Advanced Scalar-valued Intensity Measures for Residual Drift Prediction of SMRFs with Fluid Viscous Dampers

Farzin Kazemi [1*], Benyamin Mohebi [2], Neda Asgarkhani [1], and Atefeh Yousefi [3]

[1] Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, Poland; Email: mohebi@eng.ikiu.ac.ir

[2] Faculty of Engineering and Technology, Imam Khomeini International University, Qazvin, Iran; Email: neda.asgarkhani@pg.edu.pl

[3] Faculty of Engineering, Zanjan University, Zanjan, Iran; Email: atyousefi@gmail.com

*Correspondence: farzin.kazemi@pg.edu.pl

***Abstract*—Maximum Residual Inter-story Drift Ratio ($RIDR_{max}$) plays an important role to specify the state of a structure after severe earthquake and the possibility of repairing the structure. Therefore, it is necessary to predict the $RIDR_{max}$ of Steel Moment-Resisting Frames (SMRFs) with high reliability by employing powerful Intensity Measures (IMs). This study investigates the efficiency and sufficiency of scalar-valued IMs for predicting $RIDR_{max}$ of two sets of the 3-Story, 6-Story, and 9-Story SMRFs with and without using linear Fluid Viscous Dampers (FVDs). Incremental Dynamic Analysis (IDA) was performed with considering $RIDR_{max}$ as engineering demand parameters using Opensees. Results of analysis showed that two scalar-valued IMs of $IM_M(\alpha=0.5)$ and $Sa_{avg\ M\text{-}D}$ had lower values of the variations of standard deviation of natural logarithm of IM of $RIDR_{max}$, $\sigma lnIM_{RD}$, which shows the efficiency of these IMs. Moreover, these scalar-valued IMs achieved higher *p*-values with respect to seismic ground motion features of M, R, and Vs30, which shows the sufficiency of assumed IMs. Therefore, two scalar-valued IMs of $IM_M(\alpha=0.5)$ and $Sa_{avg\ M\text{-}D}$ are proposed as optimal scalar-valued IMs for predicting the $RIDR_{max}$ of SMRFs.**

***Keywords*—scalar-valued intensity measure, residual drift, spectral shape, fluid viscous damper, incremental dynamic analysis**

I. Introduction

Reliable design of structures against natural hazards such as earthquakes requires fully understanding the influence of seismic parameters on the structural behavior [1-5]. Hence, it is vital to identify ground motion properties, which are referred to as Intensity Measures (IMs), to assess the seismic response of buildings. The IMs are used to quantify the severity of a seismic event and uncertainty of them using one parameter or a vector of a few parameters. These parameters are related to a set of well-selected ground motion records. Efficiency, which is the most important characteristic of an IM, means good explanatory power of the IM regarding Engineering Demand Parameter (EDP) to reduce the number of records of analysis under given accuracy. While sufficiency means the ability of the IM for predicting the response of structure independent from other record properties. Therefore, an appropriate IM should satisfy the properties of efficiency and sufficiency [6-8]. In general, IMs are divided into two groups of scalar-valued and vector-valued IMs according to the dimension of parameters (e.g., see [9, 10]). Scalar-valued IMs imply the relationship between IM and EDP in a two-dimensional coordinate system using one parameter. Within the past years, numerous research studies comprehensively investigated the scalar-valued IMs, the peak ground acceleration (PGA), and elastic spectral acceleration (S_a) at the fundamental period of a structure, denoted as T_1, were introduced as the most-used scalar IMs [11-14]. Recent seismic events have demonstrated that some damaged buildings may need to be demolished due to excessive permanent lateral deformations at the end of the earthquake, even without suffering total collapse or severe damages. Therefore, maximum Residual Inter-story Drift Ratio ($RIDR_{max}$) at all story levels or roof play a crucial role in defining the seismic performance of the structure, determining the feasibility of retrofitting damaged structure as well as estimating the structural residual capacity [15, 16]. Therefore, the main aim of this study is to investigate the performance of scalar-valued IMs to calculate $RIDR_{max}$ of Steel Moment-Resisting Frames (SMRFs) with and without using Fluid Viscous Dampers (FVDs). Thereby, this study proposes three "optimal" scalar-valued IMs based on the effects of spectral shape and ground motion duration for predicting $RIDR_{max}$ of the framed steel structures within a certain confidence level.

II. Scalar-valued Intensity Measure

The scalar-valued IMs can be categorized into two groups as structure-specific IMs and non-structure-specific IMs including 12 and 13 IMs, respectively (see Tables I and II [7]). In this study, structure-specific IMs are further categorized into three groups as spectral,

Manuscript received October 2, 2022; revised November 11, 2022; accepted December 21, 2022.

doi: 10.18178/ijscer.12.1.20-25

spectral shape-based and combined spectral shape-based and duration-based. Similarly, non-structure-specific IMs are also classified into three sets as acceleration-related (including five IMs), velocity-related (including five IMs) and displacement-related (including three IMs). It is worth noting here that structure-specific IMs, employed in this study, are calculated from the response of the spectral components of a ground motion record assuming 5% damping value. Whereas, non-structure-specific IMs are obtained from the ground-motion time histories (further information can be found in [7]). Based on the literature review, Tables I and II present scalar-valued IMs that were used in this study.

TABLE I. NON-STRUCTURE-SPECIFIC SCALAR-VALUED IMS

Notation	Name	Definition
Acceleration-related scalar-valued IMs		
PGA	Peak Ground Acceleration	$\text{PGA}=\max\lvert a(t)\rvert$
AI	Arias Intensity	$\text{AI}=\frac{\pi}{2g}\int_0^{t_f} a(t)^2 dt$, $t_f = total duration$
I_C	Characteristic Intensity	$\text{IC}=(a_{rms})^{1.5} t_d^{\ 0.5}$, $a_{rms}=\sqrt{\frac{1}{t_d}\int_{t1}^{t2} a(t)^2 dt}$, $t_d = t_2 - t_1$
I_a	Compound Acceleration IM	$\text{IA}=\text{PGA}.t_d^{\ 1/3}$
CAV	Cumulative Absolute Velocity	$\text{CAV}=\int_0^{t_f} \lvert a(t)\rvert\, dt$
Velocity-related scalar-valued IMs		
PGV	Peak Ground Velocity	$\text{PGV}=\max\lvert v(t)\rvert$
FI	Fajfar Intensity	$\text{FI}=\text{PGV}.t_d^{\ 0.25}$
I_V	Compound Velocity IM	$I_v=\text{PGV}^{2/3}.t_d^{\ 1/3}$
CAD	Cumulative Absolute Displacement	$\text{CAD}=\int_0^{t_f} \lvert v(t)\rvert\, dt$
SED	Specific Energy Density	$\text{SED}=\int_0^{t_f} v(t)^2 dt$
Displacement-related scalar-valued IMs		
PGD	Peak Ground Displacement	$\text{PGD}=\max\lvert d(t)\rvert$
I_d	Compound Displacement IM	$I_d=\text{PGD}.t_d^{\ 1/3}$
CAI	Cumulative Absolute Impulse	$\text{CAI}=\int_0^{t_f} \lvert d(t)\rvert\, dt$

TABLE II. STRUCTURE-SPECIFIC SCALAR-VALUED IMS

Notation	Name	Definition
Spectral and spectral-shaped scalar-valued IMs		
$S_a(T_1)$	Spectral Acceleration at T_1	
ASI	Acceleration Spectrum Intensity	$\text{ASI}=\int_{0.1}^{0.5} Sa(T,5\%)dt$
SI	Spectrum Intensity	$\text{SI}=\int_{0.1}^{2.5} Sv(T,5\%)dt$
DSI	Displacement Spectrum Intensity	$\text{DSI}=\int_{2}^{5} Sd(T,5\%)dt$
IM_C		$\text{IM}_C=S_a(T_1).(S_a(T_2)/S_a(T_1))^{0.5}$, $T_2=2T_1$
IM_M		$\text{IM}_M=S_a(T_1).(S_a(T_2)/S_a(T_1))^{0.5}$, $T_2=R^{\alpha}T_1$, $\alpha=0.5\ or\ 0.3$
I_{NP}		$I_{NP}=\text{Sa}(T_1).NP^{0.4}$, $\text{NP}=\text{Sa}_{avg}(T_1..T_N)/S_a(T_1)$
Sa_{avg}		$\text{Sa}_{avg}=\text{Sa}_{avg}(C_1T_1..C_NT_1)=\left(\prod_{i=1}^{N}\text{Sa}(C_iT_1)\right)^{1/N}$, $C_1=0.2, C_N=3$
Combined spectral duration and shape scalar-valued IMs		
$IM_{M\text{-}D}$		$\text{IM}_{M-D}=S_a(T_1).(S_a(R^{\alpha}T_1)/S_a(T_1))^m t_d^{\ \beta}$
$I_{NP\ M\text{-}D}$		$I_{NPM-D}=Sa(T_1).(\text{Sa}_{avg}(T_1..T_N)/S_a(T_1))^n t_d^{\ \beta}$, $T_N=R^{\alpha}T_1$
$Sa_{avg\ M\text{-}D}$		$\text{Sa}_{avg\,M-D}=\text{Sa}_{avg}(C_1T_1..C_NT_1)t_d^{\ \beta}, C_N=R^{\alpha}$

III. STRUCTURAL MODELING

In order to investigate efficiency and sufficiency of assumed scalar-valued IMs, two sets of SMRFs were considered. The first set includes the 3-, 6-, and 9-Story-SAC SMRFs that were designed for SAC project [17] and the detail of designing process can be found in FEMA 355C [18]. Fig. 1 depicts the elevation, section and arrangement of the FVDs on 3-, 6- and 9-Story-SAC SMRFs. The second set includes the 3-, 6-, and 9-Story-Ref SMRFs, designed by Kazemi et al. [19, 20] according to ASCE 7-10 [21]. Fig. 2 depicts the elevation, section and arrangement of the FVDs on the 3-, 6- and 9-Story-Ref SMRFs. The FVDs were placed diagonally within SMRFs to improve seismic performance of these structures. During last decade, many researchers focused on the importance of P-Delta effect, and some approaches were used to considering the P-Delta effect [see e.g. 1, 13, 22-25].

In this study, it was assumed all columns except those in the SMRFs behaves like as a leaning column to consider the P-Delta effects. In addition, to improve accuracy of modeling in OpenSees [26], deteriorating moment-rotation hysteresis according to the Modified Ibarra–Krawinkler bilinear-hysteretic model was used for beams and columns of the SMRFs. To find out the efficiency and sufficiency of proposed scalar-valued IMs, the improved SMRFs using linear FVDs were considered.

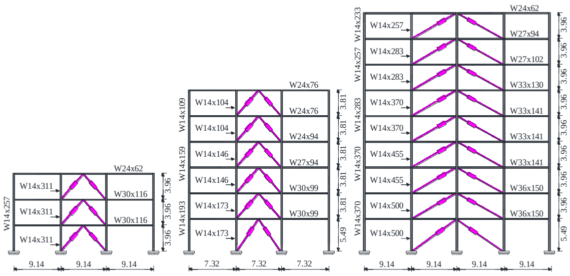

Figure 1. Dimensions and configuration of the linear FVDs on the 3-, 6- and 9-Story-SAC SMRFs.

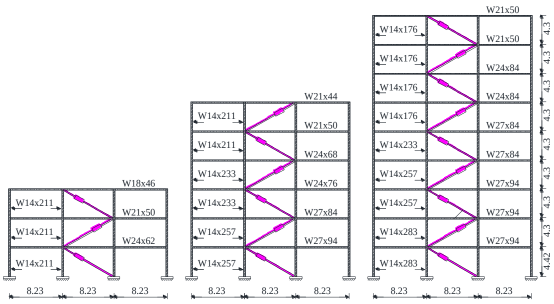

Figure 2. Dimensions and configuration of the linear FVDs on the 3-, 6- and 9-Story-Ref SMRFs.

To model linear FVDs, a uniform vertical distribution of damping coefficients were generated assuming a five percent Rayleigh damping ratio for the first and third modes of structures and supplemental viscous damping ratio of 0.15 (ξ_D=0.15). The supplemental viscous damping ratio can be calculated as follows [2, 19, 27]:

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

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

where the number of the FVD devices, N_D, the damping coefficient, C_i, the fundamental period of vibration, T_1, the number of stories, N_s, the mass of story, m_j, the angle of damper direction, θ_i, can be defined based on the characteristics of designed SMRFs. In addition, other parameters like as the relative deformation between the horizontal degrees of freedom at the ends of the FVDs, φ_{ri1}, the first mode component at the top of the story, φ_{j1}, can be achieved from the models. In order to use a uniform vertical distribution of damping coefficients, the Equation (2) was rearranged to calculate the damping coefficient for all linear FVDs, C_D. To perform Incremental Dynamic Analysis (IDA), ground motion records considered by Jamshidiha et al. [7, 8] were used. In addition, four $RIDR_{max}$ of 0.2%, 0.5%, 1.0%, and 2.0% were assumed according to Yahyazadeh et al. [28].

IV. Investigating the Efficiency of the IMs for Residual Drift Prediction

Achieving the $RIDR_{max}$ is essential for vulnerability assessment of a structure after a severe earthquakes, which shows the state of structure and the possibility of retrofitting or repairing of the structure. Therefore, it is essential to use a powerful IM with high reliability that makes the results more realistic. Efficiency is called the power of an IM to predict the seismic response (e.g. the $RIDR_{max}$ of SMRFs) with low dispersion. In this section, the efficiency of 25 structure-specific and non-structure-specific scalar-valued IMs presented in Tables I and II were investigated. Fig. 3 presents the variations of standard deviation of natural logarithm of IM of $RIDR_{max}$, $\sigma lnIM_{RD}$, values for scalar-valued IMs in the 3-Story-SAC, 6-Story-SAC, and 9-Story-SAC SMRFs. It can be seen that for predicting the $RIDR_{max}$ of 0.002 in the 3-Story-SAC, 6-Story-SAC, and 9-Story-SAC SMRFs, the $\sigma lnIM_{RD}$ values for $IM_M(\alpha$=0.5) are equal to 0.25, 0.28, and 0.20, respectively, which is lower than other assumed scalar-valued IMs. For predicting the $RIDR_{max}$ of 0.005, 0.01, and 0.02 in the 3-Story-SAC SMRF, the $\sigma lnIM_{RD}$ values for $Sa_{avg\ M\text{-}D}$ are equal to 0.31, 0.29, and 0.20, respectively. In addition, the $\sigma lnIM_{RD}$ values for $Sa_{avg\ M\text{-}D}$ in the 6-Story-SAC SMRF are equal to 0.30, 0.25, and 0.22, respectively, and for the 9-Story-SAC SMRF are equal to 0.22, 0.23, and 0.20, respectively. Therefore, two scalar-valued IMs of $IM_M(\alpha$=0.5) and $Sa_{avg\ M\text{-}D}$ have lower $\sigma lnIM_{RD}$ that shows the efficiency of assumed IMs. Moreover, these IMs have lower $\sigma lnIM_{RD}$ values in the 3-Story-SAC, 6-Story-SAC, and 9-Story-SAC SMRFs with linear FVDs and can be considered as efficient IMs.

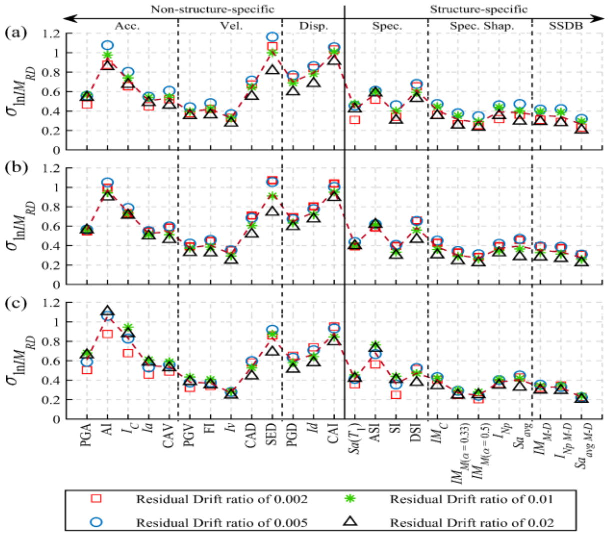

Figure 3. Variations of $\sigma lnIM_{RD}$ values for scalar-valued IMs in the, a) 3-Story-SAC, b) 6-Story-SAC, and c) 9-Story-SAC SMRFs.

Fig. 4 presents the variations of $\sigma lnIM_{RD}$ values for scalar-valued IMs in the 3-Story-Ref, 6-Story-Ref, and 9-Story-Ref SMRFs.

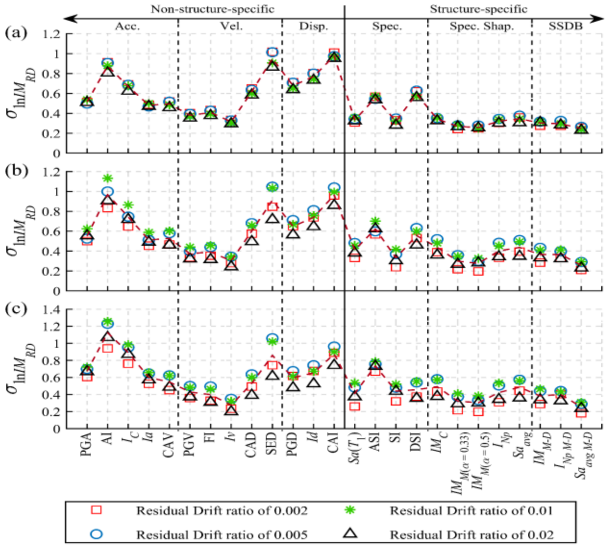

Figure 4. Variations of $\sigma lnIM_{RD}$ values for scalar-valued IMs in the, a) 3-Story-Ref, b) 6-Story-Ref, and c) 9-Story-Ref SMRFs.

It can be seen that for predicting the $RIDR_{max}$ of 0.002 in the 3-Story-Ref, 6-Story-Ref, and 9-Story-Ref SMRFs, the $\sigma lnIM_{RD}$ values for $IM_M(\alpha$=0.5) are equal to 0.24, 0.19, and 0.18, respectively, which is lower than other assumed scalar-valued IMs.

For predicting the $RIDR_{max}$ of 0.005, 0.01, and 0.02 in the 3-Story-Ref SMRF, the $\sigma lnIM_{RD}$ values for $Sa_{avg\ M\text{-}D}$ are equal to 0.26, 0.23, and 0.23, respectively. In addition, the $\sigma lnIM_{RD}$ values for $Sa_{avg\ M\text{-}D}$ in the 6-Story-Ref SMRF are equal to 0.29, 0.29, and 0.23, respectively, and for the 9-Story-Ref SMRF are equal to 0.29, 0.30, and 0.23, respectively. In addition, IMs of $IM_M(\alpha$=0.5) and $Sa_{avg\ M\text{-}D}$

had lower $\sigma lnIM_{RD}$ values assuming linear FVDs. Therefore, these two IMs can be considered as efficient scalar-valued IMs for predicting $RIDR_{max}$ of SMRFs with and without linear FVDs. Table III presents the Fractional Reduction (FR) in the mean dispersion, ($\sigma lnIM_{RD}$)avg, in four optimal scalar-valued IMs. It can be noted that the higher values of FR achieved for two IMs of IM_M(α=0.5) and $Sa_{avg\ M\text{-}D}$.

TABLE III. Fractional Reduction (FR) in (ΣlnIM$_{RD}$)avg Achieved by the Proposed Scalar-Valued IMs with and without Linear FVDs.

		I_v		$IM_{M(=0.33)}$		$IM_{M(=05)}$		$Sa_{avgM\text{-}D}$	
		$(\sigma lnIM_{RD})_{avg}$	FR (%)	$(\sigma lnIM_{RD})_{avg}$	FR (%)	$(\sigma lnIM_{RD})_{avg}$	FR (%)	$(\sigma lnIM_{RD})_{avg}$	FR (%)
Without FVD	RD=0.2%	0.30	7.98	0.25	22.58	0.23	29.43	0.24	27.89
	RD=0.5%	0.34	22.59	0.34	22.40	0.30	30.69	0.28	35.03
	RD=1%	0.31	30.28	0.33	26.05	0.30	32.93	0.27	39.29
	RD=2%	0.25	35.01	0.26	32.27	0.26	33.52	0.22	42.72
With FVD	RD=0.2%	0.30	14.33	0.27	22.57	0.24	31.74	0.24	31.81
	RD=0.5%	0.31	27.67	0.33	24.14	0.29	32.25	0.28	34.89
	RD=1%	0.32	29.39	0.35	22.80	0.29	36.51	0.30	34.13
	RD=2%	0.27	36.70	0.30	32.01	0.27	36.63	0.25	42.39

V. Investigating the Sufficiency of the IMs for Residual Drift Prediction

Sufficiency is called the ability of an IM to render the seismic response (e.g. the $RIDR_{max}$ of SMRFs) independent from the other characteristics of the seismic ground motion records. Therefore, a sufficient IM prevents a biased distribution for the seismic response (e.g. the $RIDR_{max}$ of SMRFs) assessed from IDAs. To compare the sufficiency of the IMs, the *p*-value was calculated regarding the ground motion characteristics of M, R, and Vs30. Table IV presents the percent of structures with p-values≥0.05 obtained from investigating the sufficiency of proposed scalar-valued IMs with respect to M, R, and Vs30.

TABLE IV. Percent of Structures with p-values ≥ 0.05 Obtained from Investigating the Sufficiency of Proposed Scalar-Valued IMs with Respect to M, R, and Vs30.

		% of structures with p-values ≥ 0.05		
	Scalar-valued IM	M	R	Vs30
Without FVD	I_v	25	100	87.5
	$IM_{M(=0.33)}$	91.67	91.67	91.52
	$IM_{M(=05)}$	87.5	100	95.83
	$Sa_{avgM\text{-}D}$	95.83	100	91.69
With FVD	I_v	54.17	100	87.5
	$IM_{M(=0.33)}$	91.67	100	87.5
	$IM_{M(=05)}$	95.83	95.83	83.33
	$Sa_{avgM\text{-}D}$	79.17	100	91.67

The results show that two IMs of IM_M(α=0.5) and $Sa_{avg\ M\text{-}D}$ are selected as optimal scalar-valued IMs for predicting the $RIDR_{max}$ of considered SMRFs. Figs. 5 and 6 present the sufficiency of proposed scalar-valued IMs in the assumed $RIDR_{max}$ and for aforementioned SMRFs with respect to seismic characteristics of M, R, and Vs30, without and with assuming linear FVDs, respectively.

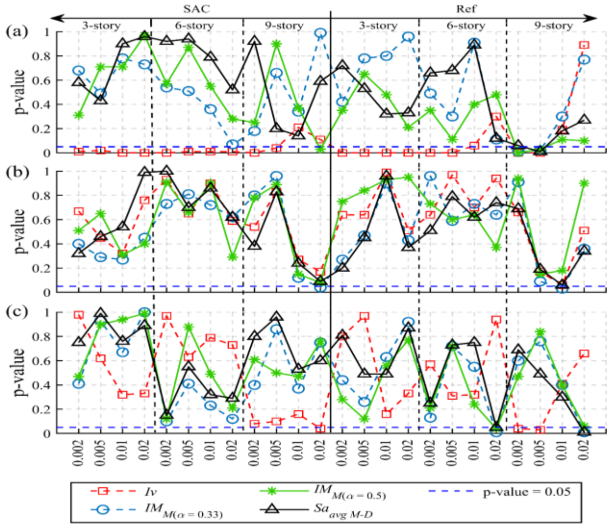

Figure 5. Sufficiency of proposed scalar-valued IMs in the assumed $RIDR_{max}$ and SMRFs, a) M, b) R, c) Vs30.

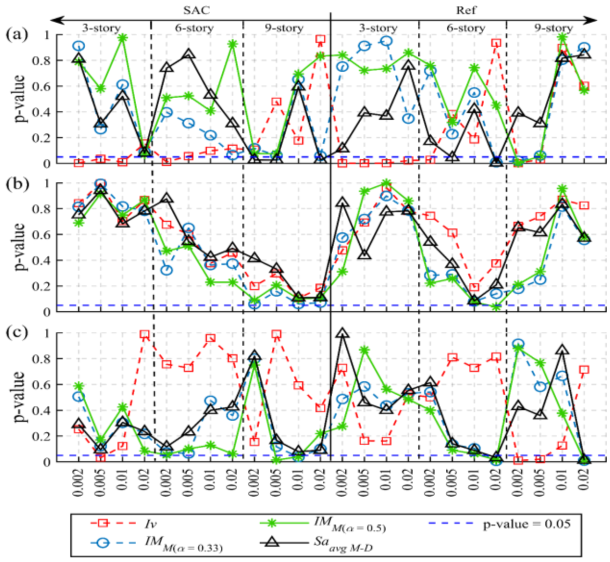

Figure 6. Sufficiency of proposed scalar-valued IMs in the assumed $RIDR_{max}$ and SMRFs with linear FVDs a) M, b) R, c) Vs30.

It can be seen that two scalar-valued IMs of *Iv* and IM_M(α=0.33) in some cases achieved *p*-values lower than 0.05 (5%) that shows the insufficiency of these IMs. While two IMs of IM_M(α=0.5) and $Sa_{avg\ M\text{-}D}$ had *p*-values higher than 0.05 in all cases. Therefore, these IMs are considered as sufficient IMs with respect to seismic characteristics of M, R, and Vs30.

VI. Conclusions

In this study, the efficiency and sufficiency of 25 scalar-valued IMs including non-structure-specific IMs and structure-specific IMs were selected to predict the $RIDR_{max}$ of two sets of the 3-Story, 6-Story, and 9-Story SMRFs with and without considering linear FVDs. The results of testing the efficiency of two scalar-valued IMs of $IM_M(\alpha=0.5)$ and $Sa_{avg\ M\text{-}D}$ showed that they had lower values of $\sigma lnIM_{RD}$ compared to other assumed scalar-valued IMs. In addition, two IMs of $IM_M(\alpha=0.5)$ and $Sa_{avg\ M\text{-}D}$ achieved higher values of FR in the mean dispersion, $(\sigma lnIM_{RD})$avg. Moreover, the sufficiency of them, which is another important factor, was compared. The *p*-value of two IMs of $IM_M(\alpha=0.5)$ and $Sa_{avg\ M\text{-}D}$ with respect to seismic ground motion features of M, R, and Vs30, were higher than 0.05, which shows the sufficiency of assumed IMs. Therefore, two scalar-valued IMs of $IM_M(\alpha=0.5)$ and $Sa_{avg\ M\text{-}D}$ are proposed as optimal IMs for predicting the $RIDR_{max}$ of SMRFs.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Farzin Kazemi and Neda Asgarkhani conducted the research and analyzed the data, Atefeh Yousefi wrote the paper; Benyamin Mohebi checked the paper; all authors had approved the final version.

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Farzin Kazemi, was born in Iran, received his M.Sc. in Earthquake Engineering from Imam Khomeini International University (IKIU), Qazvin, Iran. Currently, he is PhD student in Gdansk University of Technology, Gdansk, Poland. His main research areas are seismic performance assessment, machine learning algorithms, data scientist, and seismic hazard analysis in earthquake engineering.

Benyamin Mohebi, was born in Iran, received Ph.D. degree in Earthquake Engineering from Iran University of Science and Technology, Tehran, Iran. Now, he works as an associate professor at Faculty of Engineering and Technology, Imam Khomeini International University (IKIU), Qazvin, Iran. His research interests include nonlinear analysis of structures, seismic hazard analysis, seismic retrofitting of structures, and optimization in structural engineering.

Neda Asgarkhani, was born in Iran, received her M.Sc. in Structural Engineering from Imam Khomeini International University (IKIU), Qazvin, Iran. Currently, she is PhD student in Gdansk University of Technology, Gdansk, Poland. Her main research areas are retrofitting structures, structural modelling issues in seismic performance assessment of steel structures.

Atefeh Yousefi, was born in Iran, received her M.Sc. in Structural Engineering from Faculty of Engineering, Zanjan University, Zanjan, Iran. Her main research areas are structural modelling, retrofitting structures, and seismic performance assessment of steel structures.