Performance of Vector-valued Intensity Measures for Estimating Residual Drift of Steel MRFs with Viscous Dampers

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Abstract—**Viscous Dampers (VDs) are widely used as passive energy dissipation system for improving seismic performance levels especially in retrofitting of buildings. Residual Inter-story Drift Ratio (R-IDR) is another important factor that specifies the condition of building after earthquake. The values of R-IDR illustrates the possibility of retrofitting and repairing of a building. Therefore, this study aims to explore the vector-valued Intensity Measures (IMs) for predicting the R-IDR of two group of steel Moment-Resisting Frames (MRFs) with and without implementing VDs. Incremental Dynamic Analysis (IDA) was performed with considering RIDR using OpenSees software. Efficiency and sufficiency have been quantified for 18 vector-valued IMs with respect to the Residual Interstory Drift Ratio (R-IDR). Results showed that two vector-valued IMs of ($Sa(T_1)$, $SaRatio_{M-D}$) and ($Sa(T_1)$, I_{M-D}) had lower $\sigma lnSa_{RD}|IM_2$ values in the R-IDR of 0.002, 0.005, 0.01, and 0.02, and they had higher FR in the mean dispersion, (σlnSaRD|IM2)avg, compared to other IMs. In addition, two vector-valued IMs of ($Sa(T_1)$, $SaRatio_{M-D}$) and ($Sa(T_1)$, I_{M-D}) achieved p-values higher than 0.05 with respect to seismic ground motion features of M, R, and Vs30, and can be used as optimal vector-valued IMs.**

Index Terms— **Vector-valued intensity measure, Spectral shape, Residual drift assessment, viscous damper, Incremental dynamic analysis.**

I. Introduction

It was shown that some uncertainty in the ground motion intensity, known as Intensity Measure (IM), has some limitation for describing the seismic demands. Therefore, identifying a simple while practical IM that presents the key features of the ground motion record was the main purpose of many researchers. Some studies focused on the mathematical methods to identify the pulses in the acceleration series using continuous wavelet transformation [1, 2], while these methods are more complicated for seismic design procedures. IMs can be described based on either scalar-valued or vector-valued IMs [3, 4]. To overcome the insufficiency of some scalar-valued IMs, vector-valued IMs have been proposed to incorporate spectral ordinates at other than fundamental period known as T_1 [5, 6]. It is worth to mention that all these IMs are used for assessing the seismic response of structures or the seismic collapse capacity of structures considering interstory drift ratio as engineering demand parameter (EDP) [7-9]. While the maximum Residual Interstory Drift Ratio (R-IDR) plays a crucial role for retrofitting decision and repairing cost of a building during severe earthquake [10-12]. For example, several buildings, damaged during the 1985 Michoacán earthquake in Mexico City, had to be demolished due to the large residual drifts of columns [13]. Many researchers recommended that the estimation of residual displacement could be significant in design procedures and also the seismic performance evaluation of existing structures [14, 15]. During the past two decades, some numerical studies identified that the post-yield stiffness ratio (i.e. ratio of post-yield stiffness to initial elastic stiffness) is one of the main parameters affecting residual deformations [16, 17]. Moreover, the ground motion intensity, the component hysteretic behavior, and the over-strength of structure can influence the residual drift amplitude and distribution over the height. In addition, some studies have been conducted to investigate the seismic collapse capacities and seismic performance levels of steel buildings using $S_a(T_1)$ as IM [18, 19]. This paper aims to investigate the vector-valued IMs for predicting R-IDR of the steel Moment-Resisting Frames (MRFs) considering Viscous Dampers (VDs). This study proposes optimal vector-valued IMs based on the efficiency and sufficiency of the IM with a certain confidence level. The proposed IMs can be used in

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nonlinear dynamic analysis to achieve seismic response of structures with high reliability.

II. Vector-Valued Intensity Measure

This paper aims to elaborate the vector-valued IMs for predicting the R-IDR of two group of steel Moment-Resisting Frames (MRFs) to improve the quantification of ground motion records. In this section, 18 vector-valued IMs are defined as (IM_1, IM_2). In this definition, spectral acceleration at the fundamental period of the structure, T_1, known as $Sa(T_1)$, was selected as IM_1, and IM_2 was selected as the un-scalable part with no changing during the scaling the ground motion record. Table I presents the vector-valued IMs assumed in this study and their definition [4].

TABLE I. Vector-Valued IMs Assumed in This Study.

Name	Definition
$(Sa(T_1), PGA/PGV)$	$PGA=\max\lvert a(t)\rvert$, $PGV=\max\lvert v(t)\rvert$
$(Sa(T_1), PGA/PGD)$	$PGD=\max\lvert d(t)\rvert$
$(Sa(T_1), PGV/PGD)$	
$(Sa(T_1), Sa(T_1)/PGA)$	
$(Sa(T_1), Sa(T_1)/PGV)$	
$(Sa(T_1), Sa(T_1)/PGD)$	
$(Sa(T_1), Sa(T_1)^2/AI)$	AI(Arias Intensity)= $\frac{\pi}{2g}\int_0^{t_f} a(t)^2 dt$, t_f = *total duration*
$(Sa(T_1), Sa(T_1)/ASI)$	ASI= $\int_{0.1}^{0.5} Sa(T,5\%)\,dt$
$(Sa(T_1), Sa(T_1)/SI)$	SI(Spectrum Intensity)= $\int_{0.1}^{2.5} Sv(T,5\%)\,dt$
$(Sa(T_1), Sa(T_1)/DSI)$	DSI= $\int_{2}^{5} Sd(T,5\%)\,dt$
$(Sa(T_1), t_d)$	$t_d = t_2 - t_1;\ t_1 = 0.05AI,\ t_2 = 0.95AI$
$(Sa(T_1), I_D)$	$I_D = \int_0^{t_f} a(t)^2 dt\,/\,(PGA.\,PGV)$
$(Sa(T_1), A(T_1)_2/Sa(T_1))$	$A(T_1)_2 = \int_{T1}^{2T1} Sa(T)\,dt$
$(Sa(T_1), R_{T1,T2})$	$R_{T1,T2} = Sa(T_2)/Sa(T_1);\ T_2 = 2T_1$
$(Sa(T_1), N_P)$	$Np = Sa_{avg}(T_1..T_N)/S_a(T_1);\ T_N = 2T_1$
$(Sa(T_1), SaRatio)$	$SaRatio = Sa(T_1)/Sa_{avg}(C_1T_1..C_NT_1)$; $C_1 = 0.2, C_N = 3$
$(Sa(T_1), I_{M-D})$	$I_{M-D} = (S_a(T_2)/S_a(T_1))t_d^{\beta}$; $T_2 = R^{\alpha}T_1, \alpha=0.3, \beta=0.3$
$(Sa(T_1), SaRatio_{M-D})$	$SaRatio_{M-D} = Sa(T_1)/(Sa_{avg}(C_1T_1..C_NT_1)t_d^{\beta})$; $C_1 = 0.6,\ C_N = R^{\alpha}$

III. Models and Designing Process

To better investigate the reliability of vector-valued IMs, two group of steel Moment-Resisting Frames (MRFs) were modeled. The first group includes the 3-Story, 6-Story, and 9-Story-SAC steel MRFs that were used in the SAC project [20] and can be find in detail in FEMA 355C [21]. Fig. 1 illustrates the dimensions and configuration of the 3-Story, 6-Story, and 9-Story-Reference steel MRFs with implementing the linear VDs. The second group includes the 3-Story, 6-Story, and 9-Story-SAC steel MRFs that were used by Kazemi et al. [22-25] and designed in accordance with ASCE07-10 [26]. Fig. 2 illustrates the dimensions and configuration of the 3-Story, 6-Story, and 9-Story-Reference steel MRFs with implementing the linear VDs. It should be noted that the linear VDs were implemented as a retrofitting strategy to improve the seismic performance levels of the considered steel MRFs. The P-Delta effects play a crucial role in the seismic vulnerability assessment of steel MRFs and should be considered in modeling procedure. Therefore, all columns except those in the steel MRFs were considered as the leaning column that was used by many researcher for considering the P-Delta effects [7, 19, 22-26] to model structures in OpenSees [28]. Moreover, a concentrated plasticity model which includes the nonlinear rotational spring with nonlinear behavior of the Modified Ibarra–Krawinkler bilinear-hysteretic model was used in modeling of the structural elements like as beams and columns [1, 2, 7-9, 29-31].

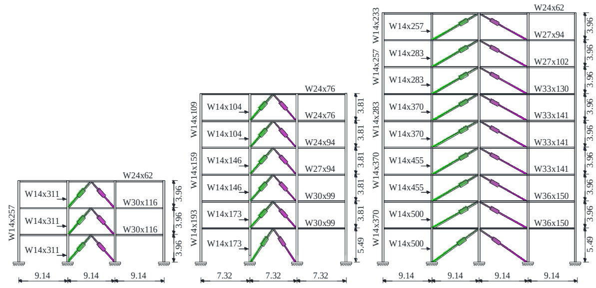

Figure 1. Documentation of the 3-Story, 6-Story, and 9-Story-SAC steel MRFs with implementing the linear VDs.

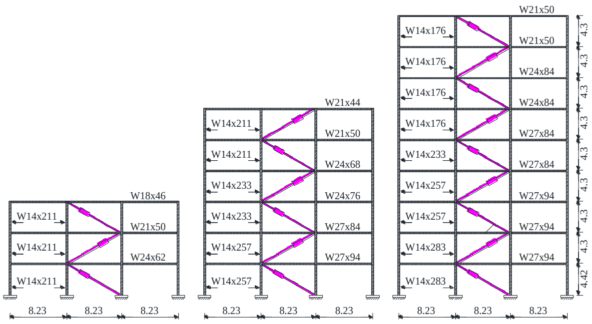

Figure 2. Documentation of the 3-Story, 6-Story, and 9-Story-Reference steel MRFs with implementing the linear VDs.

Previous studies showed that linear VDs could improve the seismic performance levels of structures more than nonlinear VDs [8, 22-24]. Therefore, in this study, the linear VDs were implemented in the aforementioned steel MRFs. For this purpose, a uniform vertical distribution of damping coefficients was assumed, and the supplemental viscous damping ratio of 0.15 (ξ_{VD}=0.15) was considered, which can be calculated from following equations:

$$\xi_{VD} = \frac{\sum_{i=1}^{N_D} (\ \pi)\ \lambda_i\ C_i\ T_1\ \cos\theta_i\ ^2\ \varphi_{ri1}^2}{8\pi^3.\sum_{j=1}^{Ns} m_j.\varphi_{j1}^2} \quad (1)$$

$$C_{VD} = \frac{\xi_{VD}.8\pi^3.\sum_{j=1}^{Ns} m_j.\varphi_{j1}^2}{\sum_{i=1}^{N_D}\ \pi\ \lambda_i\ T_1\ \cos\theta_i\ ^2\ \varphi_{ri1}^2} \quad (2)$$

Where N_D presents the number of VDs, C_i presents the damping coefficient, N_s presents the number of story levels, θ_i presents the angle of damper direction, m_j presents the mass of each story, φ_{ri1} presents the first mode component at the top of the story, and φ_{j1} presents the relative deformation between two ends of the VD. In addition, C_{VD} can be used to calculate the damping coefficient for all linear VDs. To perform Incremental Dynamic Analysis (IDA), ground motion records considered by Jamshidiha et al. [3, 4] were used. In addition, four $RIDR_{max}$ of 0.2%, 0.5%, 1.0%, and 2.0% were assumed according to Yahyazadeh et al. [32].

IV. Investigating the Efficiency of the IMs

This section investigates the efficiency of the vector-valued IMs. The efficiency of an IM describes as the ability of the IM to predict the R-IDR of steel MRFs with lower dispersion compared to other assumed IMs. The dispersion of the IMs for predicting R-IDR can be compared using the logarithmic standard deviation of IM values known as $\sigma lnSa_{RD}|IM_2$. Fig. 3 presents the comparison of $\sigma lnSa_{RD}|IM_2$ values for vector-valued IMs in the 3-Story-SAC, 6-Story-SAC, and 9-Story-SAC steel MRFs, without and with implementing linear VDs, respectively. According to Fig. 3, it can be seen that in the 3-Story-SAC steel MRF, ($Sa(T_1)$, $SaRatio_{M-D}$) achieved $\sigma lnSa_{RD}|IM_2$ values of 0.26, 0.36, 0.33, and 0.24 in the R-IDR of 0.002, 0.005, 0.01, and 0.02, respectively, which were lower than other IMs.

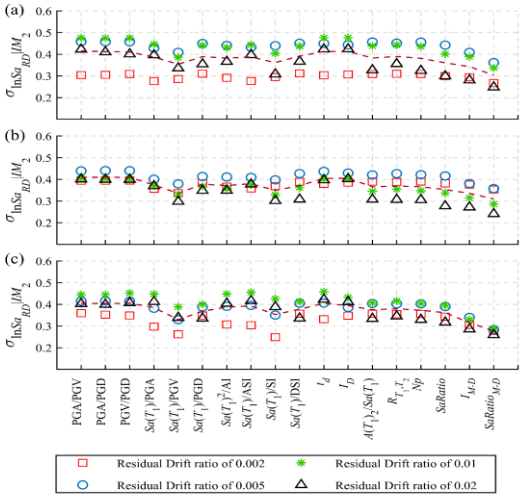

Figure 3. Comparison of $\sigma lnSa_{RD}|IM_2$ values for vector-valued IMs in the, a) 3-Story-SAC, b) 6-Story-SAC, and c) 9-Story-SAC steel MRFs.

For the 6-Story-SAC steel MRF, ($Sa(T_1)$, $SaRatio_{M-D}$) achieved $\sigma lnSa_{RD}|IM_2$ values of 0.35, 0.28, and 0.24 in the R-IDR of 0.005, 0.01, and 0.02, respectively, and for the 9-Story-SAC steel MRF, ($Sa(T_1)$, $SaRatio_{M-D}$) achieved $\sigma lnSa_{RD}|IM_2$ values of 0.28, 0.28, and 0.25 in the R-IDR of 0.005, 0.01, and 0.02, respectively. Similarly, ($Sa(T_1)$, $SaRatio_{M-D}$) achieved the lowest $\sigma lnSa_{RD}|IM_2$ values in the 3-Story-SAC, 6-Story-SAC, and 9-Story-SAC steel MRFs with implementing linear VDs.

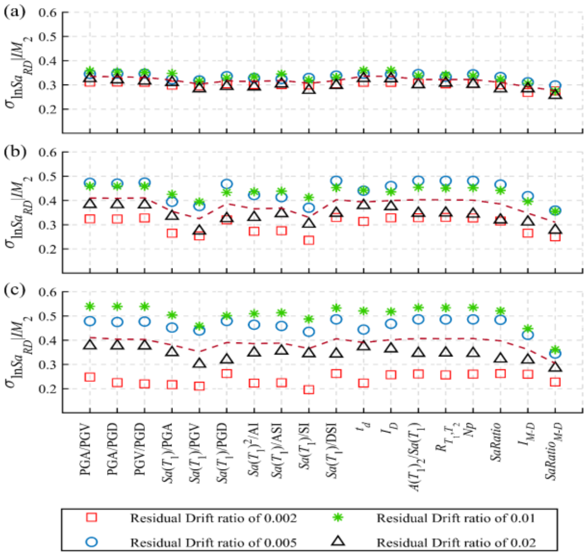

Figure 4. Comparison of $\sigma lnSa_{RD}|IM_2$ values for vector-valued IMs in the, a) 3-Story-Reference, b) 6-Story-Reference, and c) 9-Story-Reference steel MRFs.

Therefore, this vector-valued IM had the highest efficiency compared to other IMs. Fig. 5 presents comparison of $\sigma lnSa_{RD}|IM_2$ values for vector-valued IMs in the 3-Story-Reference, 6-Story-Reference, and 9-Story-Reference steel MRFs without and with implementing linear VDs, respectively. It can be seen that ($Sa(T_1)$, $SaRatio_{M-D}$) had the lowest $\sigma lnSa_{RD}|IM_2$ values in this group of structures and can be selected as optimal vector-valued IM regarding the efficiency. Table II illustrates Fractional Reduction (FR) in the mean dispersion, (σlnSaRD|IM2)avg, determined in the vector-valued IMs with and without linear VDs for four selected IMs with lower $\sigma lnSa_{RD}|IM_2$ values. It can be seen that ($Sa(T_1)$, $SaRatio_{M-D}$) and ($Sa(T_1)$, I_{M-D}) had higher FR compared to other IMs.

TABLE II. Fractional Reduction (FR) in $(\Sigma LNSA_{RD}|IM_2)$AVG Determined in the Vector-Valued IMs with and without Linear VDs.

		Sa(T1)/PGV		*Sa(T1)/SI*		*IM-D*		*SaRatioM-D*	
		$(\sigma lnIM_{RD})_{avg}$	FR (%)	$(\sigma lnIM_{RD})_{avg}$	FR (%)	$(\sigma lnIM_{RD})_{avg}$	FR (%)	$(\sigma lnIM_{RD})_{avg}$	FR (%)
Without VD	RD=0.2%	0.27	16.25	0.27	16.22	0.29	9.89	0.28	15.89
	RD=0.5%	0.38	13.80	0.39	11.17	0.38	12.74	0.33	23.31
	RD=1%	0.38	15.18	0.40	11.28	0.36	18.56	0.32	29.04
	RD=2%	0.31	21.05	0.32	17.19	0.29	24.51	0.26	32.48
With VD	RD=0.2%	0.30	14.46	0.31	10.34	0.30	13.06	0.27	21.72
	RD=0.5%	0.38	12.78	0.40	6.95	0.36	17.05	0.32	26.64
	RD=1%	0.40	11.73	0.42	7.27	0.38	15.83	0.34	25.74
	RD=2%	0.37	14.03	0.39	9.70	0.32	25.75	0.28	34.57

V. Investigating the Sufficiency of the IMs

This section investigates the sufficiency of the vector-valued IMs. The sufficiency of an IM describes as the ability of the IM to predict the R-IDR of steel MRFs with lower independency to ground motion properties such as source to site distance, known as R, ground motion magnitude, known as M, and the average shear wave velocity, known as Vs30. The lower independency to ground motion properties can cause that the IM be sufficient for seismic R-IDR assessment without biased results. To compare the sufficiency of the vector-valued IMs, the p-value of the considered IMs was calculated, which the p-value should be higher than 0.05 to imply the sufficiency of the IM. Fig. 5 presents the comparison of the p-value for four vector-valued IMs for predicting R-IDR of assumed steel MRFs without and with implementing linear VDs in the seismic features of M, R, and Vs30, respectively. It is obvious that two vector-valued IMs of ($Sa(T_1)$, $SaRatio_{M\text{-}D}$) and ($Sa(T_1)$, $I_{M\text{-}D}$) had higher p-values in the predicting the R-IDR of the all considered steel MRFs with and without VDs regarding seismic features of, M, R, and Vs30.

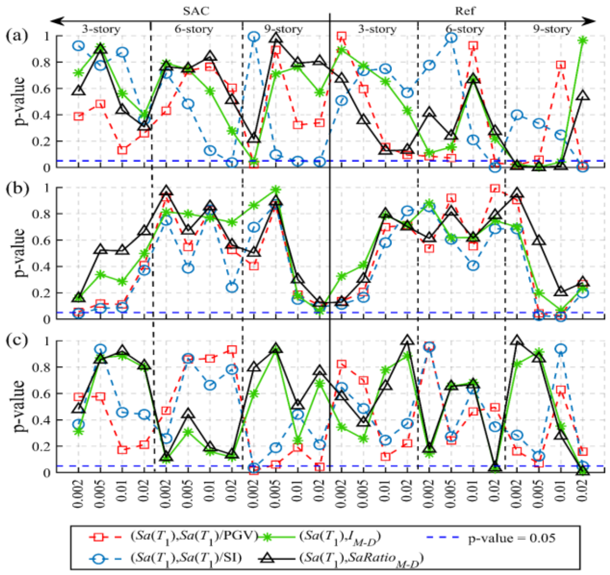

Figure 5. Comparison of the p-value for four vector-valued IMs for predicting R-IDR of assumed steel MRFs with seismic features of, a) M, b) R, and c) Vs30.

Therefore, two vector-valued IMs of ($Sa(T_1)$, $SaRatio_{M\text{-}D}$) and ($Sa(T_1)$, $I_{M\text{-}D}$), which had the efficiency and sufficiency factors are proposed as optimal vector-valued IMs for predicting R-IDR of steel MRFs with and without VDs. Table III illustrates the percent of structures with p-values ≥ 0.05 obtained for vector-valued IMs with respect to the seismic features of M, R, and Vs30. The results showed that two vector-valued IMs of ($Sa(T_1)$, $SaRatio_{M\text{-}D}$) and ($Sa(T_1)$, $I_{M\text{-}D}$) had higher percent of structures with p-values ≥ 0.05.

TABLE III. Percent of Structures with p-values ≥ 0.05 Obtained for Vector-Valued IMs with Respect to the Seismic Features of M, R, and Vs30.

		% of structures with p-values ≥ 0.05		
	IM	**M**	**R**	**Vs30**
Without VDs	**($Sa(T_1)$, $Sa(T_1)$/PGV)**	25	100	87.5
	($Sa(T_1)$, $Sa(T_1)$/SI)	91.67	91.67	91.67
	($Sa(T_1)$, IM-D)	87.5	100	95.83
	($Sa(T_1)$, SaRatioM-D)	95.83	100	91.67
With VDs	**($Sa(T_1)$, $Sa(T_1)$/PGV)**	54.17	100	81.5
	($Sa(T_1)$, $Sa(T_1)$/SI)	91.67	100	81.5
	($Sa(T_1)$, IM-D)	95.83	95.83	83.33
	($Sa(T_1)$, SaRatioM-D)	89.17	100	91.67

VI. Conclusion

In this study, the efficiency and sufficiency of 18 vector-valued IMs for predicting the R-IDR of two group of the 3-Story, 6-Story, and 9-Story-SAC steel MRFs and the 3-Story, 6-Story, and 9-Story-Reference steel MRFs with and without VDs were investigated. Results of analyses showed that two vector-valued IMs of ($Sa(T_1)$, $SaRatio_{M\text{-}D}$) and ($Sa(T_1)$, $I_{M\text{-}D}$) had lower $\sigma lnSa_{RD}|IM_2$ values in the R-IDR of 0.002, 0.005, 0.01, and 0.02, which showes the efficiency of these IMs. In addition, two vector-valued IMs of ($Sa(T_1)$, $SaRatio_{M\text{-}D}$) and ($Sa(T_1)$, $I_{M\text{-}D}$) achieved higher FR in the mean dispersion, (σlnSaRD|IM2)avg, compared to other IMs. The p-value of ($Sa(T_1)$, $SaRatio_{M\text{-}D}$) and ($Sa(T_1)$, $I_{M\text{-}D}$) with respect to seismic ground motion features of M, R, and Vs30, were higher than 0.05, which shows the sufficiency of assumed IMs. In can be concluded that two vector-valued IMs of ($Sa(T_1)$, $SaRatio_{M\text{-}D}$) and ($Sa(T_1)$, $I_{M\text{-}D}$) could be used as optimal vector-valued IMs for predicting the R-IDR of steel MRFs.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Benyamin Mohebi was the supervisor; Farzin Kazemi and Neda Asgarkhani conducted the research and analyzed the data, Pinar Ghasemnezhadsani and Anahita Mohebi wrote the paper; all authors had approved the final version.

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