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Probabilistic residual drift assessment of SMRFs with linear and nonlinear viscous dampers

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ABSTRACT

Maximum Residual Interstory Drift Ratio (MRIDR) is one of the most important Engineering Demand Parameters (EDPs) for evaluating the safety of structures after the occurrence of an earthquake. This EDP is used as an index to decide about the retrofit or demolition of structures. The main purpose of this study is to evaluate the effects of using linear and nonlinear Fluid Viscous Dampers (FVDs) on the MRIDR response of steel Special Moment Resisting Frames (SMRFs) with FVDs. Moreover, two vertical distributions of damping coefficients including Uniform Distribution (UD) and Interstory Drift Proportional Distribution determined based on the first mode deformations (IDPD) are compared for the structures considered. The values of median MRIDR capacity, median Sa_{RD}, corresponding to different MRIDR levels are determined by performing Incremental Dynamic analyses (IDAs). After computing the median Sa_{RD} for a specified MRIDR level and its corresponding logarithmic standard deviation, the Mean Annual Frequency (MAF) of exceeding that MRIDR level (λ_{RD}) is computed. Based on the results, the values of median Sa_{RD} for structures with linear FVDs are higher than those for structures with nonlinear FVDs, and hence the values of λ_{RD} corresponding to structures with linear FVDs are lower than those for structures with nonlinear FVDs. In addition, for structures with a soft story, using IDPD to determine damping coefficients results in higher median Sa_{RD} values, and hence lower λ_{RD} values.

1. Introduction

Maximum Interstory Drift Ratio (MIDR) has been extensively used as an Engineering Demand Parameter (EDP) in most of the previous studies existing in the technical literature. MIDR is the maximum of all peak Interstory Drift Ratios (IDRs) observed along the height of a multi-story frame, where peak IDR for a particular story is the peak of the absolute values of IDR in the IDR time history response of the story. MIDR is a useful parameter to predict structural damage or collapse. Although collapse prediction is an important issue during life of structures, another question is that if structures can be used after strong ground motion or not. Recently, some researchers have focused on investigating Maximum Residual Interstory Drift Ratio (MRIDR) response of structures. Residual Interstory Drift Ratio (RIDR) for a particular story is the last (absolute) value of the IDR time history of the story. The MRIDR is the maximum RIDR of all the stories of the frame. Ruiz-García and Miranda [1] reported that the amplitude and height-wise distribution of residual drift demands strongly depend on building frame mechanism, hysteretic behavior of components, the height-wise system structural overstrength and ground motion intensity. Bojórquez and Ruiz-García [2] concluded that steel structures designed for MIDR demand subjected to narrow-band ground motion records may experience large permanent displacements that may lead to take the decision of demolishing them. Christopoulos et al. [3] reported that residual drift response strongly depends on post-yielding stiffness, maximum ductility demand and unloading stiffness of system. Ruiz-García and Aguilar [4] presented a procedure to evaluate the aftershock seismic performance of structures, which considers residual drift demands after the mainshock. The results of their study indicated that the collapse potential under aftershocks depends on the modeling approach. Moreover, it was concluded that the aftershock capacity corresponding to demolition (i.e., the aftershock capacity corresponding to reaching a residual interstory drift value that necessitates the demolition of structure) is lower than that of the aftershock collapse capacity, which means that this parameter is a better measure of the structure residual capacity against aftershocks. Sultana and Youssef [5] investigated the seismic performance of steel Moment Resisting Frames (MRFs) utilizing superelastic Shape Memory Alloys (SMAs). In their study, maximum and residual interstory drifts were used to assess the seismic performance of the structures considered. They showed that the optimum use of superelastic SMA in the beam to column connections could minimize the residual drifts of the structures. McCormick et al. [6] conducted a study to evaluate the psychological and physiological effects of residual drifts on occupants of buildings in Japan. They reported that residual interstory drifts of about 0.5% are perceptible for occupants

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of building, and reaching a residual interstory drift of 1.0% causes the dizziness of occupants. Thus, they suggested the residual interstory drift of 0.5% as the permissible residual drift level. FEMA P-58 [7] presents a simplified equation to estimate residual drift, and a building repair fragility based on residual drift. Moreover, Appendix C in this document includes a table identifying four levels of residual interstory drift corresponding to four damage states (DS1-DS4). The first level (DS1) is defined as reaching a residual interstory drift of 0.2%, which represents a state that no structural readjustment is required; however, building requires repairs to nonstructural components. The second level (DS2) occurs when residual interstory drift approaches to 0.5%, implying that both structural and nonstructural components require realignment and repair. The third level (DS3) corresponds to a residual interstory drift of 1.0% in which significant structural readjustment is required to maintain the safety of building; however, the repair costs of the building are not economically feasible. Finally, the fourth level (DS4) is known as reaching a residual interstory drift of 1.0% to 4.0% as a function of building ductility, that is, building is in danger of collapse due to aftershocks. These residual interstory drift levels are approximate, and have been determined according to a combination of judgment and limits proposed in FEMA 356 [8]. Kitayama and Constantinou [9] applied four residual interstory drift levels of 0.2%, 0.5%, 1.0% and 2.0%, corresponding to the four aforementioned damage states, for probabilistic assessment of residual drift performance of structures with fluidic self-centering systems.

In recent decades, using supplemental damping systems has been developed to achieve higher performance levels in the design of new structures and improve the seismic performance of existing structures [10]. Among supplemental damping systems, Fluid Viscous Dampers (FVDs), which include linear and nonlinear FVDs, are more widely used [11]. The force generated in a FVD is determined as follows:

$$F = C|\dot{u}|^{\alpha}\ sgn(\dot{u}) \tag{1}$$

where C is the damping coefficient, $\dot{u}$ is the relative velocity between two ends of damper and α is the velocity exponent of damper. A damper with $\alpha = 1.0$ is called linear FVD and a damper with $\alpha \neq 1.0$ is called nonlinear FVD. Christopoulos and Filiatrault pointed out that the value of α is in the range of 0.2–1.0 for seismic applications [12]. FVDs manufactured by Taylor Devices Company [13] have velocity exponents that are in the range of 0.3–1.0, whereas those manufactured by Jarret Structures Company [14] have velocity exponents in the range of 0.1–0.4. Simplicity in design is one of the important advantages of FVDs, which makes them more popular than other dampers [15]. Several studies have been performed on the seismic performance of structures with FVDs. Mansoori and Moghadam [16] investigated using different distributions of FVDs to reduce seismic responses of asymmetric structures. They concluded that the distribution of FVDs has a considerable effect on the modal damping ratios of structures. Kim et al. [17] evaluated the seismic performance of special truss moment frames equipped with FVDs. They showed that adding FVDs to special truss moment frames has the most significant effect on the seismic fragility in the complete damage state. Jamshidiha et al. [18] proposed three advanced scalar Intensity Measures (IMs) to reliably predict the collapse capacity of steel Special Moment Resisting Frames (SMRFs) equipped with FVDs. These IMs include information about the spectral shape and duration of ground motion records. Karavasilis and Seo [19] evaluated the seismic structural and non-structural performance of self-centering and conventional Single-Degree-of-Freedom (SDOF) systems with FVDs. They showed that decreasing the strength of SDOF systems decreases total accelerations, whereas added damping increases total accelerations and decreases residual displacements. However, in some cases, added damping may increase residual displacements of bilinear elastoplastic SDOF systems. Bahnasy and Lavan [20] reported that by decreasing α, MRIDR responses of structures with FVDs increase, whereas damper forces decrease. Different procedures exist in the technical literature, to determine the viscous damping coefficients for a structure equipped with FVDs. Whittaker et al. [21] presented a procedure, which is based on the equivalent lateral force and response spectrum analysis methods of the 2000 NEHRP Provisions [22], for seismic design of buildings with energy dissipation systems. This procedure is the main reference of Chapter 18 in ASCE 7 [23] that is related to the design of new buildings with energy dissipation systems, including buildings equipped with FVDs. Landi et al. [24] proposed a procedure for the direct determination of the supplemental viscous damping required for the seismic retrofit of structures with FVDs. The advantage of this procedure is that it does not require performing several iterations. It is noteworthy that there are several vertical distributions of damping coefficients in the technical literature. Some of these distributions are Uniform Distribution (UD), Mass Proportional Distribution (MPD), Story Stiffness Proportional Distribution (SSTPD), Story Shear Proportional Distribution (SSPD) and Interstory Drift Proportional Distribution determined based on the first mode deformations (IDPD) [25].

Nowadays, the seismic assessment of existing structures and design of new structures is often performed by employing probabilistic approaches, such as that outlined by the Performance-Based Earthquake Engineering (PBEE) framework [26–29], developed by researchers in Pacific Earthquake Engineering Research (PEER) center. The PEER PBEE framework has four stages including seismic hazard analysis, seismic demand analysis, damage analysis and loss analysis. The result of each stage is expressed by an intermediate variable. These intermediate variables are IM, EDP, Damage Measure (DM) and Decision Variable (DV), respectively. One of the important issues in using the PEER PBEE framework is to select the proper EDP. EDPs are important parameters to evaluate the seismic performance of structures, and include structural responses such as force, maximum floor acceleration, MIDR, MRIDR, etc. By applying the two first stages of the PEER PBEE framework, the Mean Annual Frequency (MAF) of exceeding a specified level of an EDP can be obtained. Dall'Asta et al. [30] showed that MAFs of exceeding low levels of MIDR (e.g., MIDR < 0.01) for structures with nonlinear FVDs are lower than those for structures with linear FVDs, whereas for higher levels of MIDR, the trend is reversed. Tubaldi et al. [31] evaluated the effects of nonlinear behavior of FVDs on seismic response of SDOF systems in a probabilistic framework. They concluded that using deterministic approaches that neglect the dispersion of response has some limitations for the assessment of system reliability. Dall'Asta et al. [32] investigated the effect of variability in FVD properties due manufacturing on the probabilistic performance of SDOF systems equipped with linear and nonlinear FVDs. They concluded that short-period SDOF systems are more sensitive to FVD property variation than long-period ones. In the last decade, MRIDR is one of the important EDPs that has attracted the attention of researchers. Ruiz-García and Miranda [33] implemented a probabilistic approach to estimate MRIDR demands in buildings, and used this approach to compute residual drift demand hazard curves for multi-story frames. Kitayama and Constantinou [9] reported that the important parameter affecting the residual drift fragilities of structures with fluidic self-centering systems is the increase in the ultimate capacity of self-centering device-brace system. Daylami and Mahdavipour [34] performed a probabilistic assessment of MRIDR response of dual systems including Buckling Restrained Braced Frames (BRBFs). By comparing the obtained residual drift demand hazard curves, they concluded that using BRBFs as a dual system significantly improves the residual drift performance, when compared with using BRBFs alone. Although there are some studies, in the technical literature, that have evaluated MAFs of exceeding different MRIDR levels, but research works on probabilistic assessment of MRIDRs for structures with FVDs are rare. Dimopoulos et al. [35] investigated the potential of post-tensioned Self-Centering Moment Resisting Frames (SC-MRFs) and FVDs to mitigate the economic seismic losses in steel buildings. They considered both the probability of collapse and the probability of demolition due to excessive RIDRs, using the PEER PBEE methodology, and concluded that supplemental viscous damping is