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A response spectrum-based indicator for structural damage prediction

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ABSTRACT

Improving predictive relationships between strong ground motion and seismically induced damage in buildings is an important topic for seismic risk assessment. Spectral acceleration at a structure's fundamental period $S_a(T_1)$ has often been used as the indicator of the potential damage a given ground motion may induce on structural systems. However, such a scalar indicator (Damage Potential Indicator, DPI) captures only limited information about the ground motion time history and response spectrum shape. In a severely damaged state, the effective period of a structure will change, which makes the structure respond to other parts of the response spectrum. In this study, a new response spectrum-based DPI that contains an intensity component and a spectral shape component is proposed. The critical period range of the response spectrum that should be considered in spectral shape evaluation is determined using a circle rule for bilinear single-degree-of-freedom (SDOF) systems. The effectiveness of the newly proposed DPI is validated by comparing damage potential similarity using a database of ground motion records.

1. Introduction

Response spectrum is a commonly used metric for ground motions (GM) in both seismology and earthquake engineering [1]. Response spectrum reflects the maximum acceleration or displacement response of a series of linear elastic single-degree-of-freedom (SDOF) systems under a given ground motion's excitation, essentially quantifying the influence of the given ground motion on structures at different frequencies. In spite of some research efforts toward nonlinear response spectra (e.g., Iwan [2]; Riddell [3]; Aydinoğlu [4]), the linear response spectrum is widely used by researchers and engineers to evaluate a ground motion impact on structural systems due to its simplicity (e.g., Loth and Baker [5]; Li and Ellingwood [6]; Koliou and Filiatrault [7]). It is also used by researchers to compare two ground motions, especially in damage potential evaluations.

Currently, there is a need for performance-based seismic design (PBSD) to use advanced structural models and simulation techniques to estimate seismically induced damage and assess design resilience. Such a model and analysis are often complicated and structure-specific, making it difficult to compare two ground motions in terms of their potential damage to structures. In this study, we hypothesize that the elastic response spectrum can be used to derive a "damage potential indicator" (DPI) for nonlinear structural systems. The key is to consider not only the response spectral value at the building elastic period, but also the periods corresponding to nonlinear response (lengthens the effective period) and higher modes (shortens the effective period) [8].

A vector-valued DPI based on the elastic response spectrum is proposed, including a seismic intensity component (similar to traditional intensity measures) and a spectral shape component (considering the spectral shape in a given period range). For the spectral shape component calculation, a circle rule is proposed to identify the critical period range that should be used. The proposed DPI is used as an indicator to compare two ground motion time series in terms of their damage potential. The comparison based on the DPI is validated using nonlinear time history simulation results in order to demonstrate the DPI's effectiveness in representing damage potential.

2. Existing studies of response spectrum-based damage potential indicator

The purpose of a DPI is to provide a simple and quantitative parameter of a ground motion time series that can represent the damage it will induce on a structure. In the past, researchers have investigated various ground motion parameters that can potentially be used as DPIs. These parameters can be divided into two categories, namely structure-independent and structure-dependent DPIs. Structure-independent DPIs are derived only from the ground motion itself without considering structural properties. The common structure-independent DPIs are peak values from the time history, such as peak ground velocity, peak ground acceleration, and peak ground displacement [9–11], as well as the time history-related characteristics, such as Arias intensity [12] and

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earthquake power index P_a [13]. DPIs combing peak quantities and time history-related quantities have also been used (e.g., Fajfar intensity, I_F [14]; Rafael and Garcia, I_a, I_v and I_d, to consider structural energy dissipation [15]; Park characteristic intensity, I_C [16]; and Iervolino et al. duration intensity, I_D [17]). These structure-independent DPIs are not very robust in predicting damage since structural parameters will also influence damage (i.e., an earthquake that causes significant damage in one structure may not have a similar impact on another structure). With this in mind, researchers have also proposed structure-dependent DPIs, often related to the target structure's natural frequency and the response spectrum of the GM. The most commonly used one is the elastic response spectral acceleration ($S_a(T_1)$) at the fundamental period of a structure (e.g., Vamvatsikos and Cornell [18]; Yin and Li [19]; Bradley and Lee [20]; Ellingwood and Kinali [21]; Koliou et al. [22]; Li et al. [23]). However, when a structure vibrates into inelastic behavior, the period of the structure lengthens due to stiffness degradation [8]. It is thus logical to construct DPIs capturing the response spectral value at the lengthened period. For example, Cordova et al. [24] combined the spectral values at the fundamental period (T_1) and lengthened period (T_L) as:

$$DPI = S_a(T_1)\left[\frac{S_a(T_L)}{S_a(T_1)}\right]^{\alpha} = S_a(T_1)^{1-\alpha}S_a(T_L)^{\alpha} \tag{1}$$

where $T_L = C\times T_1$ is the lengthened period, and $C > 1$ is the coefficient describing the period softening, quantifying the degree of structural softening (namely, nonlinearity), which is usually assumed to be 2 [25]. Thus, the value of C should be related to the intensity level of the earthquake. α is an undetermined coefficient reflecting spectral shape which can be seen as the weight of the two spectral values at T_1 and T_L [26]. Vamvatsikos and Cornell [27] modified the DPI as:

$$DPI = S_a(T_s)^{1-\alpha}S_a(T_L)^{\alpha} \tag{2}$$

where the spectral value at the fundamental period (T_1) is replaced by the one at T_s. The value of T_s can be smaller than T_1 to consider the effects of higher modes or larger than T_1 due to structural nonlinearity. These definitions of T_s and T_L make this DPI more accurate for the tall, long-period structures dominated by higher modes of vibration or to structures controlled by strong nonlinearity. However, these DPIs only use the information at two points in the response spectrum, resulting in a lack of information on the spectral shape over a period band that the structure will transit through as it softens. The rule on determining the softened structural period, T_L, is also vague. In order to incorporate information on spectral shape over a period band, Bojorquez and Iervolino [28] introduced a new DPI as:

$$DPI = \frac{S_{a,avg}(T_1. \ldots T_e)}{S_a(T_1)} \tag{3}$$

where $S_{a,avg}(T_1 \ldots T_e)$ indicates the average spectral acceleration between T_1 and T_e. This DPI is dimensionless (without seismic intensity information) and only captures the spectral shape between T_1 and T_e. The response spectrum in this period band is expected to exhibit an average positive slope for DPI > 1 while negative for DPI < 1. But without any intensity information, two GMs with very different intensity can have similar DPI values as long as their shapes are similar. The rule for how to define T_e is still not clear. Baker and Cornell [8,29] proposed a vector-valued DPI consisting of spectral acceleration and epsilon to predict structural seismic performance. Although both the spectral magnitude and spectral shape are reflected in this DPI, the spectral shape information is very limited in that only the shape information at one point is included.

3. A vector-valued damage potential indicator

In this study, a spectral shape component similar to Eq. (3) is proposed together with a generalized rule (for bilinear systems) to determine the range of period in which the shape component should be calculated. Our measure starts at T_s instead of T_1 (fundamental period) so that the shape component may include the effects of both higher modes and nonlinearity. Thus, our proposed spectral shape component is formulated as:

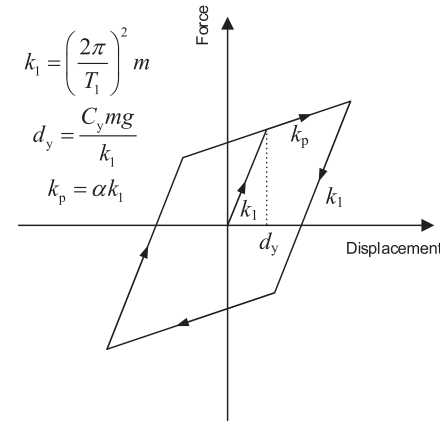

Fig. 1. Hysteretic model of a bilinear SDOF system.

$$p_2 = \frac{S_{a,avg}(T_s. \ldots T_e)}{S_a(T_1)} \tag{4}$$

It is evident that p_2 includes spectral shape information over the period band from the starting period T_s to the ending period T_e. The period band needs to be carefully calibrated so that p_2 has the strongest correlation with structural damage (referred to as the optimal period band). The optimal period band should be intrinsically a counterbalance between effective period shortening via the higher mode effects [30] and effective period lengthening via the structural response nonlinearity [2,31]. Higher modes are controlled by the structural properties while Katsanos et al. [32] postulated that the degree of period lengthening (nonlinearity of structural performance) varies with seismic intensity. The parameter, p_2 does not include information on GM intensity. But it is expected that the optimal period band will be dependent on GM intensity. To better quantify the interplay between structural nonlinearity and seismic intensity, the indicator λ is formulated to reflect intensity information by normalizing the spectral acceleration at the system fundamental period:

$$\lambda = \frac{I}{S_{a0}(T_1)} = \frac{S_a(T_1)}{S_{a0}(T_1)} \tag{5}$$

where I is the seismic intensity which can be represented by the spectral acceleration $S_a(T_1)$ at the fundamental period of the structure, and $S_{a0}(T_1)$ indicates the scaled spectral acceleration at which the ground motion starts to yield the structure. When $\lambda \le 1$, the structure remains linear and elastic during the GM excitation. The structure will only experience damage if $\lambda > 1$. λ is used as the intensity component of the DPI vector as:

$$p_1 = \lambda \tag{6}$$

Thus, the vector-valued DPI is constructed as the GM intensity component and the spectral shape component:

$$DPI = [p_1, p_2] = \left[\lambda, \frac{S_{a,avg}(T_s. \ldots T_e)}{S_a(T_1)}\right] \tag{7}$$

In order to use Eq. (7), the period band $[T_s, T_e]$ needs to be identified. A sensitivity study of the period band to the DPI quality is conducted in the following sections.

4. Response spectrum similarity index

It is often speculated that similarity in response spectrum between