_{max}/\mu_y$ is displacement ductility and $\mu_e=\mu_{elastic}/\mu_y$ is maximum elastic portion of deformation normalized by μ_y. For inelastic behavior, μ_e=1.0 and if the response remains elastic (μ<1.0), $\mu_e=\mu$. Also, μ_{mon}=monotonic displacement ductility capacity; E_H=hysteretic energy demanded by earthquake ground motion; E_{Hmon}=the hysteretic energy capacity under monotonically increasing lateral deformation; $0\le\alpha_1\le1$ and $0\le\alpha_2\le15$ constant coefficients. For the special case of elastic-perfect plastic (EPP) systems have:

$$E_{Hmon}=F_y(u_{mon}-u_y) \qquad \mu_{Hmon}=\mu_{mon} \tag{13}$$

$$DI_1=[(1-\alpha_1)(\mu-\mu_e)/(\mu_{mon}-1)]+\alpha_1(E_H/F_y u_y)/(\mu_{mon}-1) \tag{14}$$

$$DI_2=[(1-\alpha_2)(\mu-\mu_e)/(\mu_{mon}-1)]+\alpha_2[(E_H/F_y u_y)/(\mu_{mon}-1)]^{1/2} \tag{15}$$

A few characteristics of the improved damage indices of Bozorgnia and Bertero (2003) are :

1. If the response remains elastic, i.e., when there is no significant damage, then $\mu_e=\mu\le1$ and E_H=0, and both DI_1 and DI_2 will become zero. This is characteristic of a well-defined damage index.
2. Under monotonically increasing lateral deformation if the demand on displacement u_{max} reaches the displacement capacity u_{mon} , i.e., an indication of failure, both damage indices DI_1 and DI_2 will be unity. This is true for any force-deformation relationship.
3. If α_1=0 and α_2=0, the damage index is assumed to only be related to the maximum plastic deformation.
4. If α_1=1 and α_2=1, damage indices DI_1 and DI_2 will only be related to the hysteretic energy dissipation E_H .

Fig. 7 shows an examples of damage spectra for the 1940 Imperial Valley earthquake recorded at El Centro, and for the Northridge earthquake recorded at Canoga Park. In Fig. 7, the following characteristics for existing structure are used: viscous damping ξ=5%; EPP force-displacement relationship; yield strength based on the elastic spectrum of the Uniform Building Code (UBC, 1997) (without near-source factors) reduced by R_d=3.4. This is the ductility reduction factor suggested by the Structural Engineers Association of California (SEAOC, 1999) for special moment frames and it corresponds to an overstrength factor of 2.5.

Also, for Fig. 7, μ_{mon}=10, $\alpha_{1=}$0.27, and α_2=0.30 are used. These values for α_1 and α_2 are based on an analysis of the Northridge earthquake records, as explained in ‘‘Correlation Between New Damage Indices (Relations 11 and 12) and the Park and Ang Damage Index.

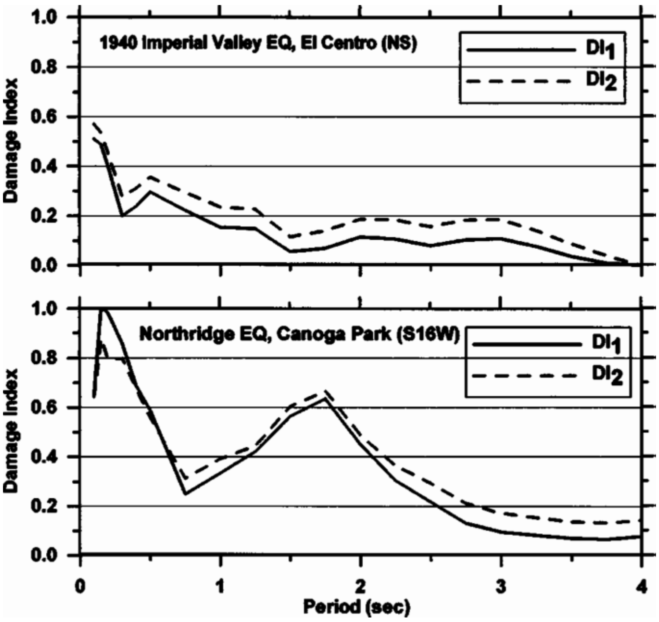

Figure 7. damage spectra, with ξ=5%, μ_{mon}=10, and EPP behavior (Bozorgnia and Bertero, 2003)

It is clear from the expressions for the damage indices that the larger the supplied deformation ductility (represented by μ_{mon}) and toughness (represented by E_{Hmon}), the smaller will be the damage spectra. On the other hand, the larger the demanded plastic deformation (μ=1) and toughness (E_H), the larger will be the damage spectra.

For the purpose of calibrating against the observed damage, there are clear advantages in using damage spectra than other ground shaking and response parameters such as the peak ground acceleration and velocity, elastic response spectra, spectrum intensity (Housner, 1952), and drift spectrum (Iwan, 1997). The damage spectra include, in a simple way, basic structural characteristics related to the strength, deformation, and energy dissipation capacities, which are important in controlling damage.

CONCLUSIONS

The primary purpose of selected ground motion intensity measures is the selection of a set of uniform ground motion records to be used for the analyses of a particular structure such that the structure undergoes various levels of deformation. This is very important because in the development of fragility curves, the selection of suitable ground motion records without carrying out nonlinear time-history analyses is needed. Analyses of the selected frames under a suit of ground motion records with varying intensities enabled evaluation of the GMIs employed in the linear as well as nonlinear response regions. The results indicated that spectrum-based intensity parameters that account for the structural characteristics (predominant period) are the most reliable ground motion intensity parameters for the structures having periods between 0.2 and 1.1 s. These parameters reflect the likely response interval of the employed frames. Among the GMI's considered, HI, VSI, and ASI (with the period range of 0.1–2.5 s) appeared to be the ones that have the strongest correlation with MIDR. However, the best GMI for the structures with periods between 0.2 and 0.5 s was observed to be PGA followed by VSI and I_c.

Within the framework of design strength specification based on seismic design spectra, the effect of the A/V ratio of ground motions on the damage of SDOF stiffness degrading systems was investigated. The effect is most pronounced for flexible systems designed with low yield strength. The effective excitation duration is also observed to be an effective and important parameter on the damage potential of strong ground motions. Those SDOF systems having intermediate periods of vibration are more vulnerable to damage under normalized ground excitations when either the A/V ratio is smaller than 10 or the effective duration is longer than 10 s, or both.

A new intensity measure that incorporates properties of the ground motion record and the structure correlates better with the nonlinear response of the frame structures than other available spectral intensity measures. This is relied on the period elongation and the yield spectral acceleration of the structure. The yield spectral acceleration can be either estimated using approximate procedures or extracted from the pushover curve. The elongated period can be either calculated directly from the proposed equation or computed using the maximum displacement that is approximately calculated using the procedures outlined in FEMA 440 (ATC, 2005).

It is believed that the results presented here would help researchers and practitioners in the selection of ground motions for certain applications, especially if the ground motion destructiveness is an important criterion for seismic response of structures.

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