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Prediction of hysteretic energy demands in steel frames using vector-valued *IMs*

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ABSTRACT

It is well known the importance of considering hysteretic energy demands for the seismic assessment and design of structures. In such a way that it is necessary to establish new parameters of the earthquake ground motion potential able to predict energy demands in structures. In this paper, several alternative vector-valued ground motion intensity measures (*IMs*) are used to estimate hysteretic energy demands in steel framed buildings under long duration narrow-band ground motions. The vectors are based on the spectral acceleration at first mode of the structure as first component. As the second component, *IMs* related to peak, integral and spectral shape parameters are selected. The aim of the study is to provide new parameters or vector-valued ground motion intensities with the capacity of predicting energy demands in structures. It is concluded that spectral-shape-based vector-valued *IMs* have the best relation with hysteretic energy demands in steel frames subjected to narrow-band earthquake ground motions.

1. INTRODUCTION

The ground motion potential of an earthquake is characterized by a parameter named intensity measure. Among all the features of an *IM*, the ability to predict the response of structures subjected to earthquakes is the most important. This ability is known as efficiency. Although, several studies have been developed to propose or to analyze ground motion intensity measures (Housner 1952, Arias 1970, Von-Thun et al. 1988, Cosenza and Manfredi 1998, Cordova et al. 2001, Baker and Cornell 2005,

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Tothong and Luco 2007, Yakut and Yilmaz 2008, Bojórquez and Iervolino 2011). In most of the cases, the proposed *IMs* are based in the prediction of maximum demands such as maximum ductility and inter-story drift. Whereas, there is a lack of studies aimed to provide new ground motion intensity measures for predicting hysteretic energy demands in structures. By other hand, nowadays, several studies promote the use of vector-valued ground motion *IMs*, especially, those based on spectral shape, because they predict with good accuracy the maximum interstory drift and maximum ductility of structures subjected to earthquakes (Cordova et al. 2001, Baker and Cornell 2005, Tothong and Luco 2007, Baker and Cornell 2008, Bojórquez and Iervolino 2011, Buratti 2011). In particular, vector and scalar ground motion intensity measures based on N_p which are representative of the spectral shape have resulted very well correlated with the nonlinear structural response (Bojórquez and Iervolino 2011, Buratti 2011, 2012). Moreover the parameter N_p has been successfully used for ground motion record selection (Bojórquez et al. 2013). However, as it was mentioned before, an appropriated *IM* should be capable of predicting all types of engineering demand parameters, as example, hysteretic energy demands. It is known, that hysteretic energy demands are very important in structures when subjected to long duration narrow-band ground motions (Terán-Gilmore 2001, Bojórquez and Ruiz 2004, Arroyo and Ordaz 2007, Terán-Gilmore and Jirsa 2007, Bojórquez et al. 2011), and for this reason it is necessary to have an *IM* capable of estimating energy demands with good accuracy. The main objective of this paper is to analyze the efficiency of several vector-valued ground motion intensity measures to predict hysteretic energy demands in regular steel frames under narrow-band motions recorded in the soft-soil site of Mexico City. All the vector-valued *IMs* here considered are based on $Sa(T_1)$ as the first component. As the second component of the vector, peak ground acceleration and velocity (*PGA* and *PGV*), ground motion duration t_D (established according to Trifunac and Brady (1975) as the time interval delimited by the instants of time at which the 5% and 95% of the Arias Intensity occurs), the I_D factor proposed by Cosenza and Manfredi (1998), the $R_{T1,T2}$ (Cordova et al., 2001) and the parameter N_p (Bojórquez and Iervolino, 2011) factors were selected.

2. METHODOLOGY

2.1 Vector-valued ground motion intensity measures

The prediction of hysteretic energy is estimated with ten different vector-valued ground motion *IMs*. The first two *IMs* are $<Sa(T_1), PGA>$ and $<Sa(T_1), PGV>$, which are representative of peak ground responses. The second two *IMs* are $<Sa(T_1), t_D>$ and $<Sa(T_1), I_D>$ which represents the influence of ground motion duration or cumulative potential, respectively, where the I_D factor is defined as:

$$I_D = \frac{\int_0^{t_F} a(t)^2\,dt}{PGA \cdot PGV} \tag{1}$$

In Eq. (1), *a(t)* is the acceleration time-history and t_F is the total duration of the ground motion.

The last two *IMs* considered are $<Sa(T_1), R_{T1,T2}>$ and $<Sa(T_1), N_p>$. These are representative of the spectral shape, which has been recently proposed as the main ground motion feature expressing the earthquake structural potential. While $R_{T1,T2}$ is the ratio between the spectral acceleration at period T_2 divided by spectral acceleration at period T_1, where T_2 is a period larger than T_1; N_p is mathematically defined in Eq. (2). According to this equation, if we have one or *n* records with a mean N_p value close to one, we can expect that the average spectrum to be about flat in the range of periods between T_1 and T_N. For a value of N_p lower than one it is expected an average spectrum with negative slope beyond T_1. In the case of N_p values larger than one, the spectra tend to increase beyond T_1. Finally, the normalization between $Sa(T_1)$ let N_p be independent of the scaling level of the records based on $Sa(T_1)$, but most importantly it helps to improve the knowledge of the path of the spectrum from period T_1 until T_N, which is related with the nonlinear structural response. In this study, a value of T_2 equal to twice the first mode period was chosen, because Cordova et al. (2001) and Baker (2005) identify it as adequate, and Bojórquez et al. (2008) confirm this for nonlinear SDOF systems and considering different performance parameters. Finally, Bojórquez and Iervolino (2011) observed that the value of T_N around 2 or 2.5 times T_1 seems adequate.

$$N_p = \frac{Sa_{avg}(T_1,...,T_N)}{Sa(T_1)} \tag{2}$$

Although $R_{T1,T2}$ and N_p were originally proposed based on the spectral acceleration spectrum, herein different types of response spectra have been used to obtain these parameters. In total three different response spectra were considered to feature $R_{T1,T2}$ and N_p as the second parameter. The first vectors considered are $<Sa(T_1), R_{Sa}>$ and $<Sa(T_1), N_{pSa}>$ where the second components are based on the spectral acceleration spectrum, and they can be obtained as discussed before. The next vector-valued ground motion intensity measures considered were $<Sa(T_1), R_{EI}>$ and $<Sa(T_1), N_{pEI}>$, where R_{EI} and N_{pEI} are based on the input energy response spectrum instead of the pseudo-acceleration response spectrum. The input energy can be defined from the equation of motion of a single degree of freedom system as follows:

$$m\,\ddot{x}(t) + c\,\dot{x}(t) + f_s(x,\dot{x}) = -m\ddot{x}_g(t) \tag{3}$$

In Eq. (3), m is the mass of the system; c, the viscous damping coefficient; $f_s(x,\dot{x})$, the non-linear force; $\ddot{x}$, the ground acceleration; and x, the displacement with respect to the base of the system. A dot above x indicates a derivative with respect to time. In case of an elastic linear system, $f_s(x,\dot{x}) = k\,x$, where k is the stiffness of the system.

Integrating each member of Eq. (3) with respects to x, yields:

$$\int m\,\ddot{x}(t)\,dx + \int c\,\dot{x}(t)\,dx + \int f_s(x,\dot{x})\,dx = -\int m\,\ddot{x}_g(t)\,dx \tag{4}$$

Eq. (4) can be written as energy balanced equation as follows (Uang and Bertero, 1990):

$$E_K + E_D + E_S + E_H = E_I \tag{5}$$

where E_K , E_D , E_S and E_H represent the kinetic (k), viscous damping (D), deformation (S) and dissipated hysteretic (H) energies, respectively; and E_I is the relative input energy, which will be used to obtain the vectors <*Sa(T*$_1$*)*, R_{EI}> and <*Sa(T*$_1$*)*, N_{pEI}>. Finally, the last vector-valued *IMs* considered are <*Sa(T*$_1$*)*, R_{VE}> and <*Sa(T*$_1$*)*, N_{pVE}>, where R_{VE} and N_{pVE} are based on the equivalent velocity, which is obtained as the square root of the ratio of the input energy divided by the mass of the system. Note that all the vectors were selected to represent maximum and cumulative potential of a ground motion shaking.

The main characteristics considered in each *IM* (e.g. peak response, duration and spectral shape) are summarized in Table 1. The first column represents the ground motion intensity measure; the second, third and fourth columns indicate if the *IMs* are based on peak ground response, duration or spectral shape response, respectively.

Table 1. Summary of the vector-valued *IMs* considered

Intensity Measure	Peak ground response	Duration	Spectral shape
<$Sa(T_1)$, PGA>	*		
<$Sa(T_1)$, PGV>	*		
<$Sa(T_1)$, t_D>	*	*	
<$Sa(T_1)$, I_D>	*	*	
<$Sa(T_1)$, R_{Sa}>	*		*
<$Sa(T_1)$, N_{pSa}>	*		*
<$Sa(T_1)$, R_{EI}>	*	*	*
<$Sa(T_1)$, N_{pEI}>	*	*	*
<$Sa(T_1)$, R_{VE}>	*	*	*
<$Sa(T_1)$, N_{pVE}>	*	*	*

2.2 Structural steel frame models

Five moment-resisting steel frames having 4, 6, 8, 10 and 14 stories, were considered for the studies reported herein. The frames are denoted as F4, F6, F8, F10 and F14, respectively. As shown in Fig. 1, the frames, designed according to the Mexico City Seismic Design Provisions (MCSDP), have three eight-meter bays and story heights of 3.5 meters. Each frame was provided with ductile detailing and its lateral strength was established according to the MCSDP. A36 steel was used for the beams and columns of the frames. Relevant characteristics for each frame, such as the fundamental period of vibration (T_1), and the seismic coefficient and displacement at yielding (C_y and D_y) are shown in Table 2 (the latter two values were established from static nonlinear analyses).

A two dimensional, lumped plasticity nonlinear model of each frame was prepared and analyzed. An elasto-plastic model with 3% strain-hardening was used to represent the cyclic behavior (in terms of bending moment and rotation) of the transverse sections located at both ends of the steel beams and columns. As discussed by Bojórquez and Rivera (2008), this model provides a good approximation to the actual hysteretic behavior of steel members. Mass-and-stiffness proportional Rayleigh damping was considered for the analysis, 3% of critical damping was assigned to the first two modes of vibration of the frames.

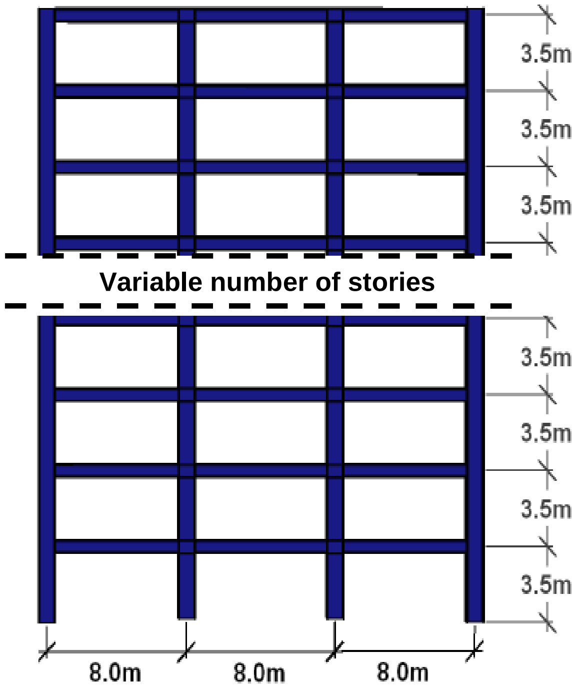


Fig. 1 Geometrical characteristics of the steel frames

Table 2. Characteristics of the steel frame models

Frame	Number of Stories	T_1 (s)	C_y	D_y (m)
F4	4	0.90	0.45	0.136
F6	6	1.07	0.42	0.174
F8	8	1.20	0.38	0.192
F10	10	1.37	0.36	0.226
F14	14	1.91	0.25	0.30

2.3 Earthquake ground motion records

A set of 30 narrow-band ground motions recorded at the Lake Zone sites of Mexico City was considered. Particularly, all motions were recorded at sites having soil periods of two seconds, during seismic events with magnitudes close to seven or larger with epicenters located at distances of 300 km or more from Mexico City. Some important characteristics of the records are summarized in Table 3. It should be mentioned that sites having soil periods of two seconds are fairly common within the Lake Zone, and that the higher levels of shaking (in terms of peak ground acceleration) have been consistently observed at these sites.

Table 3. Earthquake ground motions

Records	Date	Magnitude	Station	*PGA* (cm/s²)	*PGV* (cm/s)	$t_D(s)$	I_D
1	19/09/1985	8.1	SCT	178.0	59.5	34.8	15.5
2	21/09/1985	7.6	Tlahuac deportivo	48.7	14.6	39.9	19.9
3	25/04/1989	6.9	Alameda	45.0	15.6	37.8	17.8
4	25/04/1989	6.9	Garibaldi	68.0	21.5	65.5	11.1
5	25/04/1989	6.9	SCT	44.9	12.8	65.8	17.3
6	25/04/1989	6.9	Sector Popular	45.1	15.3	79.4	28.1
7	25/04/1989	6.9	Tlatelolco TL08	52.9	17.3	56.6	11.1
8	25/04/1989	6.9	Tlatelolco TL55	49.5	17.3	50.0	14.0
9	14/09/1995	7.3	Alameda	39.3	12.2	53.7	17.3
10	14/09/1995	7.3	Garibaldi	39.1	10.6	86.8	34.7
11	14/09/1995	7.3	Liconsa	30.1	9.62	60.0	14.5
12	14/09/1995	7.3	Plutarco Elías Calles	33.5	9.37	77.8	33.8
13	14/09/1995	7.3	Sector Popular	34.3	12.5	101.2	30.8
14	14/09/1995	7.3	Tlatelolco TL08	27.5	7.8	85.9	30.0
15	14/09/1995	7.3	Tlatelolco TL55	27.2	7.4	68.3	21.3
16	09/10/1995	7.5	Cibeles	14.4	4.6	85.5	29.4
17	09/10/1995	7.5	CU Juárez	15.8	5.1	97.6	36.6
18	09/10/1995	7.5	Centro urbano Presidente Juárez	15.7	4.8	82.6	34.9
19	09/10/1995	7.5	Córdoba	24.9	8.6	105.1	26.5
20	09/10/1995	7.5	Liverpool	17.6	6.3	104.5	29.4
21	09/10/1995	7.5	Plutarco Elías Calles	19.2	7.9	137.5	40.8
22	09/10/1995	7.5	Sector Popular	13.7	5.3	98.4	27.4
23	09/10/1995	7.5	Valle Gómez	17.9	7.18	62.3	21.9
24	11/01/1997	6.9	CU Juárez	16.2	5.9	61.1	22.6
25	11/01/1997	6.9	Centro urbano Presidente Juárez	16.3	5.5	85.7	25.2
26	11/01/1997	6.9	García Campillo	18.7	6.9	57.0	21.4
27	11/01/1997	6.9	Plutarco Elías Calles	22.2	8.6	76.7	27.7
28	11/01/1997	6.9	Est. # 10 Roma A	21.0	7.76	74.1	29.8
29	11/01/1997	6.9	Est. # 11 Roma B	20.4	7.1	81.6	24.3
30	11/01/1997	6.9	Tlatelolco TL08	16.0	7.2	57.5	19.9

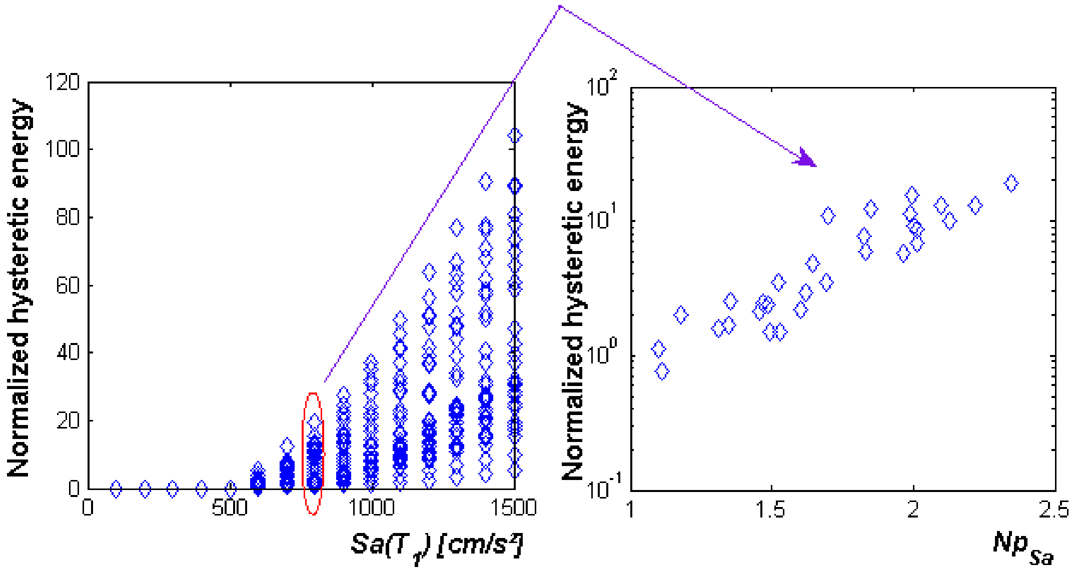
2.4 Performance parameters

The engineering demand parameter selected was the normalized dissipated hysteretic energy (E_{HN}) by the yielding displacement (D_y) and the strength (F_y), as shown in Eq. (6). E_{HN} was selected here as a performance parameter because of its direct relationship with the cumulative demands (Iervolino et al. 2006). In fact, currently various damage indexes have been proposed based on hysteretic energy (Terán and Jirsa 2005, Rodriguez and Padilla 2008, Bojórquez et al. 2010). It is important to say, that F_y and D_y were obtained from a push-over analysis, and E_H corresponds to the total plastic energy dissipated by the structure (the plastic energy dissipated by all the elements).

$$E_{HN} = \frac{E_H}{F_y D_y} \tag{6}$$

3. RELATION BETWEEN VECTOR-VALUED *IMs* AND THE STRUCTURAL DEMAND OF STEEL FRAMES

Baker and Cornell (2005) and Bojórquez and Iervolino (2011) showed the advantages of using vector-valued ground motion intensity measures instead of scalars. The main advantage is the increasing in the efficiency to predict the structural response. Herein with the aim to obtain the relation between the structural response of steel frames and the vectors selected; nonlinear incremental dynamic analysis was used to obtain the seismic response of the steel frames subjected to the 30 ground motion records by using the first parameter of the vector, in this case $Sa(T_1)$ was perform, and then the relation between the structural response of the steel frames and the second parameter of the vector is obtained. Note that it must be developed for a specific level of spectral acceleration and for all the intensity levels considered. Fig. 2a shows an example of the incremental dynamic analysis for $Sa(T_1)$ in terms of normalized dissipated hysteretic energy. It is observed a poor relation among $Sa(T_1)$ and hysteretic energy, in fact the uncertainty to predict hysteretic energy using the spectral acceleration tend to increase with the intensity of the earthquake ground motion. Fig. 2b illustrates the relation obtained for $<Sa(T_1), N_{pSa}>$ and the normalized hysteretic energy demand when $Sa(T_1)$= 800cm/s² (see the values in the circle in Fig. 2a). Note the good relation between N_{pSa} and the normalized hysteretic energy reflecting the advantage of using the vector-valued ground motion intensity measure. It explains the reduction in the uncertainty associated with the structural response when vector-valued parameters are selected as intensity measures, and this type of intensity measures could be more efficient for nonlinear structural response prediction. This is discussed below.

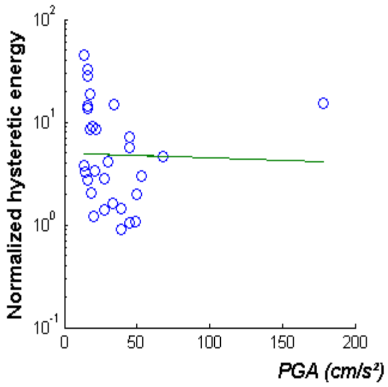


(a) (b)

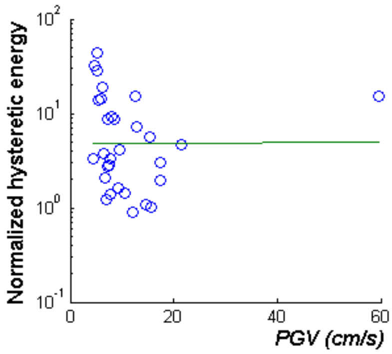
Fig. 2 (a) Incremental dynamic analysis scaling for $Sa(T_1)$; (b) Relation between N_{pSa} and the normalized hysteretic energy at $Sa(T_1)$=800cm/s²

4. RELATION BETWEEN VECTOR-VALUED *IMs* AND THE STRUCTURAL DEMAND OF STEEL FRAMES: NUMERIAL RESULTS

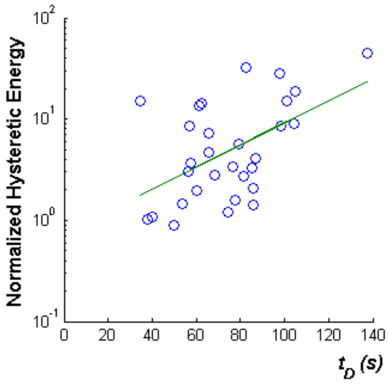
The relation between the chosen vector-valued ground motion *IMs* and normalized hysteretic energy demand of the steel frames analyzed is discussed in this section. Fig. 3 compares the selected *IMs* with E_{HN} for frame F4 and all the records scaled at $Sa(T_1)$=1000cm/s²; other scaling levels are considered as will be illustrated later. A good relation can be observed between the normalized hysteretic energy and all the parameters under consideration; especially for those based on the spectral shape. Note that the parameter based on the input energy spectral shape is less effective to predict normalized hysteretic energy demands compared with spectral acceleration shape, which is an important observation since this vector take into account structural damage potential. All these conclusions are valid also for the other frames as will be observed below. An important issue is that the variation of N_p based on spectral acceleration is in the range from 1 to 3 while in the other case this variation is larger; as for the case of input energy. The trend observed for the N_{pSa} based on pseudo-acceleration and the normalized hysteretic energy demands let suppose a very good efficiency of such parameter to estimate energy demands in steel frames subjected to narrow-band earthquake ground motions. The results also suggests that *IMs* based on peak response of the ground motion (*PGA*, *PGV* or $Sa(T_1)$) are not well related with energy demands. Nevertheless, it is necessary to confirm the results for other scaling levels of the records, as it is discussed in the following section.


Normalized hysteretic energy
10^{2} 10^{1} 10^{0} 10^{-1}
0 50 100 150 200
PGA (cm/s²)

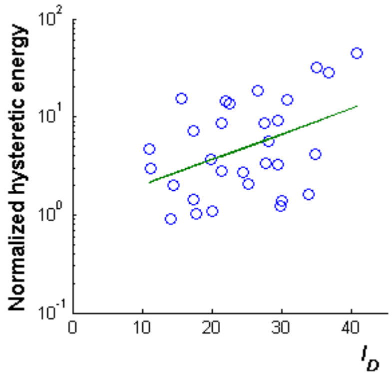
(a)


Normalized hysteretic energy
10^{2} 10^{1} 10^{0} 10^{-1}
0 20 40 60
PGV (cm/s)

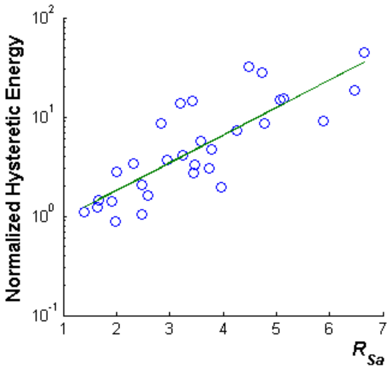
(b)


Normalized Hysteretic Energy
10^{2} 10^{1} 10^{0} 10^{-1}
0 20 40 60 80 100 120 140
t_D (s)

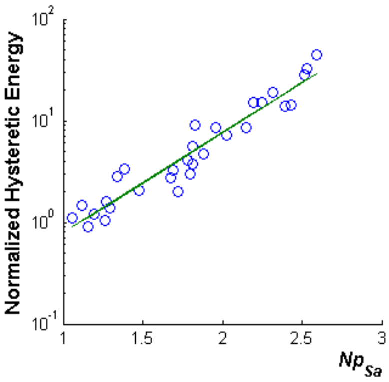
(c)


Normalized hysteretic energy
10^{2} 10^{1} 10^{0} 10^{-1}
0 10 20 30 40
I_D

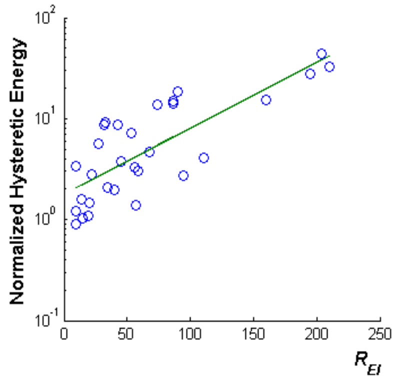
(d)


Normalized Hysteretic Energy
10^{2} 10^{1} 10^{0} 10^{-1}
1 2 3 4 5 6 7
R_{Sa}

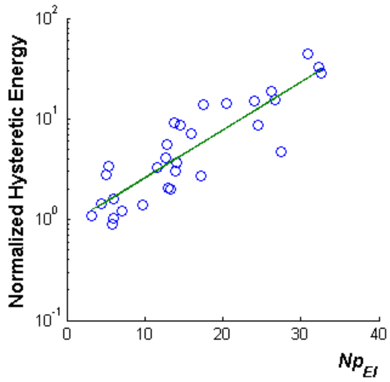
(e)


Normalized Hysteretic Energy
10^{2} 10^{1} 10^{0} 10^{-1}
1 1.5 2 2.5 3
Np_{Sa}

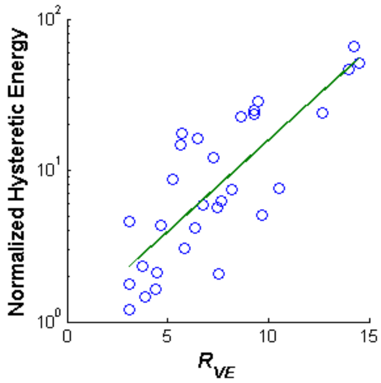
(f)



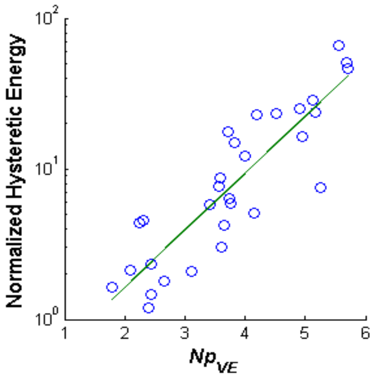
(g)



(h)



(i)



(j)

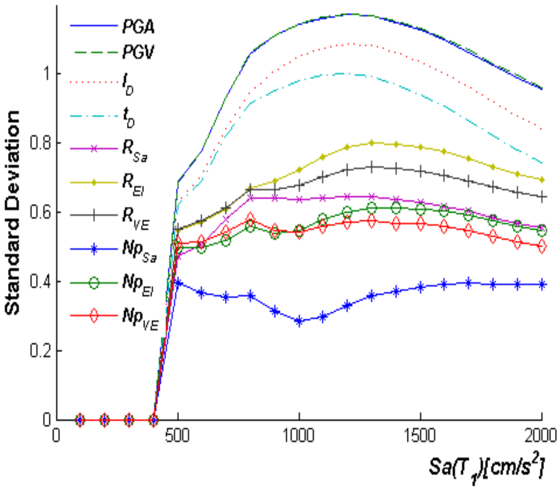
Fig. 3. Prediction of normalized hysteretic energy for the steel frame F4 with T_1=0.90s ($Sa(T_1)$=1000cm/s²) for: (a) *PGA*; (b) *PGV*; (c) I_D; (d) t_D; (e) R_{Sa}; (f) N_{pSa}; (g) R_{EI}; (h) N_{pEI}; (i) R_{VE} and (j) N_{pVE}

4.1 Efficiency of the selected vector-valued ground motion IMs

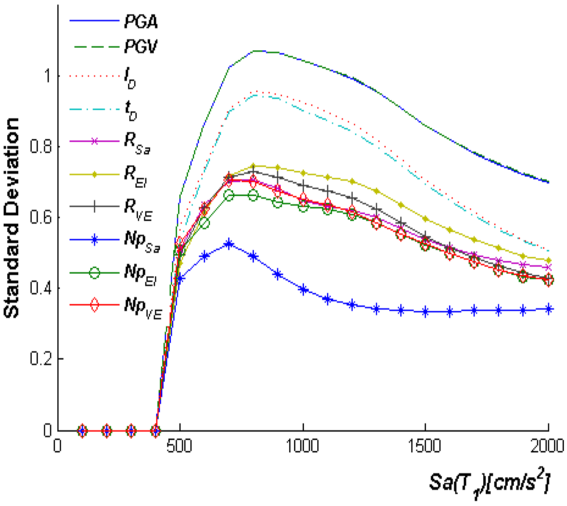
The numerical results showed in Fig. 3 are only valid for a single scaling level in terms of the spectral acceleration; to further illustrate the effectiveness of the vector-valued intensity measures selected, the standard deviation of the natural logarithm of the normalized hysteretic energy for a whole range of scaling levels and for all the frames under consideration is evaluated. The standard deviation was estimated using linear regression for different spectral acceleration values, vector-valued *IMs* and the frames under consideration. The results are observed in Fig. 4 for all the selected steel frames. Similar conclusions are obtained as in the case of Fig. 3; the parameters based on peak ground response or in duration are not good estimators of the normalized hysteretic energy demands, which can be appreciated in the very large values of the standard deviation. Among all the selected vectors, those based on spectral shape tend to have the smaller values of the standard deviation, indicating the effectiveness of these parameters to predict hysteretic energy demands. Note that the efficiency to predict the structural response in terms of hysteretic energy of R and N_p based on equivalent velocity is practically the same obtained with that based on input energy. According to the results, it can be preliminary concluded that the best predictor of the normalized hysteretic energy demands of steel frames subjected to narrow-band ground motions is the vector-valued intensity measure based on the spectral acceleration spectrum $<Sa(T_1), N_{pSa}>$.

4.2 Efficiency comparison of different types of spectral shapes to predict normalized hysteretic energy

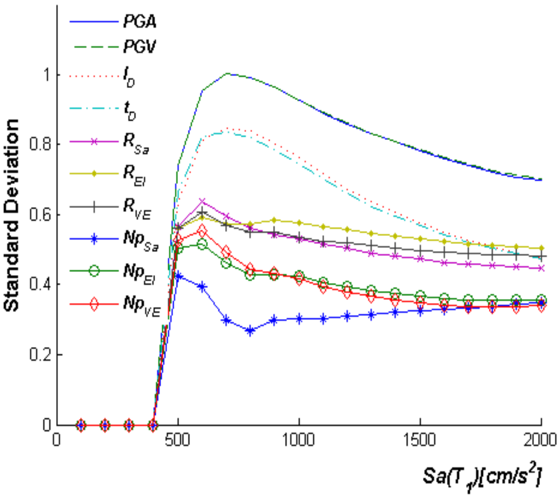
The efficiency to predict normalized hysteretic energy by using spectral shape proxies *IMs* based on spectral acceleration through the vector $<Sa(T_1), N_{pSa}>$, and elastic input energy $<Sa(T_1), N_{pEI}>$ is compared for all the selected frames. It is a common thought to expect that the elastic input energy can predict with better accuracy the normalized hysteretic energy compared with other intensity measures; nevertheless, the previous results suggest that *IMs* based on spectral acceleration shape are more related with normalized hysteretic energy demands. To further illustrate this conclusion, the standard deviation of the natural logarithm of normalized hysteretic energy is obtained at different intensity values as it was estimated in the previous section, but this time only both types of *IMs*, based on spectral shape with the use of the parameter N_p, are compared. Fig. 5 let conclude that the vector $<Sa(T_1), N_{pSa}>$, improves the efficiency for predicting the normalized hysteretic energy compared with the intensity measure based on elastic input energy spectra $<Sa(T_1), N_{pEI}>$. This conclusion is valid for most of the frames under consideration. Moreover, for most of the earthquake ground intensity levels studied, the vector-valued intensity measure based on spectral acceleration has smaller standard deviation (better relation with the normalized hysteretic energy) compared with the *IM* based on the spectrum of elastic input energy. Finally, note that for both vector-valued ground motion intensity measures the dispersion tend to be constant for larger spectral acceleration values, which implies that the uncertainty in the hysteretic energy demand does not increase considerably for larger values of nonlinear behavior in the structure.



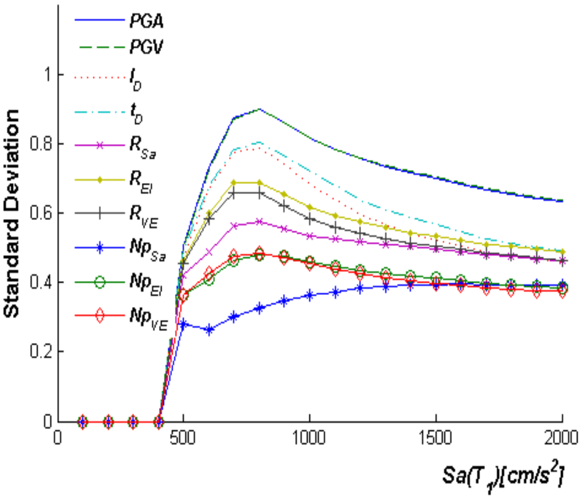
(a) Frame F4



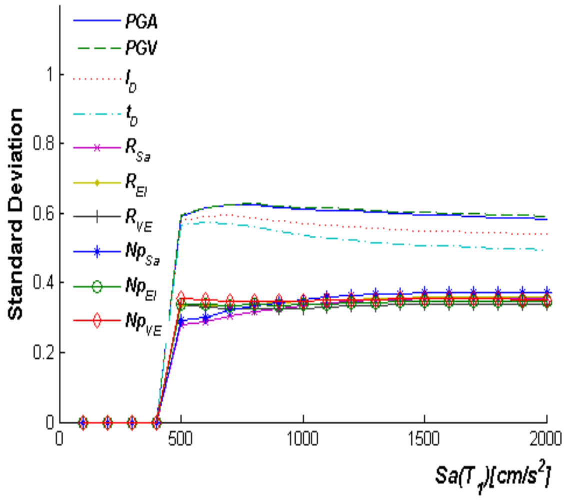
(b) Frame F6



(c) Frame F8

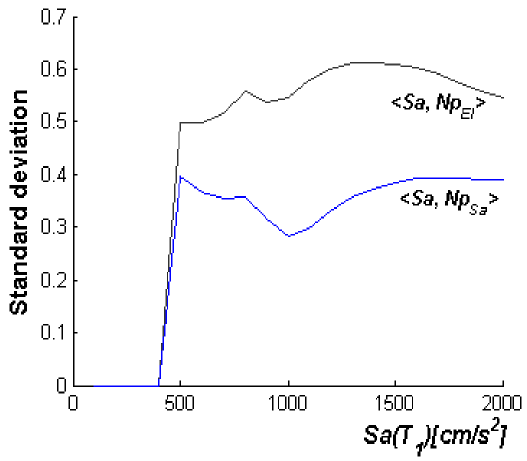


(d) Frame F10

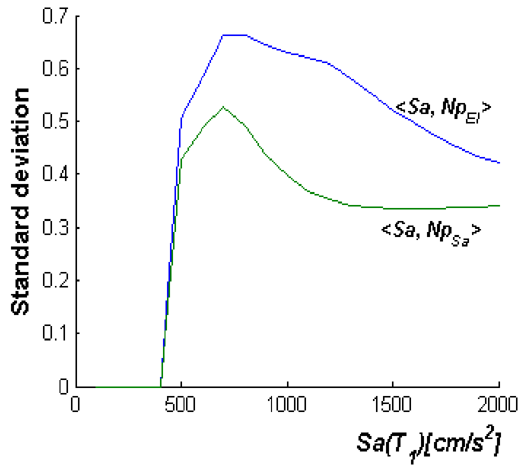


(e) Frame F14

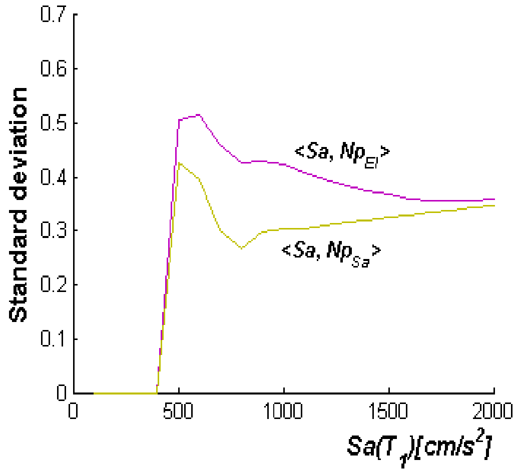
Fig. 4 Efficiency comparison of the standard deviation of the natural logarithm for the normalized hysteretic energy, all the *IMs* and steel frames at different scaling levels



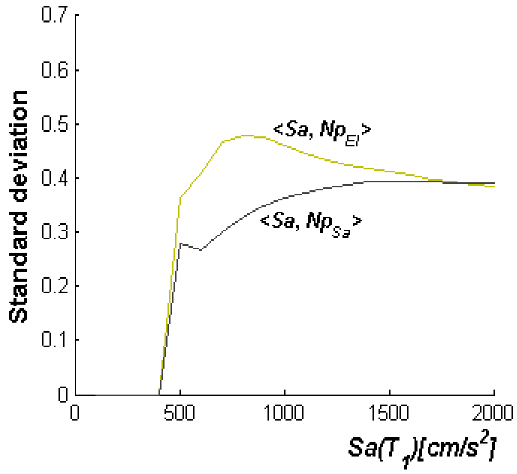
(a) Frame F4



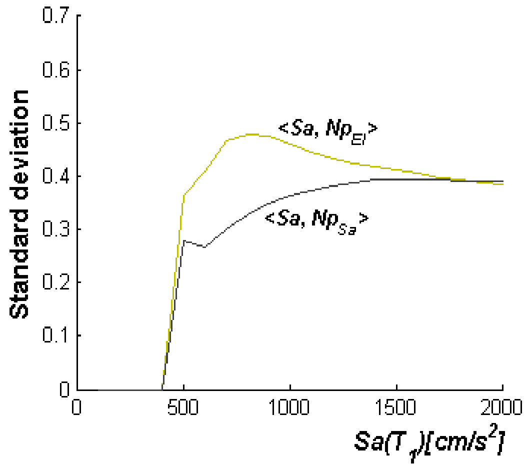
(b) Frame F6



(c) Frame F8



(d) Frame F10



(e) Frame F14

Fig. 5 Comparison of the standard deviation of the natural logarithm of normalized hysteretic energy with <$Sa(T_1)$, N_{pSa}> and <$Sa(T_1)$, N_{pEI}>

5. FUTURE STUDIES AND INCORPORING HIGHER MODES EFFECTS

The potential of a parameter to characterize the spectral shape named N_p was observed in the prediction of hysteretic energy demands in steel moment resisting frames under narrow-band earthquake ground motions. Although the present study illustrated the ability of this parameter to predict the structural response, the use of $<Sa(T_1), N_{pSa}>$ was limited to predict nonlinear structural response; however, it is necessary to incorporate the effect of higher modes in the prediction of seismic response of buildings. The higher mode effects can be incorporated by modifying the parameter N_p evaluating not only from the period T_1 up to T_N if not from the period of some mode of interest until the final period T_N. For example, with the assessment of N_p from T_{2mode} up to T_N (T_{2mode} is the period associated to the second mode of vibration of the structure). Note that several record selection strategies are based on a similar approach such as FEMA, for this reason this parameter can be easily adopted in record selection strategies for nonlinear dynamic analysis (see Bojórquez et al. 2013). Moreover, the inclusion of higher modes effects can be taken into account via a vector of three parameters $<Sa, R_{T1,T2}, R_{T1,T2mode}>$, $<Sa, N_p, R_{T1,T2mode}>$, $<Sa, I_{Np}, R_{T1,T2mode}>$ or by given a specific contribution factor to take into account the seismic response associated to elastic, nonlinear and that dominated by higher modes. Finally, it is important to emphasis that several approaches can be adopted in the present study with the aim to increase the efficiency in the prediction of the structural response of buildings.

6. CONCLUSIONS

Several alternative vector-valued ground motion intensity measures have been analyzed with the aim to obtain the best predictor of the structural response in terms of hysteretic energy demands of regular steel frames under narrow-band ground motions. The study considered *IMs* based on peak, cumulative or hybrid and spectral shape proxies. The numerical study concludes that there is no evidence to support the use of vector-valued *IMs* based exclusively in peak ground motion characteristics for predicting energy demands in buildings. In the case of *IMs* based on duration they moderately improve the efficiency to predict hysteretic energy demands, but they do not work good enough compared with spectral shape ground motion *IMs* based on the pseudo-acceleration, equivalent velocity or input energy spectra. The most effective vector-valued *IMs* to predict normalized hysteretic energy obtained in this study are those based on spectral acceleration shape. The main conclusion given in the present work is that the use of the vector $<Sa(T_1), N_{pSa}>$ is the best alternative for predicting normalized hysteretic energy demands of steel frames subjected to narrow-band earthquake ground motions.

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