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AN ADAPTIVE CAPACITY SPECTRUM METHOD FOR ESTIMATING SEISMIC RESPONSE OF STEEL MOMENT-RESISTING FRAMES

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SUMMARY: *An adaptive version of the capacity spectrum method is proposed to estimate deformation demands of steel moment-resisting frames under seismic loads. Its computational attractiveness and capability of providing satisfactory predictions of seismic demands in comparison with those obtained by other advanced nonlinear static procedures in literature are examined. Both effectiveness and accuracy of these approximated methods based on pushover analysis are verified through an extensive comparative study involving both regular and irregular steel moment-resisting frames. The results obtained by nonlinear static procedures and nonlinear dynamic time-history analysis under spectrum-compatible accelerograms are eventually compared. The proposed procedure generally gives a more accurate solution than that obtained from the other nonlinear static procedures.*

KEYWORDS: *steel moment-resisting frames, nonlinear analysis, adaptive pushover*

1. INTRODUCTION

The estimation of lateral displacement demands is of primary importance in performance-based earthquake-resistant design. In fact, both structural and non-structural damage are primarily related to lateral displacements. However, estimating seismic demands at high performance levels, such as life safety and collapse prevention, requires explicit consideration of the inelastic behaviour of the structure. To this purpose, the nonlinear response history analysis (NRHA) is the most rigorous method for the estimation of seismic demands. Nevertheless, the Nonlinear Static Procedures (NSPs) are widely used to calculate the deformation demands with satisfactory accuracy without the complex modelling and computational effort of NRHA. Some NSPs were incorporated in the new generation of seismic codes in procedures based on Capacity Spectrum Method (CSM) or Displacement Coefficient Method (DCM), such as in FEMA 273 [1997], ATC-40 [1997], FEMA 356 [2000], Eurocode 8 [2004], Italian Building Code [2008], FEMA-440 [ATC-55, 2005], ASCE/SEI 41-06 Standard [2005]. In general, applying displacement rather than force loading in pushover procedures would be the most suitable option for nonlinear static analysis of structures subjected to earthquake ground motion. However, due to the unvarying nature of the applied displacement loading vector, this approach may neglect the strong variations of the displacement pattern in post-yield failure mechanism produced, for example, by strength irregularities and soft storeys. Consequently, when an invariant load pattern is used, the force-based pushover is to be preferred to the displacement-

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based pushover. However, the accuracy of these conventional force-based pushover analyses in predicting seismic demands of structures and their limitations especially for high-rise buildings remain among the most controversial topics. In fact, the traditional pushover analysis with an invariant lateral force pattern accurately estimates the seismic response of low-rise and regular buildings when the structural response is dominated by the first mode. On the contrary, significant differences were found in high-rise buildings, where the effects of the higher modes cannot be neglected. The two major limits of the conventional pushover procedures are that, owing to the invariant loading pattern, the higher mode effects are ignored and, therefore, the changes in the dynamic properties of the structures are neglected. This is mainly because inertia force distribution changes continuously under earthquake ground motion due to higher mode contribution and stiffness degradation.

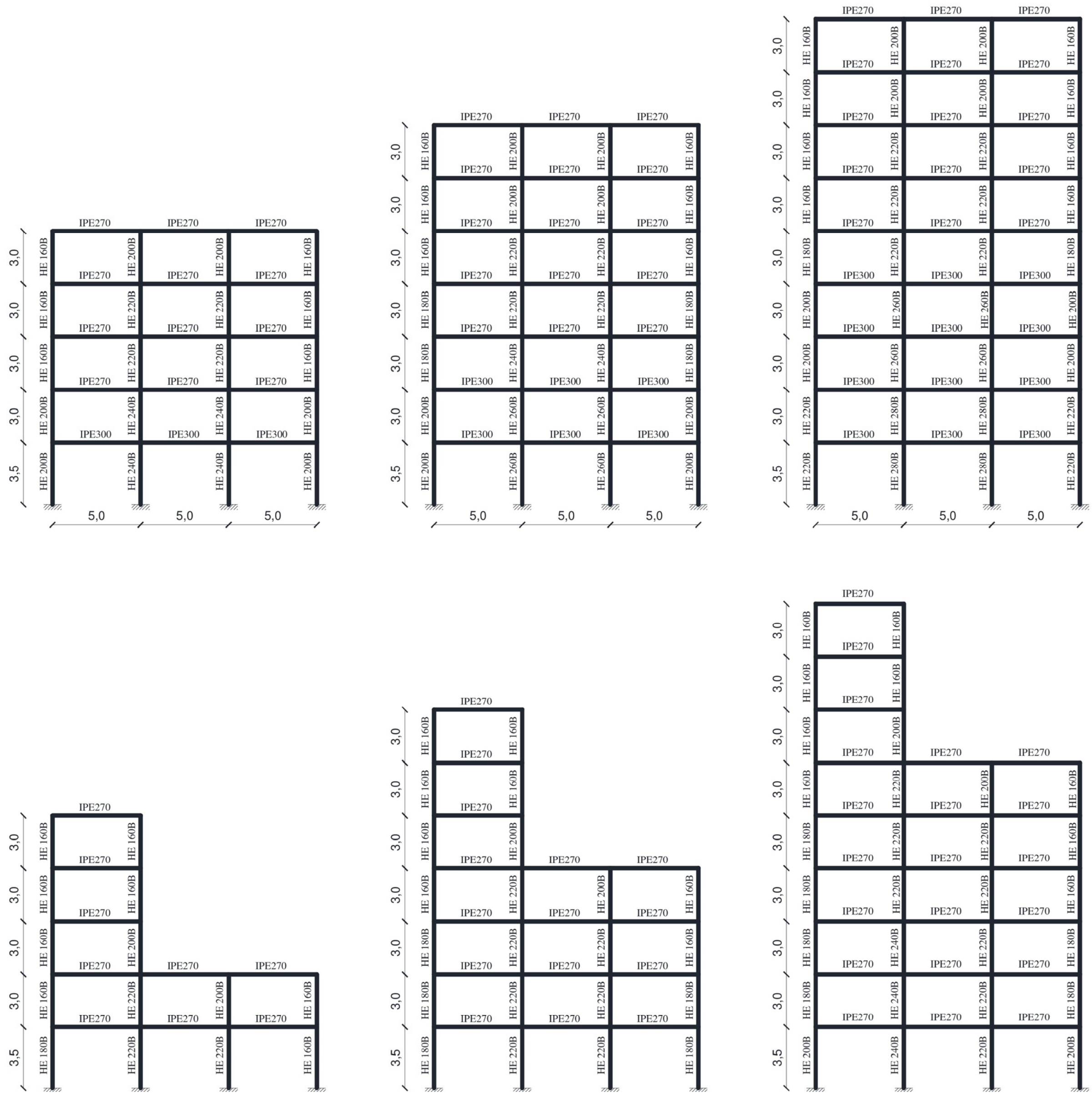

Figure 1. *Cases studies: regular and irregular moment-resisting frames*

Table 1. *Main Characteristics of accelerograms*

No.	Input	Station ID	Date	Time	Dir.	PGA (m/s^2)	M_w
1	Friuli	ST20	06/05/1976	20:00	NS	3.499	6.5
2	Montenegro	ST64	15/04/1979	06:11	EW	2.199	6.9
3	Campano Lucano	ST93	23/11/1980	18:34	NS	1.363	6.9
4	Izmit	ST575	17/08/1999	00:01	NS	1.576	7.6
5	South Iceland	ST108	17/06/2000	15:40	NS	1.238	6.0
6	Olfus	ST101	29/05/2008	15:45	EW	0.439	6.3
7	LomaPrieta	ST47379	18/10/1989	00:04	NS	4.029	6.9

In order to overcome these drawbacks, some researchers proposed invariant loading patterns taking into account the higher mode effects [Chopra et al., 2002- 2004], [Fajfar et al., 2005], [Jianmeng et al., 2008], [Poursha et al., 2009], [Reyes et al., 2011], [Kreslin et al., 2012]. Other researchers developed adaptive pushover procedures accounting for higher mode effects and progressive damage accumulation [Gupta et al., 2000], [Antoniou et al., 2004], [Kalkan et al., 2006], [Pinho et al., 2008], [Ferraioli et al., 2008], in order to overcome the most important limitations of traditional methods especially for estimating seismic demands of tall buildings. However, some of these nonlinear static procedures require very complex analyses and they fail the target of using procedures simpler than NRHA. Nevertheless, these adaptive pushover methods may represent an attractive displacement-based tool for structural assessment, fully complying with the recently introduced deformation and performance oriented trends in the field of earthquake engineering.

2. ADAPTIVE AND MULTIMODAL NONLINEAR STATIC PROCEDURES

Generally, using modal properties of the structure in nonlinear static analysis is the most accessible approach to take into account the dynamic characteristics of the system. However, the conventional nonlinear static procedures (NSPs) are based on the assumption that the structure vibrates predominantly in a single mode and that the dynamic properties of the structure remain unchanged.

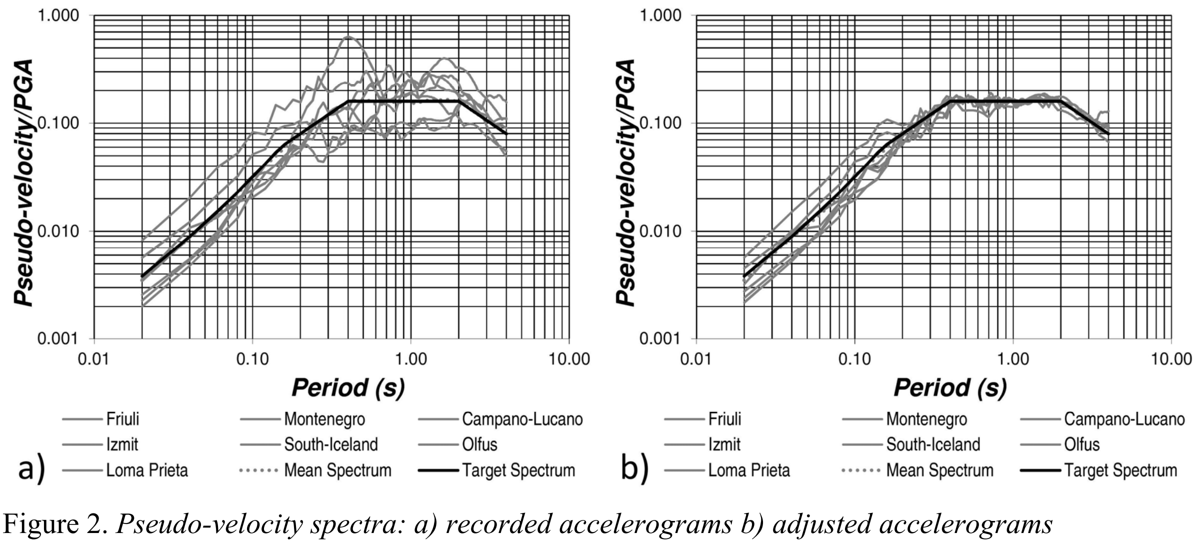

Figure 2. *Pseudo-velocity spectra: a) recorded accelerograms b) adjusted accelerograms*

The first assumption is not always fulfilled, especially in the case of high-rise buildings and/or torsionally flexible plan-asymmetric buildings [Chopra *et al.*, 2004], [Erduran *et al.*, 2008], [Kreslin *et al.*, 2012], [Ferraioli, 2010-2015].
Furthermore, the progressive changes in the modal properties due to structural yielding are generally neglected. In order to include the effects of higher modes some advanced modal pushover procedures based on the elastic modal decomposition concepts were developed in literature. Many of these procedures consider higher modes in lateral load pattern in order to take into account higher mode effects both in plan and in elevation. In particular, in the well-known modal pushover analysis (MPA) proposed by Chopra *et al.* [2004] higher mode effects are considered by analysing each mode as an equivalent single-degree-of-freedom system including nonlinear properties related to that mode. Kunnath [2004] investigated simple modal combination schemes to indirectly account for higher-mode effects. In order to take into account higher-mode effects, Poursha *et al.* [2009] proposed the consecutive modal pushover procedure that employs multi-stage and single-stage pushover analyses. The main problem of conventional nonlinear static procedures is that they are based on the assumption that the mode shape remains un-changed after the structure yields. In order to overcome this drawback in recent years some adaptive pushover methods were proposed to include the effects of higher modes and the changes in vibration characteristics due to the inelastic response. Specifically, in order to include the changes in the dynamic properties of the structure Gupta *et al.* [2000] proposed an adaptive pushover procedure based on an elastic demand spectrum. Kalkan *et al.* [2006] suggested a new pushover analysis procedure derived through adaptive modal combinations (AMC) that accounts for the effects of both higher modes and varying dynamic characteristics due to inelastic response. Antoniou *et al.* [2004] proposed an innovative displacement-based adaptive pushover (DAP) procedure, in which an incremental updating with increment of dis-placement calculated according to the spectrum scaling is applied at each analysis step. Two shortcomings of the modal combination rules can be pointed out: the first one is that the result obtained does not fulfil equilibrium; the second limitation is that signs are lost during the combination process eliminating the contribution of negative quantities and considering an “always-additive” contribution of higher modes. In addition, no solution is provided to determine the target displacement in the adaptive nonlinear static analysis. Summing up, in spite of their deep theoretical background, many of the aforementioned methods suffer from the quadratic modal combination rules, in which the change in the sign of storey components at higher modes is not considered as the sign reversals of load vectors in higher modes are neglected. Thus, the magnitudes of the applied loads in all storey levels are positive. This inappropriate always-additive inclusion of higher mode contribution through a non-weighted SRSS combination rule represents a further weakness of modal pushover procedures. Finally, no multi-run methods are able to reflect the interaction between modes in the nonlinear range.

3. PROPOSED ADAPTIVE CAPACITY SPECTRUM METHOD

In this study, a displacement-based Adaptive Capacity Spectrum Method (ACSM) based on the Inelastic Demand Response Spectra (IDRS) is proposed. At first, the displacement-based adaptive pushover (DAP) procedure proposed by Antoniou *et al.* [2004] is used to define the capacity of the structure. This results in a variation of the lateral force pattern during pushover analysis. Thus, also the equivalent Single-Degree-of-Freedom system (SDOF), which is representative of the MDOF 3D model of the building in the Capacity Spectrum Method (CSM), changes during pushover analysis. In order to consider such effect, an adaptive version of the Capacity Spectrum Method (ACSM) is proposed. At each step of the pushover analysis, a different equivalent SDOF system is defined as a function of the actual lateral displacement pattern. In particular, the equivalent mass M_{eq} and stiffness K_{eq} of the SDOF system at the i-*th* step of the pushover analysis is expressed as a function of the j-*th* storey displacement δ_j^i and force F_j^i, as follows [Ferraioli *et al.*, 2008]:

$$M_{eq}^i = \frac{\left(\sum_{j=1}^N m_j \delta_j^i\right)^2}{\sum_{j=1}^N m_j {\delta_j^i}^2} \tag{1}$$

$$K_{eq}^i = \frac{\left(\sum_{j=1}^N m_j \delta_j^i\right)^2}{\sum_{j=1}^N m_j {\delta_j^i}^2} \sum_{j=1}^N F_j^i \delta_j^i \tag{2}$$

The global force-displacement capacity curve of the structure (base shear V versus top displacement δ_{TOP}) is transformed step by step in the capacity spectrum (spectral acceleration S_a versus spectral displacement S_d) in ADRS format (Acceleration-Displacement Response Spectra), as follows:

$$\Delta S_a^i = \Delta V^i \frac{\sum_{j=1}^N m_j {\delta_j^i}^2}{\left(\sum_{j=1}^N m_j \delta_j^i\right)^2} \tag{3}$$

$$\Delta S_d^i = \Delta \delta_{TOP}^i \frac{1}{\delta_N^i} \frac{\sum_{j=1}^N m_j {\delta_j^i}^2}{\sum_{j=1}^N m_j \delta_j^i} \tag{4}$$

where ΔV^i and $\Delta \delta_{TOP}^i$ are the base shear and the corresponding top displacement increments at the i-*th* step of pushover analysis, respectively, m_j is the mass of the j-*th* storey, δ_j^i is the lateral displacement of the j-*th* storey at the i-*th* step of pushover analysis and N is the number of storeys. The seismic demand is represented through Inelastic Demand Response Spectra (IDRS) that are indirectly computed by scaling the 5% damped Elastic Demand Response Spectra (EDRS) according to the R-μ-T relations available in literature for the strength reduction factor [Vidic *et al.*, 1994]. Specifically, the inelastic pseudo-acceleration S_a and displacement S_d, which are the coordinates of the IDRS in ADRS format, are characterized by the coordinates [S_{de}; S_{ae}] of the EDRS (ξ=5%) as follows:

$$S_a = \frac{S_{ae}}{R_\mu} \tag{5}$$

$$S_d = \mu \frac{S_{de}}{R_\mu} \tag{6}$$

where μ is the ductility ratio and R_μ is the ductility reduction factor defined by Vidic *et al.* [1994], as follows:

$$T^* \le T_0 \quad R_\mu = (\mu - 1)\frac{T^*}{T_0} + 1, \tag{7}$$

$$T^* > T_0 \quad R_\mu = \mu \,. \tag{8}$$

In Eqs. (7) and (8) R_μ depends on the ductility μ and, therefore, on the lateral displacement of the equivalent SDOF system. Thus, some iterations are required in order to match the values of ductility obtained from the demand spectrum and the capacity diagram, respectively, within a given tolerance.

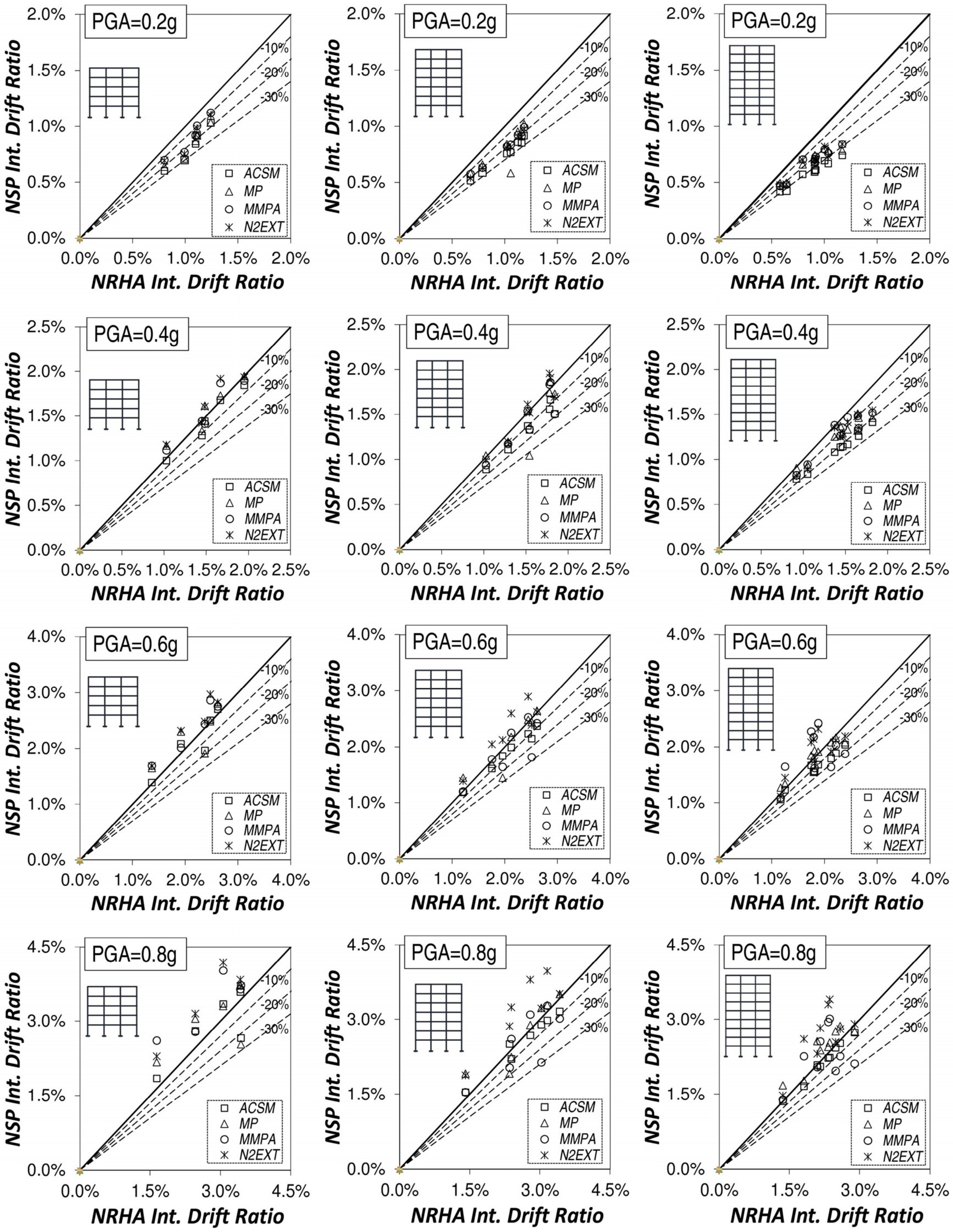

Figure 3. *Scatter plot of estimated target interstorey drift for regular frames*

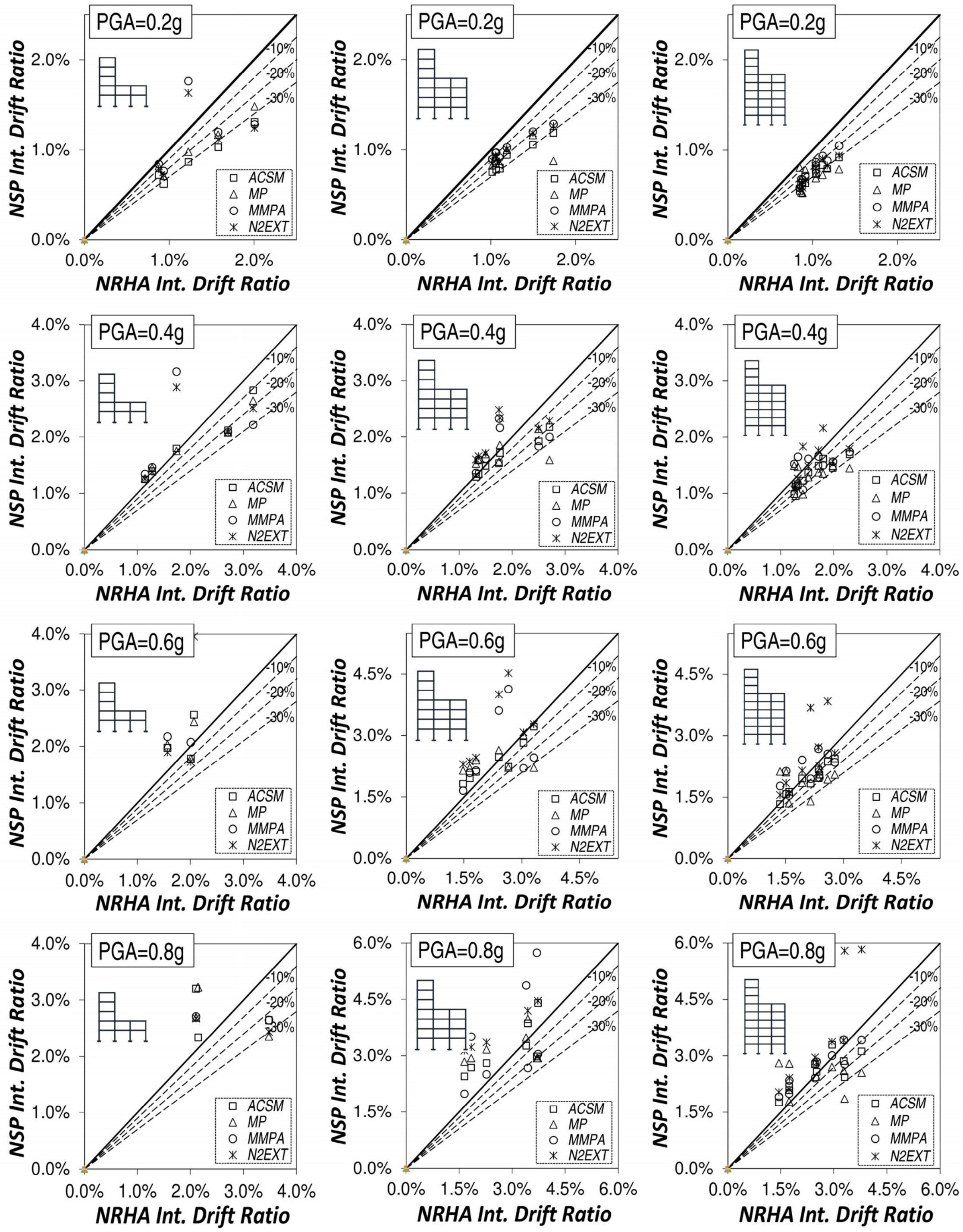

Figure 4. *Scatter plot of estimated target interstorey drift for irregular frames*

4. VALIDATION AND COMPARISON WITH OTHER NSPS

A number of steel moment-resisting frames designed to meet seismic requirements of Italian Building Code [2008] have been considered in the numerical analyses (Fig. 1). The design seismic action has been defined assuming soil class A, damping ratio ξ=5%, peak ground acceleration *PGA*=0.25g, behaviour factor *q*=6.5 for regular frames and *q*=6.5×0.80=5.2 for irregular frames. Steel members are made of S275 steel grade (f_y=275 MPa). The interstorey height is 3.5m for the first floor and 3.0m for the upper floors. The bay length is 5.0m. A distributed plasticity-fibre element model implemented in the SeismoStruct code [2004] has been used in nonlinear analyses. Sources of geometrical nonlinearity taken into account are both local and global. A bilinear kinematic hardening material model has been used for steel. More details about the case studies can be found in Ferraioli *et al.* [2014a, 2014b, 2014c]. The effectiveness of the proposed adaptive capacity spectrum method (ACSM) is evaluated by comparing its predictions with estimates obtained from a comprehensive set of nonlinear response history analyses (NRHA).

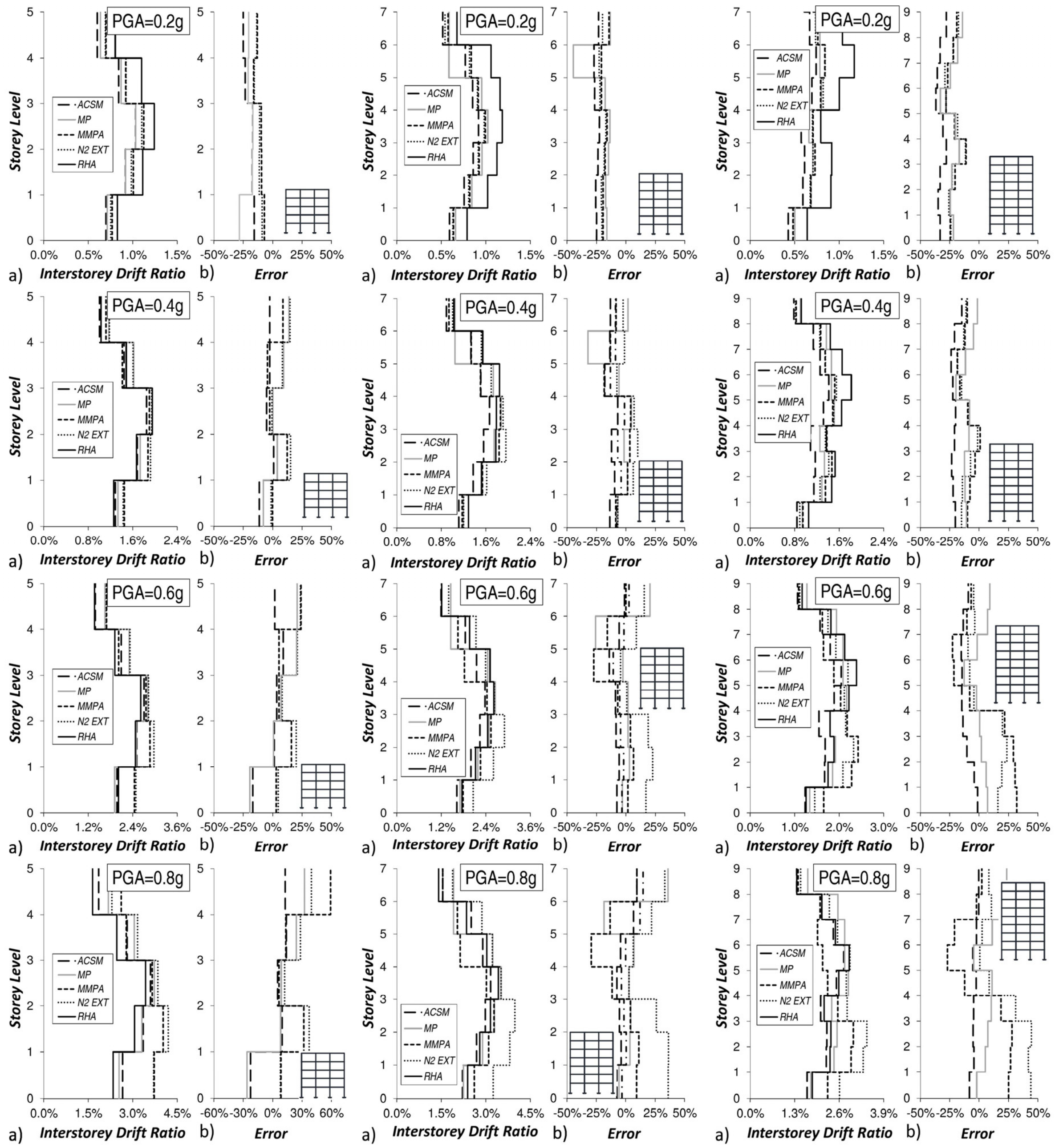

Figure 5. *a) Interstorey drift profile. b) Error profile. Regular frames*

To this aim, a set of seven input ground motions have been carefully chosen in such a way to be consistent with the selected target response spectrum (5%-damped Eurocode 8 type 1 elastic spectrum for soil class A). The SeismoMatch software [2004] has been used to enforce the spectrum-compatibility of the selected accelerograms. Table 1 shows the parameters of the ground motion records. In Fig. 2, the pseudo-velocity response spectra of both recorded and adjusted accelerograms are plotted. The accuracy of ACSM is compared with other more advanced nonlinear static procedures: 1) MP: Multi-mode Pushover analysis [Sucuoğlu *et al.*, 2011]; 2) MMPA: Modified Modal Pushover Analysis procedure assuming higher modes as elastic [Chopra *et al.*, 2004]; 3) N2-EXT: Extended N2 method considering higher mode effects both in plan and in elevation [Kreslin *et al.*, 2012]. The interstorey drift ratio of each storey (defined as the storey drift divided by the storey height) plays an important role in the amount of damage induced in the structure during earthquake ground motion. Consequently, this quantity has been used for comparing the results of Nonlinear Static Procedures (NSPs) and Nonlinear Response History Analysis (NRHA). Specifically, the mean value of the seven interstorey drifts resulted from NSPs has been compared with the mean value of the peak interstorey drifts resulted from NRHA. In Fig. 3-4, the interstorey drift ratios obtained with Nonlinear Response History Analysis (NRHA) are assumed as reference values (X-axis) and the corresponding values obtained with the Nonlinear Static Procedures (NSPs) are shown on the Y-axis. The bisector represents the cases when the NSP and the NRHA give the same results. The straight lines numbered -10%, -20% and -30% are representative of error rates (defined in subsequent Eq. (9)) equal to -10%, -20% and -30% , respectively.

$$Error(\%) = 100 \times \frac{\bar{\Delta}_{j,NSP} - \bar{\Delta}_{j,NRHA}}{\bar{\Delta}_{j,NRHA}} . \tag{9}$$

In Eq. (9) $\bar{\Delta}_{j,NRHA}$ is the mean value of the seven peak interstorey drifts in the j-*th* storey resulting from NRHA, $\bar{\Delta}_{j,NSP}$ is the mean value of the seven interstorey drifts in the j-*th* storey resulting from NSP. The scatter plot of Figs. 3-4 evaluates the coherence between NSP and NRHA. When all the points representing the pairs of values are clustered around the bisector, both methods tend to give the same results. On the contrary, when some values lie below the straight lines numbered -10%, it means that the error of the mean interstorey drift coming from the NSP with respect to the mean interstorey drift of the NRHA is greater than 10%. Finally, it is to be observed that the points over the bisector are situations where the value estimated from NSP procedure is greater than the corresponding value from NRHA. In these cases, the NSP gives conservatives estimates of the nonlinear dynamic response. Figs. 3-4 show that all the procedures tend to underestimate the interstorey drift demand for *PGA*=0.20g and underestimation is even greater than 30%. For *PGA*=0.20g, all framed structures respond elastically, and the differences between NSP and NRHA are not dependent on the inelasticity in the structure, but entirely arise due to the difference in the analysis method. For values of *PGA* ranging from 0.40g to 0.80g the amount of inelasticity in the structure increases, and the accuracy depends on the NSP used to compute the seismic demand. Specifically, both N2-EXT and MMPA tend to overestimate the interstorey drifts when compared to NRHA. The discrepancy increases with both the number of storeys and irregularity in elevation. On the other side, the MP procedure underestimates the interstorey drift demand of irregular frames, while the proposed ACSM tends to give the most accurate solutions.

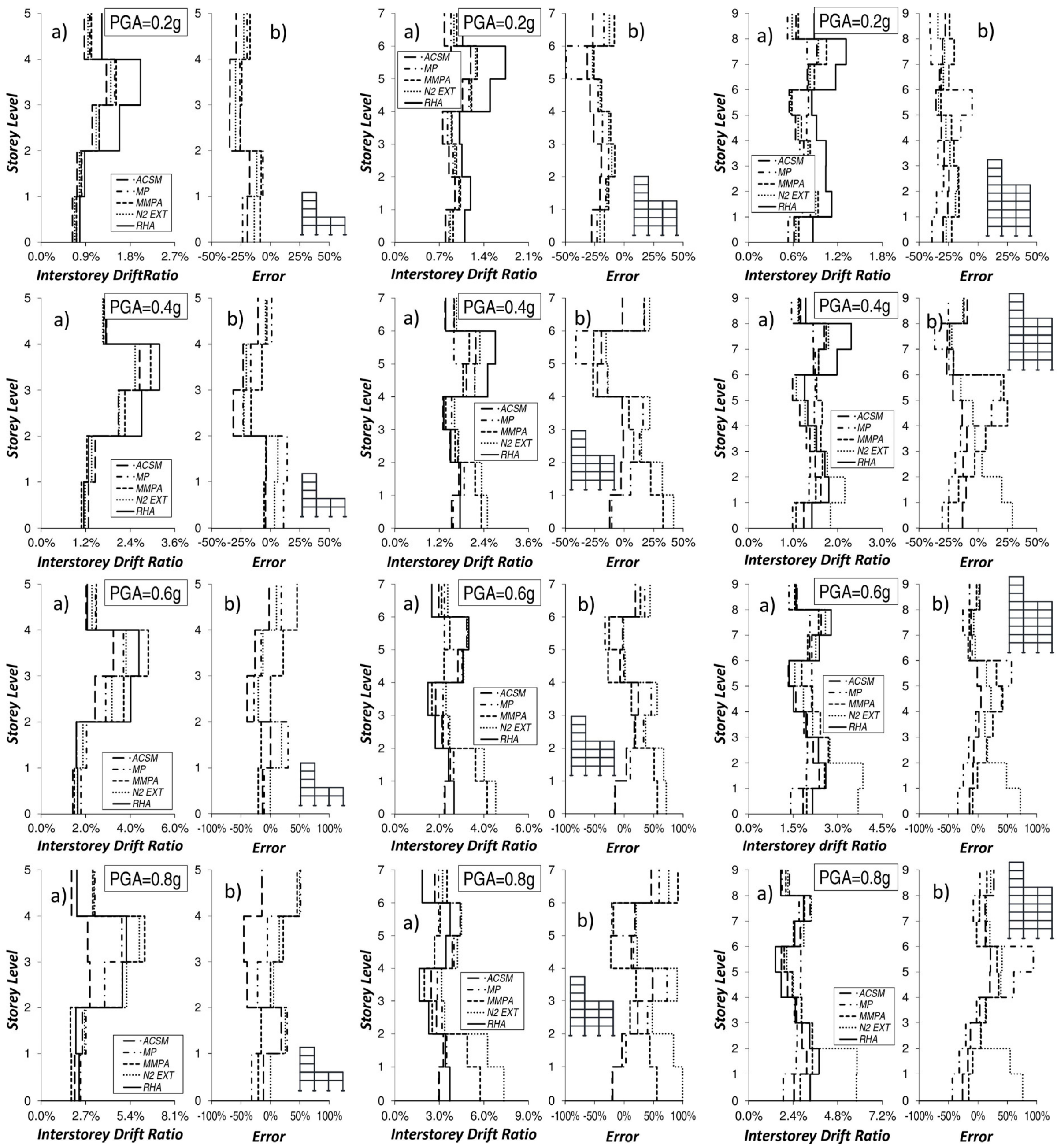

Figure 6. *a) Interstorey drift profile. b) Error profile. Irregular frames*

Practically, the pushover procedures based on invariant lateral force patterns tend to accurately estimate the seismic response of low-rise and regular frames, where the response is dominated by the first mode and the development of a collapse mechanism of the global type is possible. On the contrary, these procedures become inaccurate when applied to high-rise and irregular frames, where the higher modes effects are significant and undesired collapse mechanism typologies may be developed. In particular, high-rise frames are more prone to develop partial mechanisms involving a limited number of storeys compared to the total number. The occurrence of such storey mechanism confirms the importance of design procedures focusing on plastic mechanism control of MR-frames [Montuori *et al.*, 2012-2015] [Piluso *et al.*, 2014].

In Fig. 5 the interstorey drift and the error profiles of the regular frames are plotted. The results obtained for *PGA*=0.20g show that all procedures underestimate the interstorey drift of all storeys. Moreover, the error is slightly variable along the height. When the value of *PGA* rises to 0.40g, the differences increase both along the height and between the NSPs. For *PGA*=0.60g and even more for *PGA*=0.80g both N2-EXT and MMPA overestimate the interstorey drifts, especially in the upper and lower storeys of the taller frames. On the contrary, the proposed ACSM procedure gives errors that are lower and less variable along the height even when compared to the MP procedure. In Fig. 6 the interstorey drift profiles and the error profiles of the irregular frames are plotted. Also in this case, all procedures underestimate the interstorey drift of all storeys for *PGA*=0.20g. Greater differences, both along the height and between the NSPs, are evidenced for *PGA*=0.40g and, even more, for *PGA*=0.60g and *PGA*=0.80g. Both N2-EXT and MMPA overestimate the interstorey drift, especially in the lower storeys, also for shorter frames and for *PGA*=0.40g. In the case of irregular frames, also the MP procedure seems inaccurate since it overestimates the interstorey drifts, especially in the middle storeys for *PGA* ranging between 0.40g and 0.80g. The proposed ACSM procedure gives errors that turn to be lower and less variable along the height than other methods. In order to estimate the global accuracy of results given by the mentioned NSPs, the mean value of maximum interstorey drift obtained from NRHA is assumed as the reference value and the total error has been evaluated as follows:

$$Total\ Error(\%) = 100 \times \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(\frac{\overline{\Delta}_{j,NSP} - \overline{\Delta}_{j,NRHA}}{\overline{\Delta}_{j,NRHA}}\right)} \tag{10}$$

In Fig. 7 the total error is plotted as a function of the peak ground acceleration. The application of both N2-EXT and MMPA procedure can potentially result in very inaccurate solutions for the high values of peak ground acceleration.

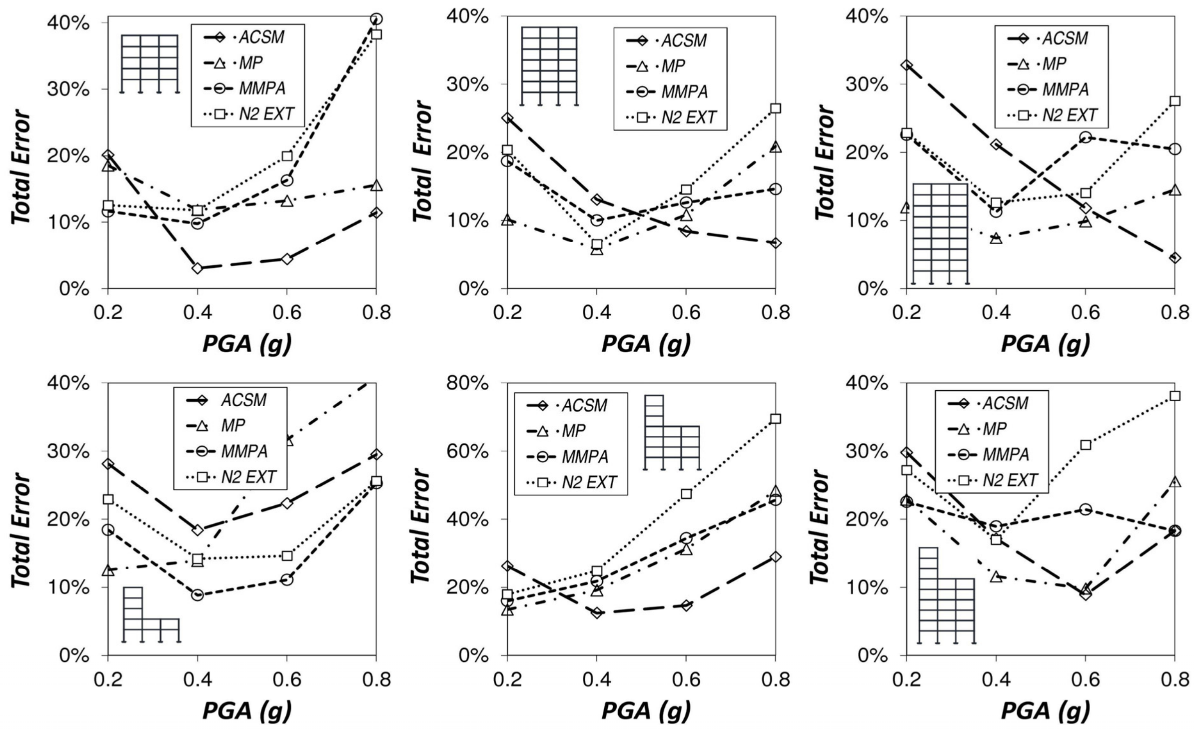

Figure 7. *Total error as a function of the peak ground acceleration*

This conclusion is true for both regular and irregular frames. On the other side, the results of MP procedure may become very inaccurate when the peak ground acceleration and the irregularity in elevation increase. On the contrary, the proposed Adaptive Capacity Spectrum Method give the most accurate solutions for both regular and irregular frames, especially for high values of peak ground acceleration.

5. CONCLUSIONS

An adaptive capacity spectrum method for estimating seismic demands of steel moment-resisting frames was presented in this paper. The proposed procedure takes into account the frequency content of response spectra, the higher mode effects, the progressive changes in the modal properties due to structural yielding and the interaction between modes in the inelastic range. The accuracy and efficiency of the proposed approach was validated by comparing its results with estimates obtained from the nonlinear response history analysis. The results were eventually compared with those provided by other methods suggested in literature. The accuracy of nonlinear static procedures based on invariant load patterns proved to be insufficient at the lower storey levels, and this discrepancy increases with both the number of storeys and the irregularity in elevation. The multimodal pushover methods accounting for higher mode effects along the elevation provide a more accurate estimation of seismic demands, but they become very inaccurate when the peak ground acceleration and the irregularity in elevation increase. The proposed Adaptive Capacity Spectrum Method generally gives a more accurate solution for both regular and irregular frames, especially for the high values of peak ground acceleration. Moreover, the estimated errors are lower and less variable along the height than other methods suggested in literature.

6. ACKNOWLEDGEMENTS

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UNA VERSIONE ADATTIVA DEL METODO DELLO SPETTRO DI CAPACITÀ PER LA VALUTAZIONE DELLA RISPOSTA SISMICA DI TELAI SISMORESISTENTI IN ACCIAIO

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SOMMARIO: *É stata proposta una variante adattiva del metodo dello spettro di capacità per la valutazione della risposta inelastica di telai sismoresistenti in acciaio soggetti ad azioni di tipo sismico. Sono stati esaminati i suoi vantaggi computazionali e la sua capacità di fornire previsioni accurate dell'effet-tiva risposta sismica in rapporto a quelle ottenute impiegando altre procedure statiche non lineari disponibili in letteratura. L'efficacia e l'accuratezza dei metodi approssimati basati sull'analisi di pushover è stata verificata attraverso un'estesa indagine parametrica condotta su telai sismoresi-stenti in acciaio sia regolari, sia irregolari. I risultati ottenuti sono stati confrontati con quelli ottenuti dall'analisi dinamica non lineare condotta utilizzando segnali accelerometrici spettrocompatibili.*

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