

# Prediction of Maximum Interstory Drift Demands in Steel Buildings Using $I_B$

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**Abstract.** The objective of this paper is to analyze a recently proposed ground motion intensity measure named  $I_B$  which is able of predicting the seismic response of structures. The new ground motion intensity measure is inspired in a proxy of the spectral shape named  $N_p$  which is directly related to the nonlinear seismic response, and it is a very good descriptor of the spectral shape. In fact, the parameter  $N_p$  has been successfully used for ground motion record selection strategies for the seismic performance of structures. It will be shown that several ground motion intensity measures are particular cases of  $I_B$  and it is very efficient to predict maximum interstory drifts of steel framed buildings compared with traditional ground motion intensity measures used.

**Keywords:** Intensity Measure, Steel Buildings, Seismic Response.

## 1. Introduction

Several parameters have been proposed to describe the earthquake ground motion potential [1]-[9]. These parameters are known as ground motion intensity measures. It has been shown that among all the ground motion intensity measures, those which try to capture the spectral shape of the pseudo-acceleration spectrum are the most efficient because they have the ability to predict the structural response of buildings under earthquakes [5]-[8], [10]. The aim of the present study is to analyse the intensity measure known as Bojórquez intensity measure ( $I_B$ ) and its ability to predict peak structural demands of steel framed buildings under earthquake loads. The new ground motion intensity measure is inspired in a proxy of the spectral shape named  $N_p$  which is directly related to the nonlinear seismic response [8], [9], and it is a very good descriptor of the spectral shape. In fact, Buratti [10] concluded that the most efficient intensity measure is that proposed by Bojórquez and Iervolino based on the parameter  $N_p$  which was compared with several intensity measures. Further,  $N_p$  has been used to estimate the structural fragility of buildings with higher efficiency compared with other intensity measures [9], [11]. However, in spite of the great advantages of  $N_p$ , this parameter does not take into account explicitly the higher mode effects in the structural response. Motivated by the need to incorporate the higher mode effects in the structural response of buildings, in this paper the parameter  $I_B$  which takes into account both nonlinear and higher mode effects is selected to predict the maximum interstory drifts of steel buildings.

## 2. Ground Motion Intensity Measure

### 2.1. $I_{N_p}$ Intensity Measure

The most used ground motion intensity measure by earthquake engineers, seismologists, and seismic design guidelines is the spectral acceleration at first mode of vibration  $Sa(T_1)$ . This parameter is very useful because is the perfect predictor of seismic response of elastic single degree of freedom systems and it is a

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good option for predicting the response of elastic multi degree of freedom structures dominated by the first mode of vibration. Nevertheless, for nonlinear structures could not be appropriated. With the aim to increase the efficiency of  $Sa(T_1)$  and to incorporate the effects of nonlinear behavior in the prediction of structural response, Bojárquez and Iervolino [8] have proposed a new scalar ground motion intensity measure based on  $Sa(T_1)$  and  $N_p$  named  $I_{Np}$  which is described in the following equation:

$$I_{Np} = Sa(T_1) N_p^\alpha \quad (1)$$

In Eq. 1 the  $\alpha$  value has to be determined. From Eq. 1, 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  $\alpha$  is equal to zero; 2)  $Sa_{avg}(T_1 \dots T_N)$  also corresponds to the particular case when  $\alpha = 1$ . Analyses developed by Bojárquez and Iervolino [8] and Buratti [10] suggest that the optimal values of  $\alpha$  are close to 0.4, also Buratti 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 Bojárquez and Iervolino [8] have demonstrated.

## 2.2. The Definition of $I_B$

Although  $I_{Np}$  has results very efficient to predict nonlinear structural response compared with other parameters [8], [10], 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 Bojárquez et al. [12] suggest). With the aim to improve the capacity of  $I_{Np}$ , in this study, the intensity measure  $I_B$  is used. This parameter is inspired in the spectral shape and it was named as  $I_B$  because it considers the prediction of structural response considering both nonlinear and higher mode effects. The new intensity measure is defined as following:

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

In Eq. 2,  $I_B$  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, an inelastic parameter and so on.  $N_p$  is similar to the proposal of Bojárquez and Iervolino but for different types of spectra, which can be rewritten as convenience as it is indicated in Eq. 3;  $R_{(T_1, T_{mi})}^{\alpha_{3(mi)}}$  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. 4). Note that the subscript  $m$  is used to denote mode of vibration.

$$N_p = \frac{S_{avg}(T_1, \dots, T_N)}{S(T_1)} \quad (3)$$

$$R_{(T_1, T_{mi})} = \frac{S(T_{mi})}{S(T_1)} \quad (4)$$

Eq. 2 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. Furthermore, parameters as spectral acceleration at first mode of vibration, 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  $\alpha_1$ ,  $\alpha_2$  and  $\alpha_3$  must be calibrated, and  $\alpha_{3(mi)}$  can change for each mode, but with the aim to express the equation in a simpler manner,  $\alpha_3$  can be assumed similar for all the modes under consideration, and  $\alpha_1$  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:

$$I_B = S(T_1) \cdot N_p^{\alpha_2} \cdot \prod_{i=2}^{i=\#modes} [R_{(T_1, T_{mi})}^{\alpha_3}] \quad (5)$$

In the case that  $I_B$  is based only in the pseudo-acceleration spectrum, and if only the second mode of vibration is considered, the equation 6 can be written as follows:

$$I_{Bsa} = Sa(T_1) \cdot N_{pSa}^{\alpha_2} \cdot [R_{(T_1, T_{m2})}^{\alpha_3}] = Sa(T_1) \cdot \left[ \frac{Sa_{avg}(T_1, \dots, T_N)}{Sa(T_1)} \right]^{\alpha_2} \cdot \left[ \frac{Sa(T_{m2})}{Sa(T_1)} \right]^{\alpha_3} \quad (6)$$

A modified version of Eq. 3 which is based only on  $N_p$  is currently been developed by the first author, where it is demonstrated that the best way to express the range of periods to define  $N_p$  is using the fundamental period of vibration as the initial period.

### 3. Structural Steel Framed Buildings and Earthquake Ground Motions

To estimate the efficiency of the new intensity measure  $I_{Bsa}$ , six moment-resisting steel frames having 4, 6, 8, 10, 14 and 18 stories, were considered for the studies reported herein. The frames are denoted as F4, F6, F8, F10, F14 and F18, respectively. 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 ( $T_1$ ), 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 analyzed 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
F18	18	2.53	0.87	0.185

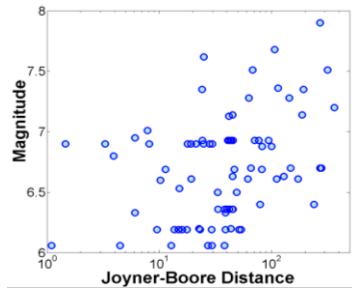


Fig. 1. Moment magnitude and Joyner-Boore distance distribution for the selected 100 records taken from the NGA database.

The efficiency (ability to predict the structural response) of the ground motion intensity measure is computed by considering several sets of earthquake records, which are divided in two categories. The first category having a total of 100 ground motion records obtained from the NGA database, corresponding to worldwide earthquakes, were used for the analyses of the steel frame buildings. The records used in this section were selected from earthquakes with moment magnitudes ( $M_w$ ) ranging from 6.0 to 7.9, and they have been taken from sites at different Joyner-Boore distances. The selected magnitudes are representative of moderate and large earthquakes. The distribution of the records in terms of moment magnitude and distance is provided in Fig. 1. In this figure, it can be observed that the records were obtained for different distances and from different events as moment magnitudes indicate; the wide range of the selected distances and magnitudes is very important to observe the influence of these parameters on the assessment of the uncertainty of the structural response due to nonlinear and higher mode effects.

The seismic records of the first category used in this study corresponding to all type of soil zones in accordance with the Geomatrix's Classification GMX's C3. From Soil type A corresponding to rock and soil type E to soft soil. A total of 20 records were chosen for each type of soil. The selected ground motion records were generated by different failure mechanisms: Strike-Slip, Normal, Reverse, Reverse-Oblique, Normal-Oblique, and Undefined. All the different characteristics of the selected records will show that the intensity measure  $I_B$  does not depends of the seismotectonic or soil characteristics.

In addition, the six steel frames designed according to the Mexico City Building Code are subjected to 30 soft-soil ground motions recorded in the Lake Zone of Mexico City and exhibiting a dominant period ( $T_s$ ) of two seconds. Particularly, all motions were recorded in Mexico City during seismic events with magnitudes near of 7 or larger.

## 4. Numerical Results

To assess the efficiency of the ground motion intensity measures, all the records have been scaled for different values of spectral acceleration at first mode of vibration in a range from 0.5g until 1.2g. From the dynamic analyses, the maximum interstory drift for each structure and type of soil were obtained. The maximum interstory drift was selected since it is the main parameter used in earthquake engineering.

The efficiency is calculated by means of the standard deviation of the natural logarithm of the maximum interstory drift  $\sigma_{\ln(\gamma)}$  (note that  $\gamma$  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 real 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. The efficiency of  $I_{BSa}$  is compared with  $I_{Np}$  and  $Sa(T_1)$ . Note that  $I_{BSa}$  is computed for several values of  $\alpha_2$  and  $\alpha_3$ , in particular when  $\alpha_3$  is equal to zero  $I_{Np}$  is a particular case of  $I_{BSa}$ , the same occurs when  $\alpha_2$  and  $\alpha_3$  are equal to zero  $Sa(T_1)$  is also a particular case of  $I_{BSa}$ , in such a way that in this study it is only necessary to estimate the efficiency of  $I_{BSa}$ . In fact, the main objective of this study is to find for the particular case  $I_{BSa}$  illustrated in Eq. 6, the values of  $\alpha_2$  and  $\alpha_3$  for which the  $I_{BSa}$  is the most efficient. Thus, the study is focus into propose the best alternative form to express  $I_B$  to increase its prediction of the seismic response of building due to nonlinear behavior and higher modes effects.

Fig. 2 illustrates the influence of the parameters  $\alpha_2$  and  $\alpha_3$  to calculate the standard deviation of the maximum interstory drift for Frame F10 using  $I_{BSa}$ . In addition, the surfaces of Fig. 2 were plotted for different value of  $T_N$  (this is a key parameter to compute  $N_p$ ). As it was discussed previously and Bojorquez and Iervolino suggest a value of  $\alpha=0.4$  let the parameter  $I_{Np}$  have the highest efficiency as Intensity measure especially for  $T_N=2*T_1$ . It can be observed in Fig. 2 which indicates that a value of  $\alpha_2=0.4$  when  $\alpha_3=0$  reduced the standard deviation or the uncertainty in the estimation of the structural response in terms of maximum interstory drift. Note that a value of  $\alpha_3$  equal to 0.2 is proposed as can be observed in the surfaces this value represents a minimum in Fig. 2 for all the  $T_N$  values analyzed. Based on the results obtained in the present study, it can be concluded that the values of  $\alpha_1$ ,  $\alpha_2$  and  $\alpha_3$  that reduce the standard deviation for case 1 of  $I_{BSa}$  are 1, 0.4 and 0.2 respectively. For this case, Eq. 3 can be rewritten as it is indicated in Eq. 7.

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

Note that in the figure when  $\alpha_2$  and  $\alpha_3$  are equals to zero the parameter  $Sa(T_1)$  is obtained. For this case, it is observed that  $\sigma_{\ln(\gamma)}$  is larger for  $Sa(T_1)$  comparing with the new intensity measures  $I_{Np}$  and  $I_{BSa}$ , which are better related with the structural response. Further, due to the dimensionless of  $N_p$  and  $R_{T1,T2}$ , the intensity  $I_{BSa}$  will have the units of the selected parameter in the first term. It is important to emphasize that similar results were obtained for all the frames and all the ground motion records; nevertheless due to the large number of figures only the results of Frame F10 were included in the present work for illustrative purposes.

## 5. Conclusions

The efficiency of  $Sa(T_1)$ ,  $I_{Np}$  and  $I_{BSa}$  to predict the structural response of steel buildings was estimated. For this aim, six moment resisting steel frames were subjected to various earthquake records obtained from different types of soils and seismic sources. The results suggests that  $I_{BSa}$  is more efficient to predict the maximum interstory drift demands compared with 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 behavior).

## 6. Acknowledgements

The support given by El Consejo Nacional de Ciencia y Tecnología to the first author under grant CB-2011-01-167419 and the scholarship to the second author is appreciated. Financial support also was received from the Universidad Autónoma de Sinaloa under grant PROFAPI.

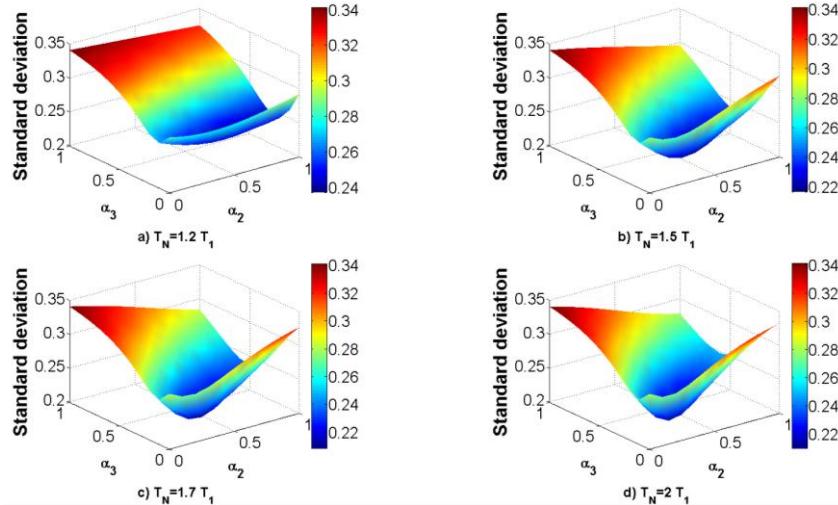


Fig. 2.  $\sigma_{\ln(\gamma)}$  for Frame F10 subjected to all the earthquake ground motions for  $I_{BSa}$ .

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