Influence Of Lateral Load Distributions On Pushover Analysis Effectiveness

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Abstract. The effectiveness of two simple load distributions for pushover analysis recently proposed by the authors is investigated through a comparative study, involving static and dynamic analyses of seismic response of eccentrically braced frames. It is shown that in the upper floors only multimodal pushover procedures provide results close to the dynamic profile, while the proposed load patterns are always conservative in the lower floors. They over-estimate the seismic response less than the uniform distribution, representing a reliable alternative to the uniform or more sophisticated adaptive procedures proposed by seismic codes.

Keywords: pushover curve, load distributions, non liner static analysis, seismic codes.

INTRODUCTION

Current civil engineering practice now tends to use non-linear static procedures or pushover analysis (POA) to estimate seismic demands, as opposed to non-linear response history analysis (NRHA). In the past few years, several researchers have discussed the underlying assumptions and limitations of pushover analysis [1]. It has been found that, if a unique invariant force distribution proportional to the fundamental mode of vibration is assumed, satisfactory predictions of seismic demands are mostly restricted to regular plane, low and medium-rise elevation structures, for which inelastic demand is distributed through the height of the structure, and higher mode effects are likely to be minimal. Invariant force distributions are not able to take into account the redistribution of inertia forces due to yielding, and the associate change in the mode shape. Moreover, force distribution and displacement pattern, related to the fundamental period of vibration, do not account for the contribution of higher modes.

To overcome these limitations, and with the aim of bounding the likely distribution of interstorey drifts and local ductility demands along the height of the structure, seismic codes [1,2,3] require that analysis is performed enveloping the results obtained by using two different seismic force patterns: - a load pattern aimed at reproducing the distribution of seismic forces acting on the structure in the elastic state; - a uniform or adaptive load pattern aimed at bounding or reproducing the change in distribution of seismic forces due to progressive yielding of the structure.

However, numerical analyses, performed in the last decade, have shown that the uniform load pattern is too conservative for the estimation of the response parameters for the lower floors of buildings, while all the adaptive load patterns proposed in literature, sometimes improve the effectiveness of pushover procedure, but cannot provide a better estimation of seismic response for all structures, as they do not provide suitable solutions for conservative bounding of seismic response.

Recently [4], two very simple load distributions have been proposed. When used in conjunction with a load pattern aimed at reproducing the elastic load distribution, both were found to be effective in bounding seismic response of the structure without introducing the large overestimation at the lower floors that characterizes uniform load distribution.

Most of the numerical analyses in literature aimed at investigating the influence of load distribution on the assessment of seismic response by pushover analysis are performed on moment resisting frames (MRF). MRF are characterized by high redundancy and show a smooth variation of structure stiffness when a plastic hinge is activated. Therefore, load distributions, derived on the basis of dynamic properties of the elastic system, are effective for assessment of seismic demand by POA. By contrast, in steel braced frames, often only a few braced frames are designed to withstand seismic load. When yielding of the dissipative zone occurs, seismic behaviour is affected by a sharp variation of the dynamic properties, namely mode shapes and vibration periods associated to the tangent stiffness matrix. Therefore, POA load distribution must reflect these behaviour.

Here, a comparison of the effectiveness of several load distributions for pushover analysis in assessment of seismic demand of eccentric braced steel frames (EBF) is performed, assuming non-linear response history analysis as the benchmark. It will be shown that the load distributions proposed in [4] are effective in bounding the seismic response, when employed in conjunction with the results provided by a load pattern derived from elastic properties of the system or by the Modal Pushover Analysis (MPA) method proposed by Chopra and Goel [5].

LOAD PATTERNS IN PUSHOVER ANALYSES

Recent seismic codes [1,2,3] suggest the use of two different groups of load distributions to assess the response of systems with weakly and strongly non-linear behaviour, respectively.

In particular, for the former group, the load pattern must be selected among the following load distributions: a) a triangular distribution, proportional to the product of the seismic weight W_i at storey i and the height at the same storey; b) a load distribution proportional to the shape of the fundamental mode (indicated in the following numerical applications by 1M); c) a distribution, corresponding to the Modal storey Shear (MS) of the building, evaluated by a modal response spectrum analysis. Thus, the force at the i level is given by the following equations:

$$F_i = \alpha(\mathrm{Q_i} - Q_{i+1})\ (i = 1,2....,n-1); \qquad F_n = Q_n; \qquad Q_i = \sqrt{\sum_{j=1}^{N\,mod\,i} \mathrm{Q}_{ij}^2} \qquad \text{(1a,b,c)}$$

where Q_{ij} is the seismic shear at the i level due to the j-mode and α the load multiplier.

The second group of patterns, useful for providing the response of strongly non-linear behaviour systems, consists of the following load patterns:

d) a uniform distribution (U) for which the force at the *i* level is proportional to the total mass W_i at the same storey; e) adaptive load distributions in which the load shape changes during analysis according to progressive stiffness degradation.

A well-known multi-modal force-based adaptive procedure has been proposed by Gupta and Kunnath [6] and Elnashai [7], indicated in [8] as FAPM, which provides an incremental update of the load distribution. According to this, the storey force at a given analysis step "*k*", is obtained by adding a new load increment ΔF_i to the load $F_{i,k}$ of the previous step "k-1", as follows:

$$F_{i,k} = F_{i,k-1} + \alpha \Delta F_i; \quad \Delta F_{i,j} = \Gamma_j M_i S_{pa}(T_{j,k}); \quad \Delta F_i = \sqrt{\sum_{j=1}^{n\,mod\,i} \Delta F_{ij}} \qquad \text{(2a,b,c)}$$

where Γ_j is the modal participation factor for the j^{th} mode, $S_{pa}(T_{j,k})$ the acceleration response spectrum ordinate corresponding to the period of the j^{th} mode at step k, and M_i is the mass of the i^{th} storey.

Notwithstanding the superiority of adaptive procedures, compared to standard procedures, sometimes they do not yield conservative results, underestimating seismic demand. Instead, a conservative demand can be obtained with results from the envelope of the response assessed by uniform distribution and by a distribution belonging to the first group of patterns described above. However, in most cases the use of the uniform distribution strongly overestimates seismic demands at the lower storeys.

According to these indications, two very simple load distributions, belonging to the second group of patterns, have been proposed in a previous work [4]. They can be seen as an alternative to uniform distribution, or to the more complex adaptive procedures.

Extensive numerical investigations [9] has shown that, during an adaptive POA; the MS load pattern is the most accurate in providing maxima member forces of structures in the elastic phase. A criterion of theoretical derivation to define the load distribution, when structural elements overcome the yielding strength, is not yet available. By contrast, when the results are used according to the enveloping procedure, the uniform distribution is found to be conservative. Therefore, a simplified conservative adaptive load pattern (indicated with PropA) was proposed, as follows:

$$\mathrm{F_i} = \alpha_1 \left(\mathrm{Q_i} - \mathrm{Q_{i+1}}\right) \qquad 0 \le \alpha_1 \le \alpha_y \qquad \text{(3a)}$$

$$\Delta \mathrm{F_i} = \alpha_2 \mathrm{W_i} \qquad \mathrm{F_i} = \alpha_y \left(\mathrm{Q_i} - \mathrm{Q_{i-1}}\right) + \Delta \mathrm{F_i} \qquad \text{(3b,c)}$$

where α_1 is the load factor of the MS distribution, α_y its value at the first yielding, and α_2 the load factor of the uniform distribution. Let us stress that in Eqs. 3 any other load distribution belonging to the first group can be used.

Alternatively, an invariant load distribution of the second group has been proposed (PropI), by combining MS and uniform distributions, proportionally to load factors of the MS distribution at the first yielding α_y and at ultimate state α_u, as follows:

$$F_i = \alpha\left[\alpha_y\left(Q_i - Q_{i+1}\right) + \beta\left(\alpha_u - \alpha_y\right)\left(Q_1 \Big/ \sum_{i=1}^{n} W_i\right) W_i\right] \tag{4}$$

where Q_1 is the base shear, and β a coefficient that amplifies the uniform load distribution counterpart. The greater the coefficient β, the more conservative the seismic demand in the lower storeys, thus approaching the results provided by the uniform load pattern. In particular, by means of numerical investigations carried out on many structural typologies, it has been shown [9] that, for $\beta = 2$, a sufficient conservative demand in all the analyzed cases can be obtained.

The effectiveness of the proposed procedures will be verified, according to seismic code guidelines, by comparing seismic demand obtained by the envelope between the results from a couple of distributions of the first and second groups, including the proposed ones, with the results of the non-linear dynamic analysis, which is the benchmark. The Modal Pushover Analysis (MPA) method, proposed in [5] and mentioned in [1], has been also considered, along with the load patterns and procedures described above, because it has been found to be highly accurate for the assessment of weakly non-linear structure seismic response.

COMPARISON OF LOAD DISTRIBUTION EFFECTIVENESS

The effectiveness of the load distributions described in the previous sections, in reproducing the seismic demands evaluated by NRHA is compared for three EBFs, with 4, 8, and 12 storeys. Each structure is made up of pinned steel frames having four sides, bay length 8m and storey height 3.2 m (Fig.1). Seismic action is withstood by K eccentrically braced frames only located in the central bays of the external frames, with short links, length e=0.1 l_t., pinned beam to column joints and column pinned at the base. The structures have been designed to carry dead and live storey loads of G_k=4.4 kN/m^2 and Q_k=2.0 kN/m^2 respectively, and seismic design action evaluated according to EC8 for soil type B and peak ground acceleration (PGA) of 0.35g, assuming a behavior factor q=6. In Table 1, designed element cross sections are reported. Modeling the seismic action with spettrocompatible accelerograms [10], for each structure, the PGA that induces collapse rotation of the links (γ_u=0.09 rad) is evaluated by NRHA. Mean values of maximum response parameters for 50 samples of seismic excitation are compared with the results of pushover procedures, performed by imposing a top storey displacement equal to the mean value found by NRHA. Thus, the distribution of response parameters along structure height can be compared.

In Figure 2, the storey displacements U, the storey drifts ΔU and the plastic rotations of the links γ_{pl}, evaluated by NRHA and by POA with the six load distributions and by MPA procedure for the four storey EBF are shown. The structure exhibits a global collapse mechanism, as can be recognized by the values of the storey drifts, which are almost constant along the height. This deformed shape is similar to that exhibited in the elastic phase, and only the uniform distribution fails in the assessment of seismic demand, except at the top storey, where none of the distributions is able to predict the storey drift.

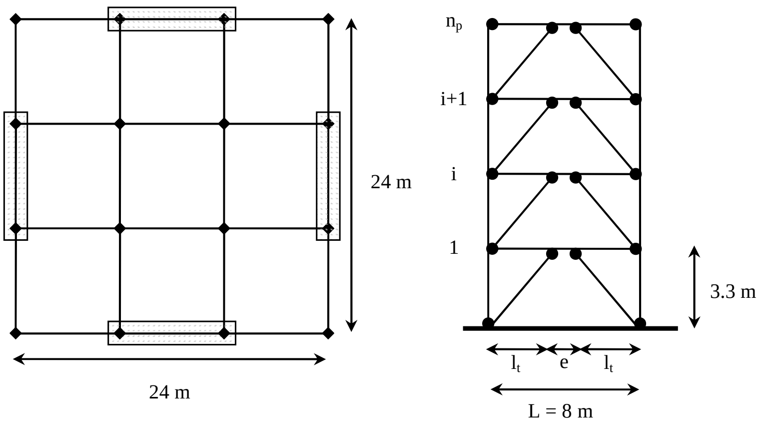

FIGURE 1. Plan and frame structural scheme of the Eccentric Braced Frames

TABLE 1: Structural sections

	STOREY	LINK	COLOUMN	BRACES		STOREY	LINK	COLOUMN	BRACES
4 ST. FRAME	4	HEA 180	HEA 160	HEM 140	**12 STOREY FRAME**	12	HEA 160	HEA 180	HEM 120
	3	HEA 220	HEA 160	HEM 140		11	HEB 180	HEA 180	HEM 140
	2	HEA 260	HEA 260	HEM 160		10	HEB 220	HEB 240	HEM 140
	1	HEA 280	HEA 260	HEM 160		9	HEB 240	HEB 240	HEM 160
8 STOREY FRAME	8	HEA 180	HEA 180	HEM 120		8	HEB 260	HEB 300^{1}	HEM 160
	7	HEB 200	HEA 180	HEM 140		7	HEB 280	HEB 300^{1}	HEM 180
	6	HEB 240	HEB 240	HEM 140		6	HEB 300	HEB 340^{1}	HEM 180
	5	HEB 280	HEB 240	HEM 160		5	HEB 300	HEM 340^{1}	HEM 180
	4	HEB 300	HEB 320	HEM 160		4	HEB 320	HEM 340^{1}	HEM 180
	3	HEB 320	HEB 320	HEM 180		3	HEB 340	HEM 340^{1}	HEM 180
	2	HEB 320	HEM 320	HEM 180		2	HEB 340	HEM 340^{1}	HEM 200
	1	HEB 340	HEM 320	HEM 180		1	HEB 340	HEM 340^{1}	HEM 200
Section steel: FE 360, except sections marked by superscript ^{1} that have steel FE 430.									

In Figures 3, storey percentage errors in the estimation of storey drifts $s_{i,\Delta U}$ and link plastic rotations $s_{i,\gamma pl}$ given by the 7 procedures (Figs. 3a and 3b), and by the envelope prescribed by [3], are depicted (Fig.3c). The results clearly show that the proposed load distributions give an accurate and conservative estimation of the seismic demands at the lower storeys, strongly reducing overestimation provided by uniform distribution. The best performance is obtained if the envelope of the results provided by the proposed adaptive load distribution and by the MPA is retained.

In Figures 4 and 5, the corresponding results for the eight storey structure are shown. In this case, a concentration of the storey drift at the top storey is obtained in the NRHA analysis. Only MS distribution and MPA procedures are able to capture this phenomenon. In the lower storey, the proposed load distributions are the most accurate, providing errors for both the interstorey drifts and plastic rotations, more than three times smaller than those provided by uniform or FAPM load distributions.

Load distributions or procedures derived on the basis of elastic behaviour, namely 1M, MS and MPA, fail at the lower storeys, giving an underestimation of the seismic demand. In this case, the lowest errors are obtained by enveloping the results provided by the proposed adaptive and MS distributions; but also the envelope with MPA procedure provides satisfactory prediction of the response.

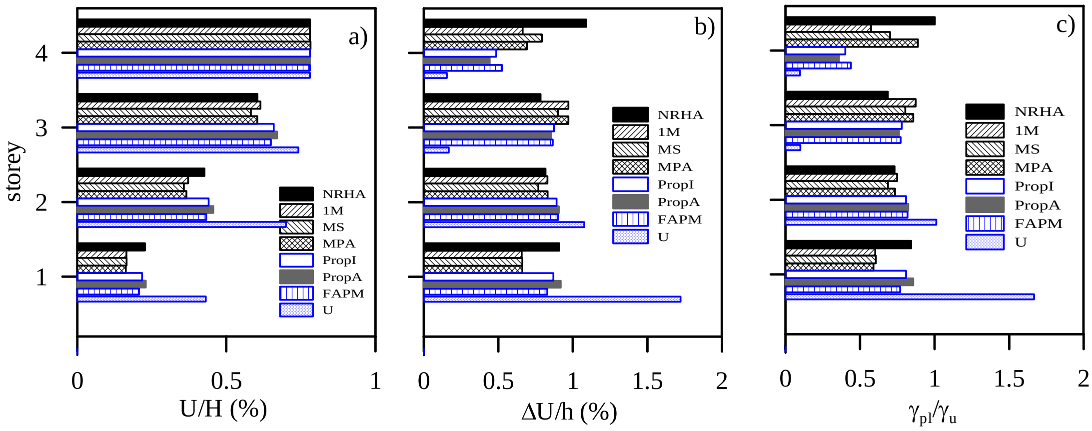

FIGURE 2. Four storey frame: a) storeys displacement; b) storeys drifts; c) plastic link rotations

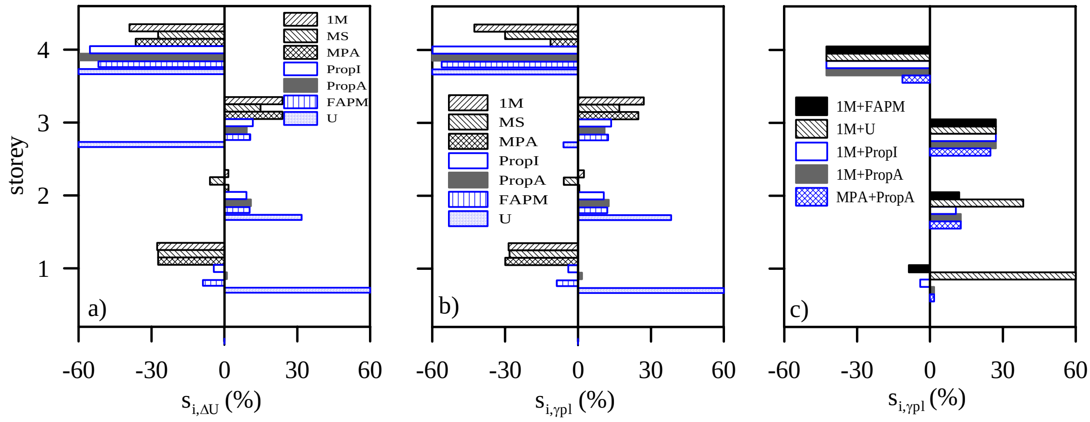

FIGURE3 Four storey frame: errors in the assessment of: a) storeys drifts; b and c) plastic link rotations

Lastly, in Figures 6 and 7, the results for the twelve storey frame are shown. In this case also, a global collapse mechanism is obtained, and the ultimate link rotation is attained at the first and tenth storey almost simultaneously. At the top floor, only MPA is able to provide an accurate prediction of interstorey drifts and plastic link rotation. However, the latter is small (less than 15% of the ultimate value), and its prediction is not particularly useful for design purpose. MS distribution is effective in prediction of response parameters between 8th and 11th storey. In the lower storey, the proposed procedures lead to a very small underestimation of storey drifts, and are very accurate in the assessment of link plastic rotations. The envelope of the results obtained by the proposed adaptive load and MS distributions gives the better prediction of link plastic rotations along structure height, but also the envelope with MPA procedure provides satisfactory prediction of the response.

CONCLUSION

The effectiveness of two new load patterns in the assessment of the seismic demand by pushover analysis has been shown by investigation of seismic response of eccentric braced frames. The proposed load patterns are able to provide an accurate and conservative estimation of the seismic demand when the results are enveloped with those provided by modal shear load pattern. The results shown here encourages further

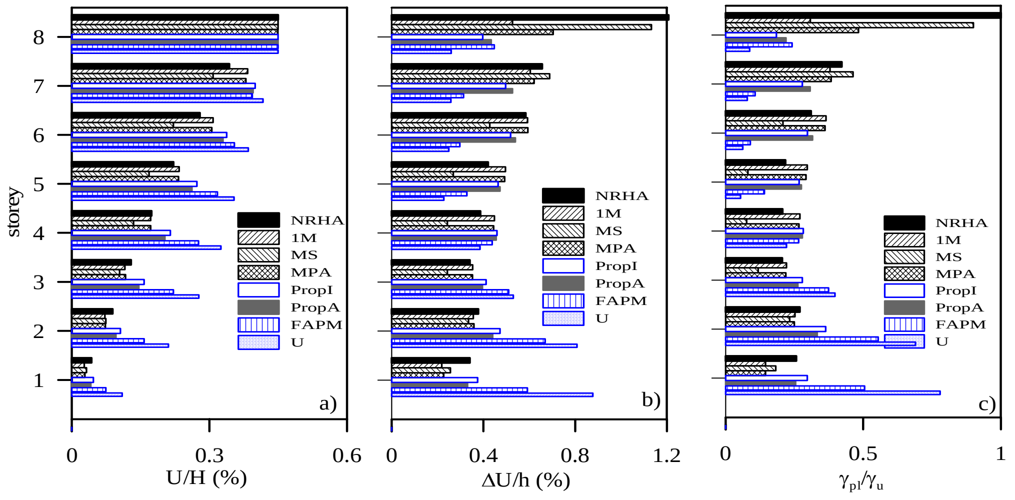

FIGURE 4 Eight storey frame: a) storey displacement; b) storey drifts; c) plastic link rotations

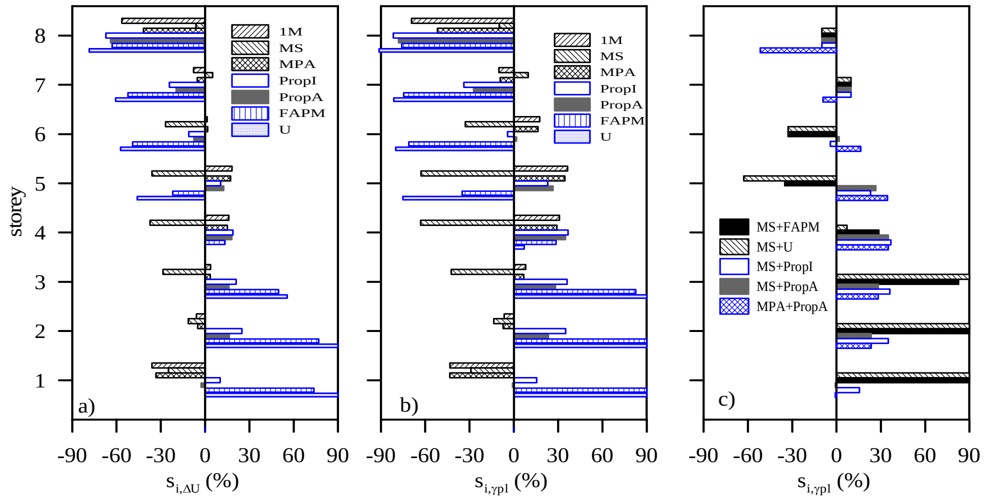

FIGURE 5 Eight storey frame: errors for: a) storey drifts; b and c) plastic link rotations

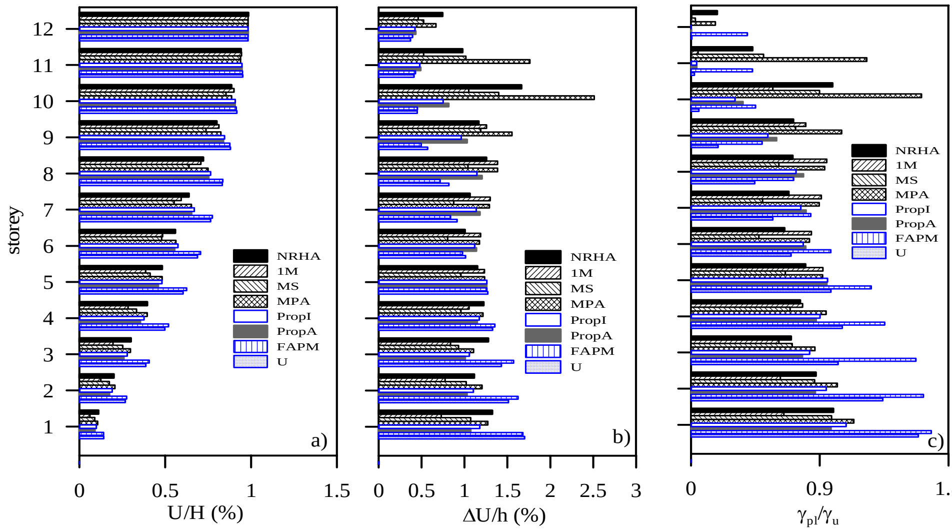

FIGURE 6 Twelve storey frame: a) storey displacement; b) storey drifts; c) plastic link rotations

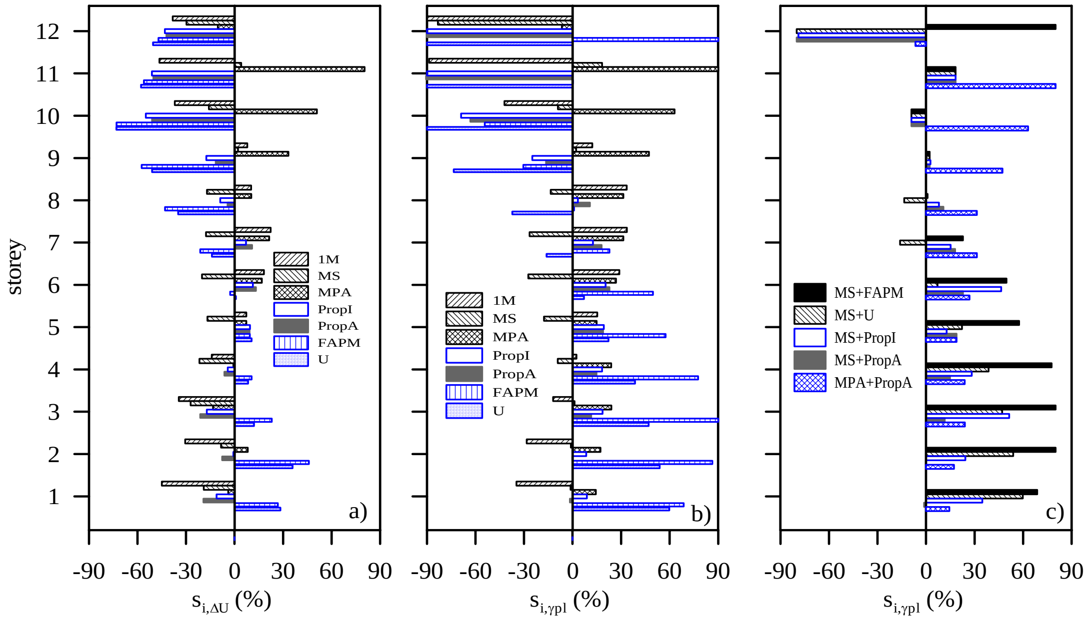

FIGURE 7: Twelve storey frame: errors for: a) storey drifts; b and c) plastic link rotations

investigation to prove that the proposed load distributions give safe and accurate results for all structural systems, and are eligible to be included in seismic codes.

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