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Advanced scalar intensity measures for collapse capacity prediction of steel moment resisting frames with fluid viscous dampers

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ABSTRACT

Nowadays, passive energy dissipation systems are used in the seismic design of new structures and the retrofit of existing structures. Fluid Viscous Dampers (FVDs) are one of the important types of passive energy dissipation systems. Using FVDs can considerably decrease the seismic demands on structures. In this study, seismic collapse behavior of steel Special Moment Resisting Frames (SMRFs) equipped with FVDs is investigated using different scalar Intensity Measures (IMs). Incremental Dynamic Analysis (IDA) method is applied to determine the collapse capacity, IM_{col}, values for low- to mid-rise steel SMRFs equipped with FVDs. After determining the collapse capacity, IM_{col}, values by using each of the IMs, the efficiency and sufficiency of the IMs for predicting the seismic collapse capacity of the structures are investigated. Then, advanced scalar IMs, including the effects of spectral shape and ground motion duration, are proposed to reliably predict the collapse capacity of steel SMRFs equipped with FVDs. The results indicate that the proposed IMs possess high efficiency and sufficiency for collapse capacity prediction of steel SMRFs equipped with FVDs.

1. Introduction

Using passive energy dissipation systems, including Fluid Viscous Dampers (FVDs), hysteretic dampers, viscoelastic dampers and friction dampers, is one of the effective ways to mitigate excitations due to strong ground motions [1,2]. FVDs are a type of passive energy dissipation systems that are extensively used for the seismic design of new structures and the retrofit of existing structures [3,4]. For elastic structures, using FVDs reduces both displacements and accelerations simultaneously [5,6]. However, as pointed out by Karavasilis and Seo [7], for highly inelastic structures, FVDs may increase accelerations, as the damper forces are not out of phase with the peak drifts and internal member forces, due to the nonlinearity of the structure. FVDs provide a velocity-dependent force and can behave as linear or nonlinear elements. The force developed by a FVD is as follows:

$$F_d = C \cdot |v|^{\alpha_d} \cdot \mathrm{sgn}(v) \quad (1)$$

where C is the damper coefficient, v is the relative velocity between the two ends of the damper, α_d is the velocity exponent, and sgn is the signum function. In seismic applications, the exponent α_d is in the range of 0.2–1.0 [8]. When α_d is equal to one, the damper is called "linear FVD", and values of α_d lower than one represent nonlinear FVDs.

Several researchers have investigated the seismic response of structures equipped with FVDs (e.g., see [9,10]). Although a number of procedures have been developed for the design of these structures [11–13], the seismic collapse of these structures has not been extensively investigated. The collapse of structural systems due to strong ground motions is the primary source of casualties and loss of life during earthquakes. Seismic collapse occurs when a structural system is unable to withstand gravity loads under earthquake shaking. In recent years, due to significant advancements in the computational capability of computers and the methods of nonlinear analysis, assessing the seismic collapse of structures has become an interesting field of study for researchers. Thus, several studies have been performed to assess the seismic collapse of structures [14–16], and to develop engineering approaches for seismic collapse assessment. The ATC-63 document [17] presents a new methodology for seismic collapse assessment of structures, to assess design criteria and seismic performance factors existing in seismic codes. Recently, some studies have been performed to assess the seismic collapse of structures equipped with FVDs. For instance, Hamidia et al. [18] proposed a simplified approach to assess the seismic collapse of structures equipped with FVDs. Seo et al. [19] investigated the seismic resistance of steel Moment Resisting Frames (MRFs) with supplemental FVDs against collapse. They observed that in some cases, the collapse mode consists of a combination of beam and column plastic hinges. Karavasilis [20] investigated the effects of column capacity design rules on the collapse performance of MRFs with FVDs. He showed that taller steel MRFs (i.e., 10-story and 20-story MRFs) are

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prone to column plastic hinging.

Intensity Measure (IM) is a parameter that describes the strength of a ground motion and quantifies its effect on structures. In fact, an IM links the output of the ground motion hazard analysis to the seismic response of structure. An optimal IM should meet the requirements of efficiency and sufficiency [21]. In other words, efficiency and sufficiency are the main desirable features of an optimal IM. Efficiency is the ability of an IM to predict the response or capacity of a structure subjected to ground motion with small dispersion, whereas sufficiency is the ability of an IM to predict the response or capacity of a structure conditionally independent of other ground motion properties. In fact, using an efficient IM leads to smaller variability in the structural response or capacity prediction, which allows the use of a lower number of ground motion records in seismic analyses. Moreover, using a sufficient IM reduces the complexity of record selection procedure, because no other ground motion information (i.e., magnitude, source-to-site distance, etc.) is required to predict the structural response or capacity [22,23]. To determine the seismic response or capacity of a structure, ground motion records are scaled, and thus the results may become biased due to record scaling. Another desirable feature of an optimal IM is scaling robustness, which means that the IM is sufficient with respect to Scale Factor (*SF*), when predicting the response or capacity of a structure [23,24]. The last desirable feature of an optimal IM is predictability, that is, the IM should be predictable using a Ground Motion Prediction Equation (GMPE).

In general, IMs are classified into two groups of scalar and vector (e.g., see [25,26]). Common scalar IMs are spectral acceleration at the fundamental period of structure, $Sa(T_1)$, Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) and Peak Ground Displacement (PGD). Shome et al. [27] showed that $Sa(T_1)$ is more efficient and sufficient than PGA. Thus, nowadays, seismic codes throughout the world use $Sa(T_1)$ as the most common scalar IM. It should be noted that when a structure behaves nonlinearly, its fundamental period lengthens. Moreover, higher mode effects may have a significant contribution in the response of a structure. Therefore, spectral regions far away from the fundamental period of a structure, T_1, may play an important role in the response of the structure. Hence, some researchers have proposed more advanced scalar IMs, which contain information about the spectral shape of ground motion records. Cordova et al. [28] proposed a power-law form scalar IM consisting of $Sa(T_1)$ and the ratio of spectral acceleration at a period greater than T_1, $Sa(T_2)$, to $Sa(T_1)$ to account for the period lengthening of structures due to nonlinear deformations. Mehanny [29] enhanced this power-law form IM by defining the lengthened period, T_2, as the multiplication of a nonlinear demand dependent period multiplier by T_1. Baker [30] pointed out that in some cases, an IM which averages spectral acceleration values over a range of periods (i.e., the geometric mean of spectral accelerations over a range of periods) might be a better indicator of structural response. Bojorquez and Iervolino [31] proposed a scalar IM, I_{Np}, which is similar to the power-law form IM proposed by Cordova et al. [28] but uses the geometric mean of spectral accelerations over a range of periods (i.e., T_1 to a lengthened period) instead of $Sa(T_2)$. Although many of the studies in the field of ground motion IMs have focused on investigating the efficiency and sufficiency of IMs to predict the structural response (e.g., [21,32]), due to the importance of assessing the seismic collapse of structures, some studies have focused on investigating the efficiency and sufficiency of IMs for collapse capacity prediction (e.g., [24,33–35]). Eads et al. [34,35] indicated that the geometric mean of spectral accelerations over the period range of $0.2T_1$ to a lengthened period, $3T_1$, is a good scalar IM to predict the collapse capacity of structures. Some researchers (e.g., Chandramohan et al. [36]) showed that ground motion duration has a significant effect on the seismic collapse of structures. Therefore, combining the effect of ground motion duration with the other characteristics of ground motion records (e.g., spectral shape) may lead to advanced optimal IMs for collapse capacity prediction. In fact, using such an idea may progress the state-of-the-art in terms of IMs for predicting the collapse capacity of steel and reinforced concrete Special Moment Resisting Frames (SMRFs). A review on the technical literature existing in the field of investigating the efficiency and sufficiency of IMs indicates that an assessment of the efficiency and sufficiency of IMs to predict the collapse capacity of SMRFs with FVDs has never been performed. Based on the results of the studies performed by Seo et al. [19] and Karavasilis [20], described previously, there may be differences between the collapse mechanisms of steel SMRFs with and without FVDs. Thus, the need for conducting an assessment of the efficiency and sufficiency of IMs to predict collapse capacity of SMRFs with FVDs can be justified.

The aim of this study is to investigate the efficiency and sufficiency of scalar IMs to predict the collapse capacity of steel SMRFs equipped with FVDs. For this aim, 12 low- to mid-rise steel SMRFs and 27 scalar IMs are considered. Then, different levels of supplemental viscous damping are added to each structure, and the collapse capacities of the structures with and without supplemental viscous damping are determined using the IMs. After investigating the efficiency and sufficiency of the IMs, three advanced scalar IMs, including the effects of spectral shape and ground motion duration, are proposed for collapse capacity prediction of the structures. To satisfy the predictability criterion for the proposed IMs, GMPEs are presented for these IMs.

2. Selected IMs

In this study, the considered scalar IMs were classified into two groups: (1) non-structure-specific IMs and (2) structure-specific IMs. Non-structure-specific IMs are obtained only from the time histories of a ground motion record, whereas to calculate structure-specific IMs the spectral components of a ground motion record are involved. It should be mentioned that all of these spectral components are estimated at 5% damping.

The first group includes acceleration-, velocity- and displacement-related IMs. The acceleration-related IMs are Peak Ground Acceleration (PGA), Arias Intensity (AI) [37], characteristic intensity, I_C, [38], the IM proposed by Riddell and Garcia, I_a, [39] and Cumulative Absolute Velocity (CAV) [40]. The velocity-related IMs are Peak Ground Velocity (PGV), Fajfar Intensity (FI) [41], the IM proposed by Riddell and Garcia, I_v, [39], Cumulative Absolute Displacement (CAD) [42] and Specific Energy Density (SED). The displacement-related IMs are Peak Ground Displacement (PGD), the IM proposed by Riddell and Garcia, I_d, [39] and Cumulative Absolute Impulse (CAI). Table 1 presents the non-structure-specific IMs and their definitions.

The second group includes $Sa(T_1)$ as the most common scalar IM, spectral shape based IMs, and combined spectral shape and duration based IMs. The spectral shape based IMs considered in this study are Acceleration Spectrum Intensity (ASI) [43], Spectrum Intensity (SI) [44,45], Displacement Spectrum Intensity (DSI) [46] (which are the integrals of pseudo-acceleration, pseudo-velocity and displacement response spectra, respectively), the power-law form scalar IM proposed by Cordova et al. [28] (IM_C), I_{Np} [31], the power-law form scalar IM proposed by Mehanny [29] (IM_M), and Sa_{avg} [34,35]. IM_C is defined as:

$$IM_C = Sa(T_1)\cdot\left(\frac{Sa\ (T_2)}{Sa\ (T_1)}\right)^{0.5}; \quad T_2 = 2\ T_1 \tag{2}$$

where $T_2 = 2T_1$ is the lengthened period. The enhanced version of IM_C is IM_M that is defined, by changing the lengthened period, as:

$$IM_M = Sa(T_1)\cdot\left(\frac{Sa(T_2)}{Sa(T_1)}\right)^{0.5}; \quad T_2 = R^{\alpha}T_1; \quad \alpha = 0.5 \text{ or } 0.33 \tag{3}$$

where R is the lateral strength required to maintain the system elastic relative to the lateral yielding strength of the system. In this study, the parameter R was assumed as follows: