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Improving the efficiency of ground motion intensity measures

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ABSTRACT: Currently, several studies focused to select new intensity measures suggest the use of spectral shape parameters to capture the potential of an earthquake ground motion. Among scalar or vector-valued intensity measures, in the last years those which are based on the parameter N_p (a proxy of the spectral shape) have the potential to predict the nonlinear structural response of framed structures under seismic ground motions as well as to estimate the structural fragility of buildings with higher efficiency compared with other intensity measures. Vector-valued and scalar intensity measures based on N_p have been successfully used, especially in combination with the spectral acceleration at first mode of vibration as the case of the parameter I_{Np}. However, this parameter does not take into account explicitly the higher mode effects in the structural response, or it must be included by changing the initial period selected to estimate the value of N_p. Motivated by the need to predict the structural response of buildings accounting for higher mode effects, in this paper, the new generalized ground motion intensity measure I_B is analysed.

1 INTRODUCTION

The ground motion potential of an earthquake is characterized by a parameter named ground motion intensity measure (IM). This parameter has been studied since the beginning of Earthquake Engineering (Housner (1952), Arias (1970), Shome (1999), Baker and Cornell (2005), Tothong and Luco (2007), Mehanny (2009), Bojórquez and Iervolino (2011), Bojórquez et al. (2012, 2013), Buratti (2012), Modica and Stafford (2014), De Basio et al. (2014)). One of the main objectives of the IM is to be related with the structural demand of buildings subjected to earthquakes (this is known as efficiency), which is the key issue to reduce the uncertainties on the estimation of the structural response. Some important characteristics of a desirable intensity measure are the relation with the structural response and its capacity to uncouple the seismological and structural uncertainties. Although several ground motion intensity measures have been proposed, currently the parameters most used as intensity measures are the peak ground acceleration *PGA*, peak ground velocity *PGV* and the spectral acceleration at first mode of vibration $Sa(T_1)$. In particular, the most used ground motion intensity measures by earthquake engineers, seismologists, and seismic design guidelines is the spectral acceleration at first mode of vibration. This parameter is very useful because is the perfect predictor of seismic response of elastic single degree of freedom systems and it is a good option for predicting the response of elastic multi degree of freedom structures dominated by the first mode of vibration. Further, some studies have demonstrated the sufficiency of $Sa(T_1)$ with respect to magnitude and distance (Shome, 1999, Iervolino and Cornell 2005). Nevertheless, for structures dominated by higher mode effects the use of $Sa(T_1)$ could not be appropriated (Bazzurro and Cornell 2002). Various studies have demonstrated the inefficiency of $Sa(T_1)$ for example to predict the response of buildings under near source ground motion records (Luco, 2002), and narrow-band motions (Bojórquez and Iervolino, 2011). The limitations of spectral acceleration at first mode of vibration can be observed with the elastic response spectra where the scatter in the spectral shape due to the effect of the elongated period, or some spectral ordinates at higher periods is not considered. Inspired by this issues Bojórquez and Iervolino (2011) have proposed the parameter N_p and the I_{Np} intensity measure which is described in the next section.

1.1 The spectral shape parameter N_p

Recent studies suggest that the spectral shape is crucial to predict the structural response of buildings under earthquakes and for this reason the earthquake engineering and seismology community has highlighted the limitations of spectral acceleration at first mode of vibration. For example: $Sa(T_1)$ does not provide information about the spectral shape in other regions of the spectrum, which may be important for the nonlinear behaviour (beyond T_1) or for structures dominated by higher modes (before T_1). In the case of nonlinear shaking, the structure may be sensitive to different spectral values associated to a range of periods, from the fundamental period until a limit value of practical interest, say T_N. To further illustrate some limitations of $Sa(T_1)$, let's consider a structure with a fundamental period T_1 equal to 1s subjected to a set of different seismic records scaled to the same $Sa(T_1)$ level. Figure 1 shows the response spectra for typical records from Mexico City with significant local site effects. For this example, the final period is supposed to be T_N equal to 2s. It can be observed that, although the records have the same $Sa(T_1)$, the spectral ordinates are affected by significant scatter at T_N, which is likely to be reflected in the structural response. This calls for intensity measures providing information about the spectral shape in a whole region of the spectrum as $<Sa, R_{T1,T2}>$ and $Sa_{avg}(T_1,..., T_N)$, where $R_{T1,T2}$ is the ratio of spectral acceleration at mode T_2 of vibration divided by $Sa(T_1)$, and $Sa_{avg}(T_1,..., T_N)$ is the geometrical mean of spectral acceleration values in the range T_1 until T_N.

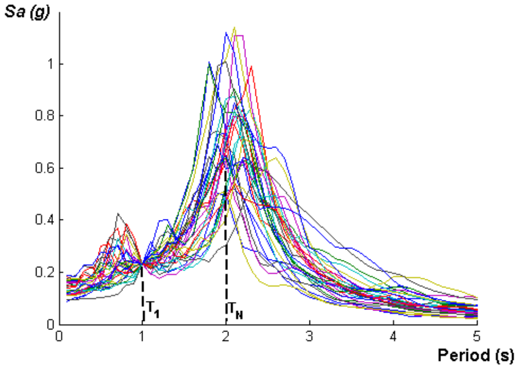

Figure 1. Response spectra for records scaled to similar $Sa(T_1)$. After Bojórquez and Iervolino (2011).

Although parameters as $Sa_{avg}(T_1,..., T_N)$ or the area under the spectrum, account for the spectral shape, a specific value of $Sa_{avg}(T_1,..., T_N)$ or area under the spectrum may be associated to different patterns of the spectrum between T_1 and T_N, that is, with different spectral shapes. A useful improvement may be the use of $Sa_{avg}(T_1,..., T_N)$ but normalizing it by $Sa(T_1)$. To this aim the parameter named N_p (Eq. 1) was proposed by Bojórquez and Iervolino (2011). The additional subscript *o* in N_p (see Eq. 1) is used to represent the original equation.

$$N_{po} = \frac{Sa_{avg}(T_1,..., T_N)}{Sa(T_1)} \tag{1}$$

The information given by this equation is that 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 period range between T_1 and T_N. For a mean N_p lower than one it is expected an average spectrum with negative slope. 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 to nonlinear structural response. Further information can be found in Bojórquez and Iervolino (2011).

1.2 I_{Np} intensity measure

To incorporate the effects of nonlinear behavior in the prediction of structural response, Bojórquez and Iervolino (2011) have proposed a new scalar ground motion *IM* based on $Sa(T_1)$ and N_p which is described in the following equation:

$$I_{Np} = Sa(T_1)\, {N_p}^{\alpha} \qquad (2)$$

In Equation 2 the α value has to be determined. From Eq. 2, it is possible to note that 1) the spectral acceleration at first mode of vibration is a particular case of I_{Np}, and this occurs when α is equal to zero; 2) $Sa_{avg}(T_1 \ldots T_N)$ also corresponds to the particular case when $\alpha = 1$. Analyses developed by Bojórquez and Iervolino (2011) and Buratti (2012) suggest that the optimal values of α are close to 0.4, also Buratti (2012) demonstrated that this intensity measure is more efficient to predict nonlinear structural response compared with several intensity measures of the literature. Note that the previous equation provides different weights to the contributions of the spectral accelerations beyond the first-mode compared with the spectral value at T_1. Furthermore, probabilistic seismic hazard analysis can be developed using this ground motion intensity measure as Bojórquez and Iervolino (2011) have demonstrated.

1.3 The definition of the new intensity measure I_B

Although I_{Np} has results very efficient to predict nonlinear structural response compared with other parameters (Bojórquez and Iervolino 2011, Buratti 2012), one of the main limitations of this intensity measure is the lack of consideration of higher mode effects, because it does not take into account spectral ordinates associated with periods lower than the fundamental periods of vibration of the structure (note that the higher mode effects can be taken into account by using a different range of spectral ordinates for the parameter N_p, as Bojórquez et al., 2013 suggest). With the aim to improve the capacity of I_{Np}, in this study, the new ground motion intensity measure I_B is proposed. This parameter is inspired in the spectral shape and it was named as I_B because it considers the prediction of structural response accounting for both nonlinear and higher mode effects. The new intensity measure is defined as following:

$$I_B = S(T_1)^{\alpha_1} \cdot N_p^{\alpha_2} \cdot \prod_{i=2}^{i=\#modes} \left[R_{(T1,Tmi)}^{\alpha_{3(mi)}} \right] \qquad (3)$$

In equation 3, I_B represents the new intensity measure proposed by the first author; $S(T_1)$ represents a spectral parameter taken from any type of spectrum as in the case of acceleration, velocity, displacement, input energy, inelastic parameter and so on. N_p is similar to Equation 1 but for different types of spectra, which can be rewritten as convenience as it is indicated in Equation 4; $R_{(T1,Tmi)}$ is defined as the ratio of a spectral parameter in the period of *mode i* of vibration of the structure ($S(T_{mi})$) and a spectral parameter at the fundamental period of vibration $S(T_1)$, where T_1 is larger than T_{mi} (see Eq. 5). Note that the subscript m is used to denote mode of vibration.

$$N_p = \frac{S_{avg}(T_1, \ldots, T_N)}{S(T_1)} \qquad (4)$$

$$R_{(T1,Tmi)} = \frac{S(T_{mi})}{S(T_1)} \qquad (5)$$

Equation 3 indicates that I_B incorporate information of both nonlinear and higher mode effects in the prediction of seismic response of structures. It is important to observe that I_{Np} is a particular case of I_B when the spectral acceleration shape is selected and $\alpha_{3(mi)}$ is equal to zero for all the modes. Further, parameters as spectral acceleration $Sa(T_1)$, spectral velocity, spectral displacement, peak ground acceleration and velocity, geometrical mean of spectral values in a range of periods, spectral input energy at first mode of vibration and others are particular cases of I_B. In addition, the parameters α_1, α_2 and α_3 must be calibrated, where $\alpha_{3(mi)}$ can change for each mode, but with the aim to express the equation in a simpler manner, α_3 can be assumed similar for all the modes under consideration, and α_1 will be equal to 1. It is very important to keep the units of the intensity measure similar to the units of $S(T_1)$ because N_p and R are dimensionless, then the parameter I_B can be rewritten as:

$$I_B = S(T_1) \cdot N_p^{\alpha_2} \cdot \prod_{i=2}^{i=\#modes} \left[R_{(T1,Tmi)}^{\alpha_3} \right] \qquad (6)$$

Currently, a modified version of Equation 3 which is based only on N_p is currently been developed by the first author (Bojórquez, 2015).

1.4 Particular cases of I_B

I_B is a generalized intensity measure because several intensity measures are particular cases of this new parameter. Moreover, I_B consists of three parts, the first one is the spectral value, the second is the N_p and the last part is the R parameter. Note that several combination of I_B can be obtained if we use different spectral shape to define the three parts of I_B. For example, if we select three types of spectral shapes to define I_B let's says the pseudo-acceleration *Sa*, velocity *V* and displacement *D* spectra, and if we consider two modes of vibration (the initial period of parameter N_p was defined equal to the fundamental period of vibration and it also can be different); for the parameters *Sa*, *V* and *D* and by considering the second mode of vibration there are 27 possibilities or particular cases of I_B. Finally, a useful nomenclature for a particular case of I_B obtained with two modes and the same spectral parameter, the I_B can be written as I_{BSa} (note that this is valid for the spectral acceleration), as it will be described below. It is important to say that the number of combination that can be obtained for I_B depends on the number of types of spectra that are used. One of the main objectives is try to find for several particular cases of I_B the values of α_2 and α_3 for which this intensity measure has the highest efficiency; thus the ability to predict with good accuracy the behaviour of structures under earthquakes due to nonlinear and higher modes effects. To assess the efficiency of I_B, Bojórquez et al. 2014 estimated the maximum interstory drift of steel buildings subjected to ground motion records scaled at different values of spectral acceleration at first mode of vibration in a range from 0.5g until 1.2g. They computed the efficiency by means of the standard deviation of the natural logarithm of the maximum interstory drift $\sigma_{\ln(\gamma)}$ (note that γ was used to represent the maximum interstory drift) in the range of intensity levels given previously. First, linear regression analysis was used to calculate the interstory drift in terms of intensity (expected interstory drift) and then the standard deviation of the natural logarithm was computed as the difference with the expected and the actual drift. The most efficient intensity measure is that able to minimize the standard deviation of the structural demand, hence the reduction of the uncertainty in the seismic response. Bojórquez et al. conclude that a good alternative particular case of I_B is that illustrated in Equation 7, in which I_B indicates that the intensity measure is based exclusively on the pseudo-acceleration spectral shape and by considering two modes, this spectral shape parameter is commonly used for seismic hazard and risk analyses.

$$I_{BSa} = Sa(T_1) \cdot N_p^{0.4} \cdot R_{T1,T2}^{0.2} \qquad (7)$$

In this study, the efficiency of I_{BSa} is compared with respect to I_{Np} and $Sa(T_1)$. Note that I_B is computed for the values of α_2 and α_3 given in Equation 7, and when α_3 is equal to zero I_{Np} is a particular case of I_B. The same occurs when α_2 and α_3 are equal to zero that represents $Sa(T_1)$ which also is a particular case of I_B (this is valid when the case I_{BSa} is selected), in such a way that in this study it is only necessary to estimate the efficiency of I_{BSa}. It is important to say that the efficiency study was computed for steel structures subjected to the different types of ground motions recorded at different soil characteristics.

2 EFFICIENCY STUDY: METHODOLOGY

2.1 Steel frame models

The efficiency of the new intensity measure I_B is estimated through the nonlinear time history analysis of five moment-resisting steel frames having 4, 6, 8, 10 and 14 stories. The frames are denoted as F4, F6, F8, F10 and F14, and they were designed according to the Mexico City Seismic Design Provisions (MCSDP) having 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), the period of the second mode of vibration (T_{m2}) and the seismic coefficient at yielding (C_y) are shown in Table 1 (the latter two values were established from static nonlinear analyses). An elasto-plastic model with 3% strain-hardening was used to represent the cyclic behavior. The frames were analysed considering 3% of critical damping.

Table 1. Characteristics of the steel frame models.

Frame	Number of stories	Period of vibration (s)		C_y
		T_1	T_{m2}	
F4	4	0.90	0.27	0.45
F6	6	1.07	0.34	0.42
F8	8	1.20	0.39	0.38
F10	10	1.35	0.45	0.36
F14	14	1.91	0.65	0.25

2.2 Selection and scaling of the ground motion records for I_B

In this study, five sets of earthquake ground records are considered. The first set corresponds to 20 soft-soil ground motions recorded in the Lake Zone of Mexico City and exhibiting a dominant period (T_s) of two seconds, which are represented as Narrow-band motions. Particularly, all motions were recorded in Mexico City during seismic events with magnitudes near of 7 or larger. Table 2 summarizes the main characteristics of the seismic records under consideration.

Table 2. Narrow-band earthquake ground motions.

Record	**Date**	**Mag**	***PGA* (cm/s²)**	***PGV* (cm/s)**		**Record**	**Date**	**Mag**	***PGA* (cm/s²)**	***PGV* (cm/s)**
1	19/09/1985	8.1	178.0	59.5		11	14/09/1995	7.3	30.1	9.62
2	21/09/1985	7.6	48.7	14.6		12	14/09/1995	7.3	33.5	9.37
3	25/04/1989	6.9	45.0	15.6		13	14/09/1995	7.3	34.3	12.5
4	25/04/1989	6.9	68.0	21.5		14	14/09/1995	7.3	27.5	7.8
5	25/04/1989	6.9	44.9	12.8		15	14/09/1995	7.3	27.2	7.4
6	25/04/1989	6.9	45.1	15.3		16	09/10/1995	7.5	14.4	4.6
7	25/04/1989	6.9	52.9	17.3		17	09/10/1995	7.5	15.8	5.1
8	25/04/1989	6.9	49.5	17.3		18	09/10/1995	7.5	15.7	4.8
9	14/09/1995	7.3	39.3	12.2		19	09/10/1995	7.5	24.9	8.6
10	14/09/1995	7.3	39.1	10.6		20	09/10/1995	7.5	17.6	6.3

The other four sets of seismic records were obtained from the NGA database, corresponding to worldwide earthquakes. The records used in this section were selected from earthquakes with moment magnitudes (M_w) ranging from 6.0 to 7.5, and they have been taken from sites at different epicentral distances. These records have been recommend by FEMA 440 and the sets with 20 records corresponds to soil type B, C, D and E according with the NEHRP classification, which is based on the shear waves velocity. Additional information of the sets can be found in FEMA 440. Finally, the different sets of records have been considered to represent all the types of soils, in such a way that the earthquake motions are representative of different spectral shapes. This let to show the potential of I_B to predict the seismic behaviour of framed buildings subjected to ground motion records with very different characteristics. The efficiency of the selected ground motion intensity measures is computed by scaling the records for different values of spectral acceleration at first mode of vibration, I_{Np} or I_B through incremental dynamic analysis (Vamvatsikos and Cornell 2002). For the seismic analyses the well-known computer program RUAUMOKO (Carr 2011) was used. From the dynamic analyses, first the maximum interstory drift for each structure and record set is obtained, then the standard deviation of the natural logarithm of the maximum interstory drift is computed, which is a clear indicator of the efficiency since smaller values of the standard deviation indicates large efficiency. The maximum interstory drift was selected since it is the main parameter used in earthquake engineering for structural performance assessment, and it is the key engineering demand parameter used by the seismic design codes. Notice that this is the first time that ground motion records have been scaled using I_B as intensity measure.

3 EFFICIENCY STUDY: RESULTS

The results of the incremental dynamic analysis in terms of maximum interstory drifts for the Frame F6 are shown in Figure 2 considering the set of 20 narrow-band records. The figure suggests that I_{Np} and I_B are better related with the structural response in comparison with spectral acceleration, in fact, less scattering is observed for I_{Np} because no influence of higher modes is observed in the structural response. This is explained through the comparison of the fundamental period of the structure equals with 1.20s which is smaller than the periods of the soil close to 2 seconds. However, for the same structural steel frame but subjected to the records of the set B (see Fig. 3), it is observed that I_B is better related with the structural response, since for this type of soil higher mode effects are more likelihood to occurs because in this case the structural period is larger than the soil period. Figures 2 and 3 suggests that I_{Np} and I_B improve the efficiency in comparison with the well-known spectral acceleration at first mode of vibration. Particularly, for structures influenced by higher modes I_B results a good candidate as intensity measure. Similar results are valid for other steel frame models and set of records which are not include for the sake of brevity. Nevertheless, to further illustrate the potential of I_B, Figure 4 compares for the three selected intensity measures, the standard deviation of maximum interstory drift at different performance levels in terms of median peak drifts for Frame F14 which is the tallest structure considered in the present study. Note that this figure was obtained from the incremental dynamic analysis. For the set of narrow-band ground motion the results are similar to those observed in the incremental dynamic analysis, the parameters I_{Np} and I_B have a similar efficiency to predict the maximum interstory drift (smaller standard deviation was observed). However, for the ground motion records of the set B, C, D and E, I_B have better efficiency compared with the most used intensity measure $Sa(T_1)$ and with respect to I_{Np}. This suggests the advantages of the new intensity measure I_B as a parameter to describe the ground motion potential of an earthquake.

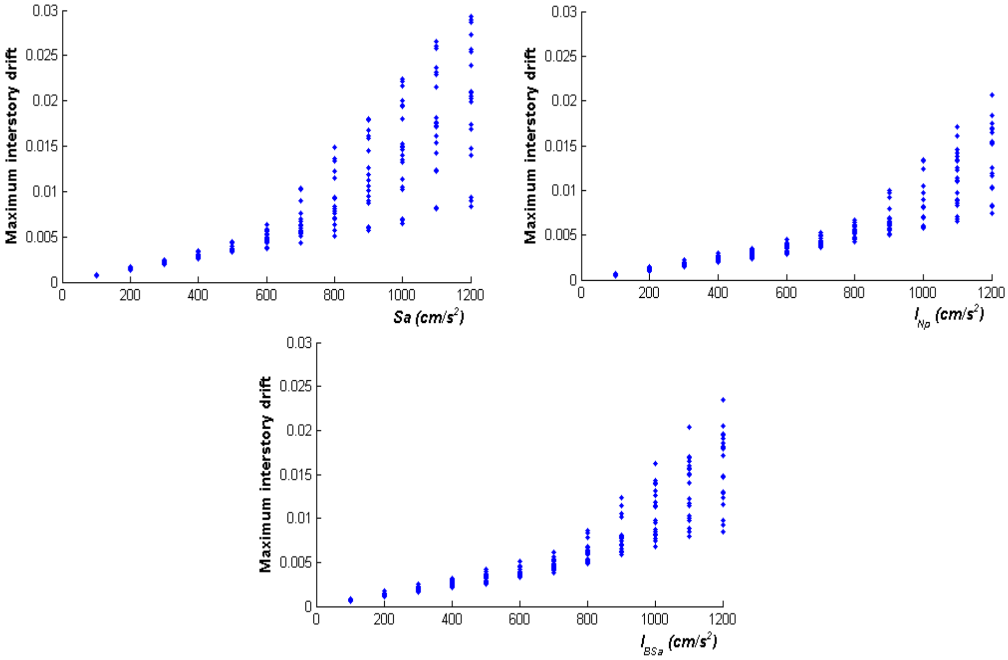

Figure 2. Incremental dynamic analysis for Frame F6 and narrow-band motions.

4 CONCLUSIONS AND FUTURE STUDIES

An efficiency study of $Sa(T_1)$, I_{Np} and the particular case I_{BSa} to predict the structural response of five moment resisting steel frames has been developed. The structural models were subjected to various earthquake ground motion records obtained from different types of soils. The study conclude that for steel frames with fundamental periods smaller than the soil period, I_{BSa} and I_{Np} have similar efficiency to predict the structural response. In the case of tall building (dominated by higher mode effects), the results preliminary suggests that I_B is more efficient than the traditional spectral acceleration at first mode of vibration and I_{Np} (which is a very good predictor of the structural response in terms of nonlinear behaviour). Although this work shows the advantages of I_{BSa}, future studies are required, in particular for several other cases of the generalized I_B intensity measure, and considering one, two or three modes of vibrations. Moreover, the use of I_B as part of a vector-valued intensity measure could be very promising which improve the efficiency in comparison with traditional ground motion intensity measures.

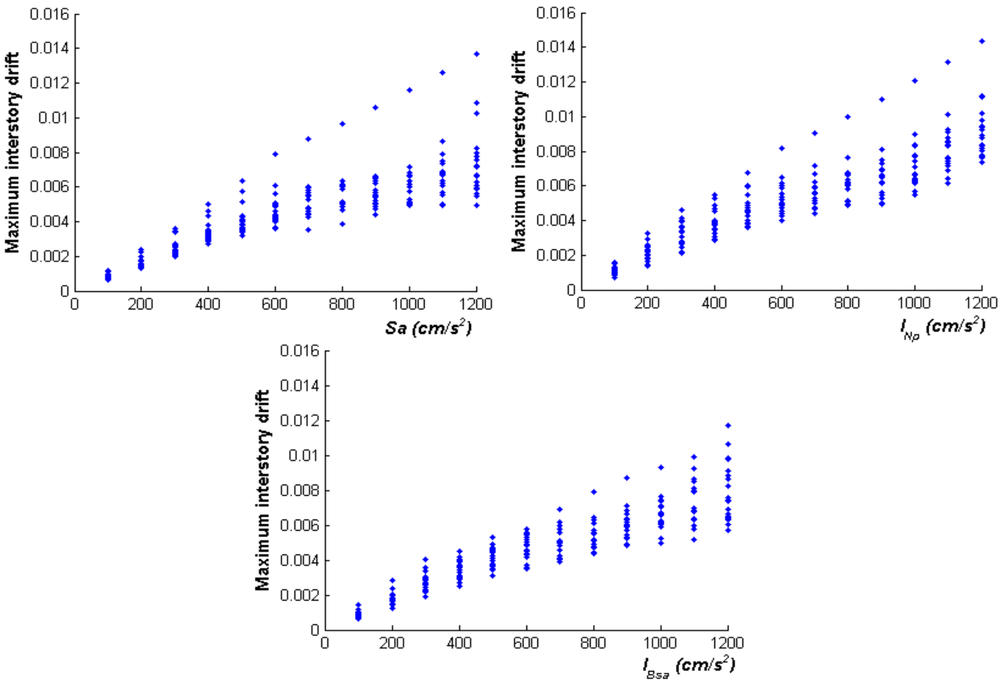

Figure 3. Incremental dynamic analysis for Frame F6 and soil type B.

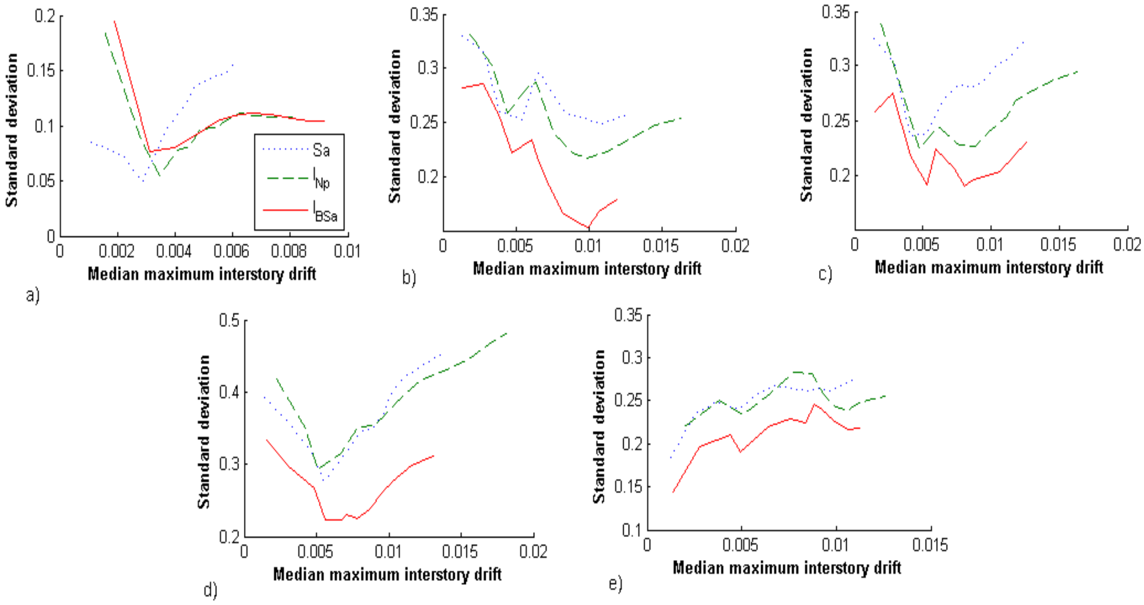

Figure 4. Standard deviation of maximum interstory drift for Frame F14 at different median drift values and soil type: a) Narrow-band, b) B, c) C, d) D, e) E.

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