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Damage Spectrum and Its Applications to Performance-Based Earthquake Engineering

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SUMMARY

This paper presents the basic definitions of improved damage indices (DIs), their corresponding damage spectra, and potential applications to performance-based assessment of existing structures as well as performance-based design of new systems. Specifically two formats of damage spectra are presented in this paper: The first format of damage spectrum is a plot of the computed DI for an existing system versus structural period. Such damage spectra are convenient for performance-based damage assessment of existing facilities. For example, they can be used for post-earthquake near real-time damage assessment of structures based on recorded ground motions. The second format of the damage spectrum is a plot of the required strength, or maximum deformation, versus structural period for constant values of DI. Such damage spectra can be used for performance-based design of new systems. To present the concept, strength and deformation spectra for ten near-fault ground motions with directivity effects are computed. Average required yield strength and maximum deformation spectra for these near-fault records for constant values of DI are presented.

INTRODUCTION

Structural performance states, which are associated with different damage limit states, can be quantified by *damage indices* (DIs). For a single-degree-of-freedom (SDF) system, a well-defined DI is a normalized quantity that will be zero if the system remains elastic (i.e., no significant damage is expected), and will be one if there is a potential of failure. Other structural performance states (such as "operational", "life-safe", "near collapse", etc.) correspond to values of DI between zero and one (Bozorgnia and Bertero [3]). It should be noted that the serviceability performance is not covered by the above definition of DI. ***"Damage spectrum"*** can have different formats. It can be a plot of a computed DI for an existing system versus period (Bozorgnia and Bertero [1,2,3]). Such damage spectra can be used for performance-based damage assessment of the existing structural system. Various applications of such damage spectra have been

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presented by Bozorgnia and Bertero [1, 2, 3], including post-earthquake near real-time damage assessment of existing structural systems using recorded ground motions.

For performance-based design of new systems, it is more convenient to present the damage spectra in another format. An alternative format is to compute the yield strength of the SDF versus period for constant values of DI. In this format, given a set of input ground motions that should be considered at the site, period, and desired performance level (associated with a specific value of the DI), one can estimate the design yield strength. Other useful variation of damage spectrum is a plot of the maximum deformation of the SDF versus period for constant values of DI.

In this paper, first an overview of the basic definitions of improved damage indices is presented. Different formats of damage spectra and their potential applications are also discussed. Finally, damage spectra for a set of ten near-fault ground motions with directivity effects are presented.

IMPROVED DAMAGE SPECTRA

Two improved damage indices and their corresponding damage spectra have been introduced by Bozorgnia and Bertero [1, 2, 3]. These can be considered as generalized versions of the commonly used Park and Ang [4] damage index. The damage indices are as follows:

$$DI_1 = [(1 - \alpha_1)(\mu - \mu_e) / (\mu_{mon} - 1)] + \alpha_1 (E_H/E_{Hmon}) \quad (1)$$

$$DI_2 = [(1 - \alpha_2)(\mu - \mu_e) / (\mu_{mon} - 1)] + \alpha_2 (E_H/E_{Hmon})^{1/2} \quad (2)$$

where,

$$\mu = u_{max} / u_y = \text{Displacement ductility} \quad (3a)$$

$$\mu_e = u_{elastic} / u_y = \text{Maximum elastic portion of deformation} / u_y, \quad (3b)$$

$\mu_e = 1$ for inelastic behavior; and

$\mu_e = \mu$ if the response remains elastic

μ_{mon} is monotonic displacement ductility capacity, E_H is hysteretic energy dissipation due to plastic deformation demanded by the earthquake ground motion, E_{Hmon} is hysteretic energy dissipation capacity (due to plastic deformation) under monotonically increasing lateral deformation, and $0 \le \alpha_1 \le 1$ and $0 \le \alpha_2 \le 1$ are constant coefficients. These coefficients are mainly dependent on the mechanical characteristics of the structure and input ground motion. For the special case of elastic-perfectly-plastic (EPP) systems,

$$E_{Hmon} = F_y (u_{mon} - u_y) \quad (4)$$

$$DI_1 = [(1 - \alpha_1)(\mu - \mu_e) / (\mu_{mon} - 1)] + \alpha_1 (E_H/F_y u_y) / (\mu_{mon} - 1) \quad (5)$$

$$DI_2 = [(1 - \alpha_2)(\mu - \mu_e) / (\mu_{mon} - 1)] + \alpha_2 [(E_H/F_y u_y) / (\mu_{mon} - 1)]^{1/2} \quad (6)$$

The proposed damage indices will be zero if the structure remains elastic, i.e., no significant damage is expected; and will be unity if the SDF response reaches its ultimate deformation capacity under monotonically increasing lateral deformation.

Applications of Damage Spectra for Existing Systems (<u>Performance-Based Assessment</u>)
If the SDF system represents a simplified model of an existing system, ideally some fundamental dynamic and mechanical characteristics can be approximated. These include its initial elastic period, viscous damping, force-deformation relationship, and approximate deformation and energy capacities of the system under monotonically increasing deformation. The SDF system, representing a simplified model, can be subjected to a ground acceleration record, and the various response quantities such as displacement ductility ratio (μ) and hysteretic energy (E_H) spectra can be computed. The damage spectra corresponding to damage indices DI_1 or DI_2 can be constructed by proper combination of μ and E_H spectra according to equations (1) or (2). Hundreds of such damage spectra have been constructed by Bozorgnia and Bertero [1, 2, 3]. An example of such damage spectra is presented in Figure 1. For this figure, the SDF system is assumed to have 5% viscous damping; EPP force-displacement relationship with yield strength based on elastic spectrum of UBC (1997) (without near-source factors) reduced by a period-independent factor of R_d=3.4; μ_{mon}=10, α_1= 0.27 and α_2=0.30. These values for α_1 and α_2 are based on an analysis of the Northridge earthquake records (Bozorgnia and Bertero [3]).

When the fundamental characteristics of the SDF system can be approximately estimated, the computed damage spectra, such as the ones plotted in Figure 1, can quantify the performance state of the existing system. Thus, the damage spectra can be useful for performance-based damage assessment of existing structures. For example, if the computed damage spectral ordinate is zero, the system is expected to remain elastic (i.e., no significant damage) and other values of the damage spectral ordinates (between zero and one) correspond to damage states such as "operational", "life-safe", "near collapse", and "collapse" states. An application of this concept can be in near real-time performance-based damage assessment of existing structural systems (Bozorgnia and Bertero [1, 2]).

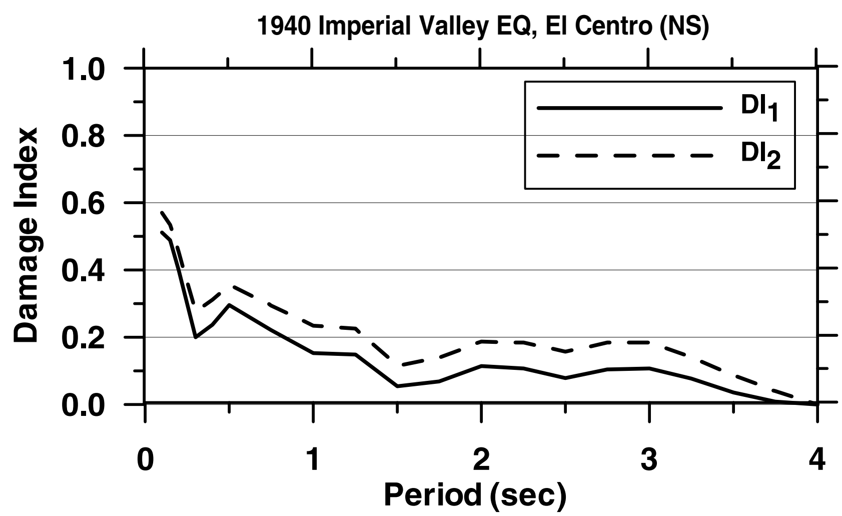

Figure 1: Example of damage spectra, for *<u>performance-based assessment</u>* of a model of an existing system.

Application of Damage Spectra for New Systems (<u>Performance-Based Design</u>)
For new structures, the system's characteristics are estimated through design process based on the chosen performance objectives. For any given performance objective, there is a coupling between the ground motion hazard and the desired performance level. For example, one of the most commonly used performance objective is to satisfy life-safety performance level for a severe ground motion hazard level. A convenient way to quantify a performance level is to use the value of damage index corresponding to the performance level.

To focus on the application of damage spectra to performance-based design of new systems, it is assumed that the elastic structural period has been already determined, e.g., through using pre-specified target deformations (see e.g., Bertero and Bertero [5]). Given the performance level, which corresponds to a value of damage index, the next step is to determine the yield strength of the system. For this process, a new format of damage spectrum is desirable, as discussed next.

The problem can be summarized as follows. Given: the period of the system, viscous damping, performance level quantified by a value of damage index, and ground motion time-history; Compute: the yield strength (as related to the base-shear) of the system. This computed yield strength (and consequently the base shear) can then be used for deign (see e.g., Bertero and Bertero [5]). To solve this problem it is convenient to have spectrum of yield strength (versus period) for given values of the damage index (i.e., performance level). An example of such spectra is presented in Figure 2 (Bozorgnia and Bertero [2]). Using yield strength spectra for constant values of damage index, and by having the initial period and the desired performance state (i.e. value of the damage index), one can easily estimate the required yield strength of the system. Such yield strength spectra for constant values of damage index can be constructed by an interpolation process. Consistent with the previous results, zero value for DI corresponds to the elastic spectrum.

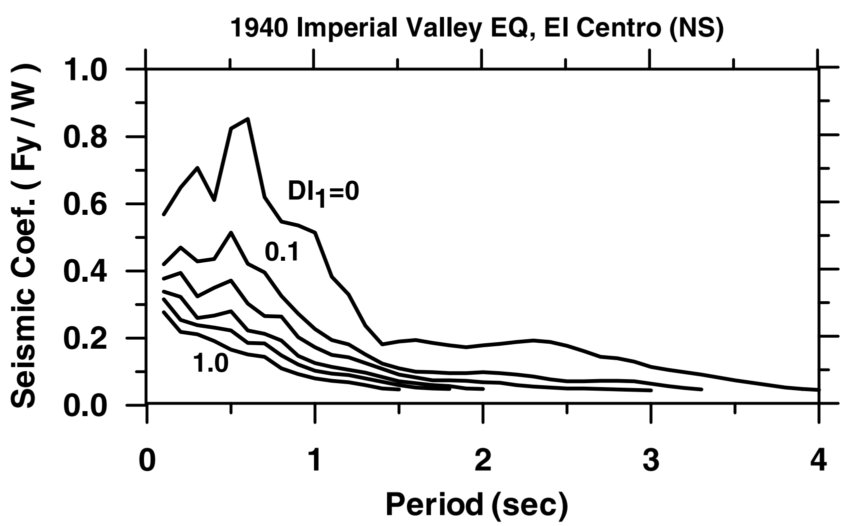

Figure 2: Example of damage spectra, for *performance-based design* of a new system. The seismic coefficients are for constant values of damage index (DI_1= 0, 0.1, 0.2, 0.4, 0.6, 1.0). See also Bozorgnia and Bertero [2].

CONSTAT DMAGE INDEX SPECTRA FOR NEAR-FAULT GROUND MTIONS

In this section, yield strength and maximum deformation spectra for constant values of damage index for a set of near-fault ground motion records are presented. The selected ground motion records are listed in Table 1. These are the ground motions with strong directivity effects and the associated severe long period pulses. As Table 1 presents, the selected recording stations are all within 5 km from the causative faults. Peak ground acceleration (PGA) and peak ground velocity (PGV) are also listed in Table 1.

Table 1: Near-fault ground motion records used in this study

EARTHQUAKE	M_W	FAULTING MECHANISM	STATION	R_{JB} [1] (km)	COMPONENT	PGA (G)	PGV (CM/S)	REF.
1978 Tabas, Iran	7.4	Thrust	Tabas	3.0	N16W	0.93	112	6
1979 Imperial Valley	6.5	Strike-Slip	El Centro Array 6	1.2	Fault-Normal	0.43	106	7,8
1984 Morgan Hill	6.2	Strike-Slip	Anderson Dam Downstream	4.8	Fault-Normal	0.44	27	7,8
1992 Landers	7.3	Strike-Slip	Lucerne Valley	1.1	Fault-Normal	0.71	136	7,8
1992 Erzincan, Turkey	6.7	Strike-Slip	Erzincan	2.0	Fault-Normal	0.43	120	7,8
1994 Northridge	6.7	Thrust	Rinaldi Receiving Station	0.0	Fault-Normal	0.89	174	7,8
1994 Northridge	6.7	Thrust	Sylmar County Hospital	1.5	Fault-Normal	0.73	122	7,8
1994 Northridge	6.7	Thrust	Newhall	3.7	Fault-Normal	0.72	118	7,8
1995 Kobe	6.9	Strike-Slip	Takatori	2.3	Fault-Normal	0.79	174	7,8
1999 Chi-Chi, Taiwan	7.6	Thrust	TCU075	3.2	N90E	0.33	102	9 [2]

(1) Closest distance to surface projection of fault rupture plane.

(2) Processed recorded motion is from Strong Motion Instrumentation Program, California Geological Survey.

Very high PGV values in most of the selected records are indicative of the severe damage potential of these ground motions.

An EPP SDF system model with 5% viscous damping is used for this analysis. The period of the SDF varies from 0.1 to 4.0 sec. For each ground motion record, the required yield strength to result in a specified value of DI_1 (see equation 5) is computed using $\mu_{mon} = 10$ and $\alpha_1 = 0.269$. The average yield strength spectra for the selected near-fault records (see Table 1) corresponding to $DI_1 = 0.4$, 0.6, 0.8 and 1.0 are presented in Figure 3. It is evident from this figure that the design yield strengths for such severe near-fault records are large. Such yield strength spectra can be used to quantify damage potential of the ground motion. For each ground motion record, one can also compute the maximum deformation of the SDF system for the specified value of the damage index (i.e., specified performance goal). The average

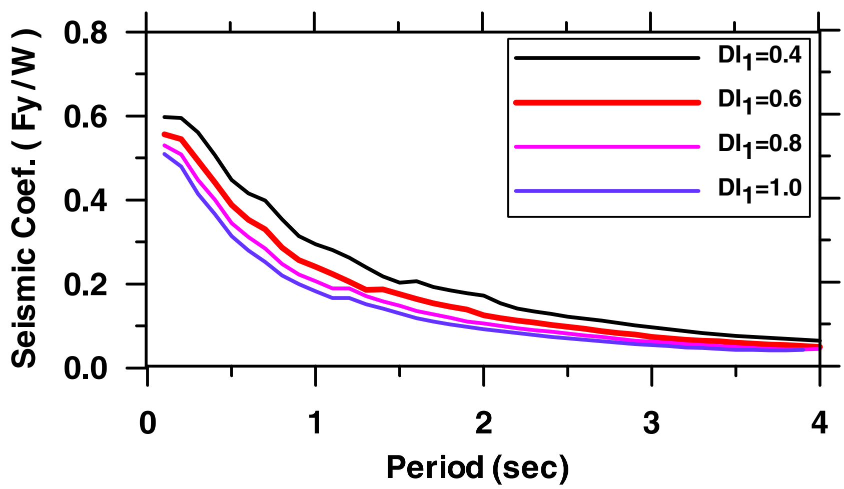

Figure 3: Average yield strength spectra for constant values of damage index DI_1 for the near-fault ground motions listed in Table 1.

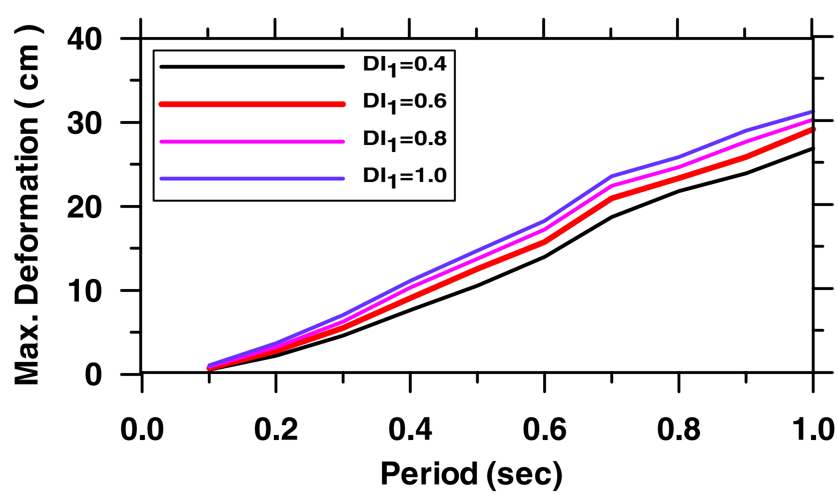

Figure 4: Average deformation spectra for constant values of damage index DI_1 for the near-fault ground motions listed in Table 1.

deformation spectra for constant DI_1 values for the near-fault ground motions listed in Table 1 are presented in Figure 4. The deformation spectra are plotted up to period of one second. For longer periods the deformation curves are not uniquely separated from each other. Given the target deformation and performance goal, such deformation spectra can also be used to check the selected period of the system.

It should be noted that Figures 3 and 4 present the average spectra; however, the scatter of the spectral ordinates can be significant and a measure of the scatter should be considered in the design.

SUMMARY AND CONCLUSIONS

The concept of damage spectra can be used for two applications: (a) performance-based assessment of existing structural systems; and (b) performance-based design of new systems. In application (a), the basic characteristics of the systems are known and its response is presented in form of damage index versus period. For example, this form of damage spectra can be used for near real-time damage assessment of structural systems using recorded ground motions. In application (b), yield strength and deformation spectra for constant values of damage index are computed. In this application, given the structural performance goal quantified by a value of the damage index, and given the period and basic characteristics of the force-deformation relationship (e.g., EPP), one can estimate the design yield strength and maximum deformation of the system.

Deformation spectra for constant values of damage index can also be used to check the selected period of the system. Given the performance level and its corresponding target deformation (e.g., in terms of interstory drift), one can use the deformation spectra to estimate the period. The final selected period of the system is the lesser of that based deformation spectra (such as those presented in Figure 4) and that based on a separate serviceability analysis.

Strength and deformation spectra for constant values of damage index for a set of near-fault ground motions with the directivity effects were computed and presented in this paper. Besides their other applications, such spectra can also be used to quantify the damage potential of the recorded earthquake ground motions.

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