A SIMPLIFIED PUSHOVER METHOD FOR EVALUATING THE SEISMIC DEMAND IN ASYMMETRIC-PLAN MULTI-STOREY BUILDINGS

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ABSTRACT:

Buildings with in-plan non symmetric mass and stiffness distributions are characterized by a seismic behavior that is commonly defined as irregular. The reason for such classification is twofold. First, when excited by a lateral ground motion, such buildings instead of simply translating also exhibit torsional behavior. This is basically due to the translational-rotational coupling of the modes. The other reason is that the response of asymmetric-plan buildings usually changes when transitioning from elastic to inelastic behavior. In particular, depending on the elastic properties of the system, on the in-plan distribution of the resisting elements strengths and on the level of the seismic action intensity, the torsional effects may either increase or decrease. Consequently, the seismic demand in such buildings cannot be evaluated through simple conventional analysis procedures, commonly adopted for regular structures. The objective of the present paper is to propose a new pushover method that explicitly takes into account the torsional behavior of asymmetric-plan buildings. The effectiveness of the method is evaluated by comparing the seismic demand of selected case studies with that obtained through both nonlinear dynamic analyses and other pushover methods from literature.

KEYWORDS: asymmetric-plan buildings, multi-storey, inelastic demand, pushover

1. INTRODUCTION

In the present paper the results of a series of analyses carried out by the authors for investigating the seismic behavior of asymmetric-plan buildings are reported. The intent of the work is to add to the current understanding of the inelastic torsional response of such type of structures and to propose a simplified nonlinear static procedure for their seismic evaluation. Many studies (e.g. Fajfar 2002), in fact, showed how much conventional pushover methods, originally conceived for the analysis of regular structures only, are ineffective in estimating the torsional response of asymmetric-plan buildings. First, the results of time history analyses of selected multi-storey frame structures regular in-elevation and excited with earthquakes of increasing intensities are presented. Then, based on observed general trends in the nonlinear dynamic response of the studied cases a new non-adaptive pushover method is proposed. The presented method is finally evaluated with respect to the obtained time history results and with respect to other pushover methods from the literature specifically proposed for asymmetric-plan buildings.

2. STUDIED BUILDINGS

The asymmetric-plan building investigated in the present study is the rectangular plan three-storey frame structure shown in Figure 1. In the selected structural system each floor consists in a rigid diaphragm. The six columns, characterized by the same translational stiffness along both the x and y directions, are symmetrically placed such as the center of the lateral stiffness of the building CS is located in the geometric center of the plan. In each storey the mass is lumped in the center of mass CM placed to a distance e from CS in order to make the building non symmetric with respect to the y direction. The mass, geometry and stiffness distribution of the structure are fixed in order to define a building with close values of the uncoupled translational and rotational periods T_y and T_θ (respectively equal to 0.50s and 0.52s), namely a system characterized by a significant torsional behavior. The building is considered excited along the y direction, that is, along the axes of asymmetry only. Thus, the translational displacements u_y and the torsional rotations u_θ of the three rigid diaphragms are the six only primary *DOFs* of the building. The ground motion used to dynamically excite the structure is the strongest component of the accelerogram recorded during the Friuli earthquake (Italy, May 6 1976) at the Tolmezzo station. The nonlinearities produced in the building by the seismic excitation are supposed to be concentrated in the plastic hinges located at the columns ends. For each plastic hinge, a rigid-plastic constitutive behavior is assumed, with a yielding point defined by a circular interaction surface, that is, by a single yielding force value f_i. Hysteretic laws with no stiffness and resistance degradation under cyclic loadings are considered. The i-storey lateral strength is fixed to be α_i times 6f, with f 10% of the single storey weight and α_i coefficient equal to 1.00, 0.80 and 0.44 for the first, second and third storey respectively. Varying the in-plan strength distribution of the yielding forces f_i, systems characterized by different nonlinear properties can be defined. In the present study, as shown in Figure 2, three different in-plan resistance distributions are considered respectively denoted as R_1, R_2 and R_3.

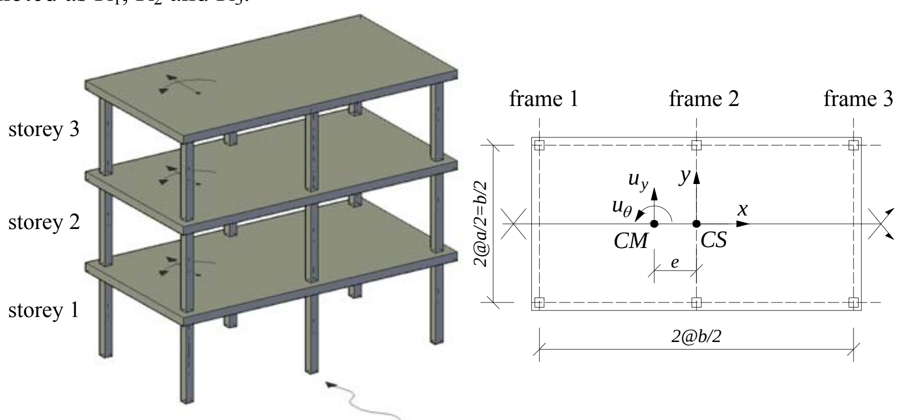

Figure 1 Studied multi-storey building

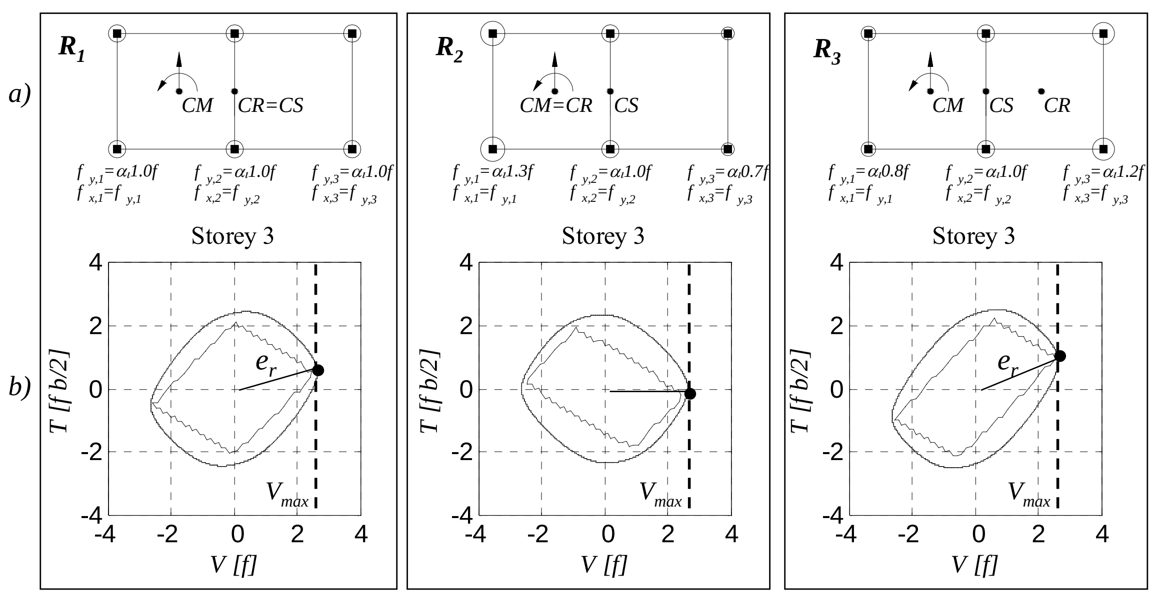

Figure 2 Studied torsional systems characterized by three different resistances in-plan distributions: a) i-storey resistances in-plan distributions; b) BST surfaces and elastic domains

In order to easily represent the differences in the nonlinear properties of the selected systems the BST surface, that is the storey capacity interaction surface in the shear-torque domain, can be used. As proposed by De La Llera et al. (1995), the BST surface is defined by the set of storey shear and torque combinations *V-T* corresponding to the different collapse mechanisms that can be developed in the single storey of the building. In Figure 2, as an example, the elastic domains and the BST surfaces of the third storey of the selected systems are reported. In each case, among all of the possible collapse mechanisms, the one that provides the maximum lateral strength V_{max} of the storey in the imposed direction of the seismic excitation is identified. Hereafter the centers where the resultants of the storey resisting forces associated with this mechanism are located and their distance T_{Vmax}/V_{max} from *CM* will be respectively denoted as *CR* and e_r.

3. OBSERVED NONLINEAR DYNAMIC RESPONSE

In this section of the paper, the results of time history analyses carried out for investigating the dynamic behavior of the selected multi-storey structures are presented. For each building the observed responses produced by excitations of increasing intensity are discussed. Such incremental dynamic analyses have been used to evaluate, for each system, the evolution of the response when moving from the linear to the nonlinear range. The obtained results are presented as follows: first the evolution of the in-elevation distribution of the seismic demand in each resisting frame of the building is shown; then the changes in the in-plan distribution of the seismic demand in each of the three storeys of the building is described.

3.1. In-Elevation Distribution of the Seismic Demand

In Figure 3 the time history results obtained for the R_1 system are shown. In particular, in plot a) the different seismic demands in each of the three resisting frames of the building (respectively identified by an asterisk, a circle and a square marker) are reported. The single curve represents the shear $V_{Sy,imax}$ acting at each storey level of the considered frame, which produces the maximum floor displacement demand $s_{y,imax}$ in the same frame. The shear plots normalized with respect to the $V_{Sy,imax}$ value at the base level $V_{BS,i}$ are reported in plots b). In order to show the effect of the yielding, the responses to ground motion exciting the system both in the linear and nonlinear range are reported.

From observing the plots, two significant trends can be noticed. First, all the $V_{Sy,imax}/V_{BS,i}$ curves match with the vertical shear distribution of the first mode of the single resisting frame (denoted in all the plots with a bold line). Second, moving into the nonlinear range the $V_{Sy,imax}/V_{BS,i}$ curves do not change. These trends, also observed in the R_2 and R_3 systems, clearly show the in-elevation regularity of the selected buildings: in each case, in fact, the seismic response is governed in elevation by a single mode and does not change when getting into the nonlinear range. Actually, such type of behavior could be a-priori easily predicted from observing the in-elevation distribution of the mass, geometry and resistance of the systems.

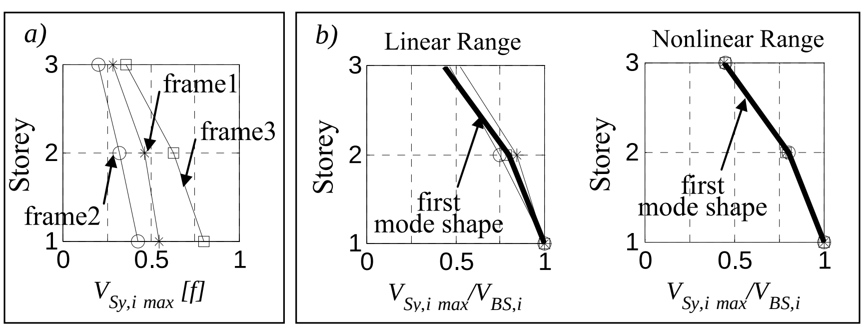

Figure 3 In-elevation distribution of the seismic demand in each *i*-th resisting frame of the building: a) shear $V_{Sy,imax}$ corresponding to the maximum displacement demand in each floor; b) $V_{Sy,imax}$ curves and shear distribution of the first mode of the single resisting frame normalized with respect to the base shear $V_{BS,i}$

3.2. In-Plan Distribution of the Seismic Demand

In the plots of Figure 4, the R_1 system in-plan distribution of the seismic demand evaluated for excitations of increasing intensities is shown. In particular, the building response at each storey level both in the displacement and in the *V-T* domains is reported. Plots a) show, for each storey, the maximum displacements in the *y*-direction $s_{y\,max}$ of the three resisting frame normalized with respect to the maximum *CM* displacement at the roof $s_{CMtop\,max}$. Four envelops are used to represent the evolution of the seismic response when moving from the linear to the nonlinear range: the dotted line is used to denote the elastic response, while the dashed, solid and the bold lines are used to denote the nonlinear responses produced by earthquakes of increasing intensity respectively. While in the linear range, due to the coupling of the translational and rotational response, the displacement envelopes are strongly curved, getting deeper in the nonlinear range the envelope profile becomes more flat. This means that moving significantly into the nonlinear range the maximum displacement demand in the different resisting elements tend to be reached with the same deformed configuration of the system.

In plots b), the $V_{Sy,i\,max}$-$T_{Sy,i\,max}$ paths, that is, the storey shear-torque pairs corresponding to the observed maximum displacement demands at the considered storey level are shown: the asterisk, the circle and the square marker are used to denote the building response in frame 1, 2 and 3 respectively. In addition, the elastic domains and the BST surfaces of each storey are also reported. It can be clearly observed that the $V_{Sy,i\,max}$-$T_{Sy,i\,max}$ paths converge in the nonlinear range toward the *V-T* points of the BST surfaces which provide the maximum storey lateral strengths. The results show that getting deep into the nonlinear range the seismic shears, that is the $T_{Sy,i\,max}$ to $V_{Sy,i\,max}$ ratios, tend to locate at the storey centers of resistances *CR*.

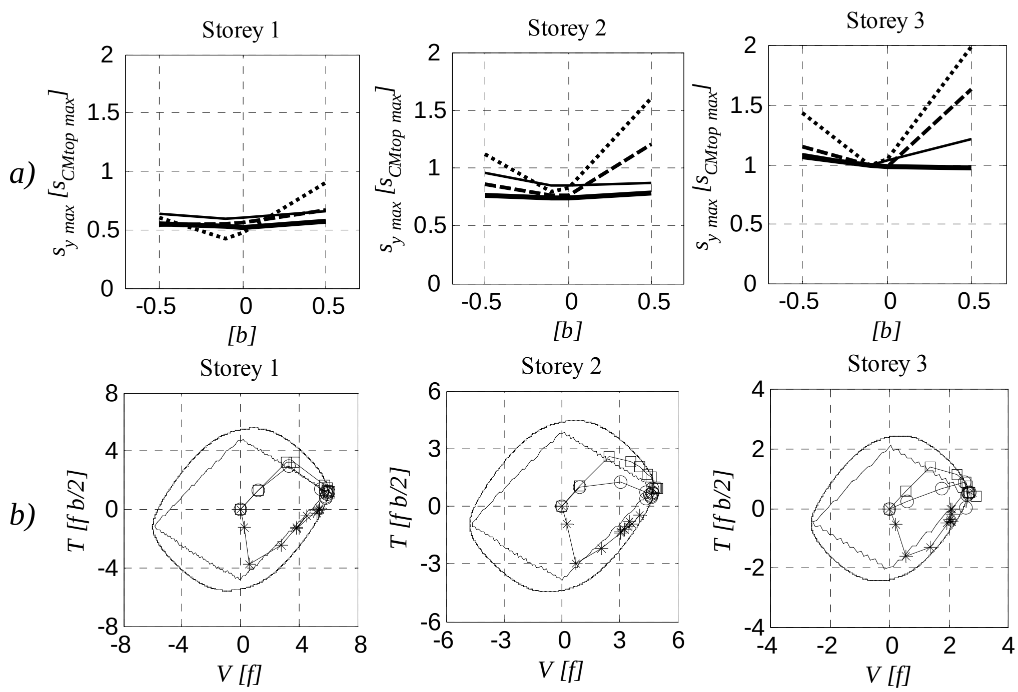

Figure 4 R_1 system in-plan distribution of the seismic demand for earthquakes of increasing intensities: a) maximum displacement in the *y*-direction $s_{y\,max}$ normalized to the maximum *CM* displacement at the roof $s_{CMtop\,max}$; b) $V_{Sy,imax}$-$T_{Sy,imax}$ paths, and the elastic domain and the BST surfaces of each storey of the building

Finally, for the case considered in the above simulations, as the seismic excitation intensity increases, the shape of the nonlinear response both in the force and in the displacement domains point towards a fixed configuration. This significant trend, observed in the seismic response of the R_1 system, has been actually found in all the studied multi-storey buildings.

4. PROPOSED PUSHOVER METHOD: R-METHOD

Based on the results obtained in the dynamic analyses presented in the previous section, a new pushover method for the seismic demand evaluation of asymmetric-plan buildings is proposed. According to the proposed method, the seismic demand is computed by nonlinear static analysis of the structure subjected to monotonically increasing lateral forces with an invariant distribution, until a target displacement is reached. A single load vector, defined based both on the elastic dynamic properties of the system and on the resistance-distribution of the lateral resisting elements of the structure, is used to push the building. As torsional effects are directly evaluated in the pushover analysis, no correction factors for the evaluated nonlinear demand are needed. It is important to note that with respect to other improved pushover procedures the proposed method keeps the conceptual and computational simplicity of the analysis methods commonly used for symmetric-plan buildings.
In the following section of the paper the proposed method, denoted hereafter as the R-method, is first described. Evaluations of the methodology through comparison with results from nonlinear dynamic simulations and other pushover methods from the literature are then presented.

4.1. Description of the Methodology

The time history analyses results previously described eventually lead to an interesting observation on the seismic behavior of asymmetric-plan buildings: in case of a regular in-elevation structure, the maximum displacement demand in the different resisting elements of each storey tend to be reached with the same deformed configuration of the system. While in the elastic range, because of coupling of the modes, it is impossible to statically force the system with a single load vector to evaluate the seismic demand this seems to be more likely in the nonlinear range. The dynamic analyses also showed that the seismic storey shears finally locates into the centers of resistance *CR* of the system.

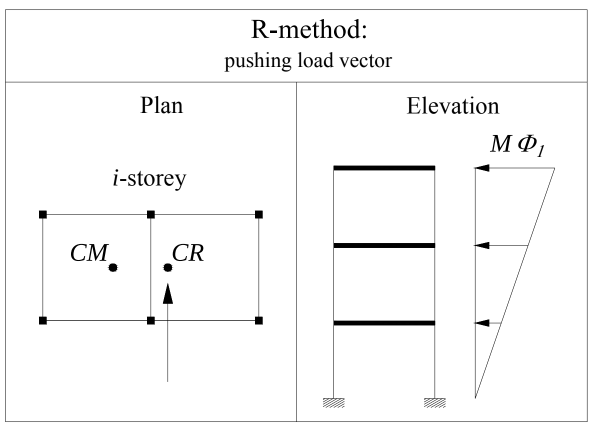

Figure 5 R-method: pushing load vector for a multi-storey asymmetric-plan building regular in elevation

On the basis of these observations it seems reasonable that in the nonlinear range the seismic demand of the asymmetric-plan building can be evaluated with a pushover analysis using a single load vector defined as follows (see Figure 5): consists of lateral forces in the applied direction of the seismic action; has a vertical distribution proportional to $M_i \Phi_{1i}$, with M_i and Φ_{1i} equal to the *i*-th floor translation mass and displacement of the first mode respectively; is located at the center of resistance *CR* of each storey.

4.2. Evaluation

The most significant results of the comparisons between the proposed R-method and other nonlinear static procedures from the literature, viz., the Extended N2-method (by Fajfar et al. 2005) and the Modal Pushover Analysis (by Chopra et al. 2004), are presented in the plots of Figure 6. In particular, the results of the case study of the R_3 system are reported. In each plot, the effectiveness of the pushover methods in evaluating the dynamic response is shown for excitations of increasing intensities, i.e. for different levels of the requested inelastic demand. For each of the three *PGA* values considered, the target displacement of both the pushover methods from the literature and the R-method is the maximum *CM* displacement at the roof $s_{CMtop\ max}$ evaluated with the nonlinear dynamic analysis. The comparisons are shown in terms of envelopes of the maximum displacement demands at each floor.

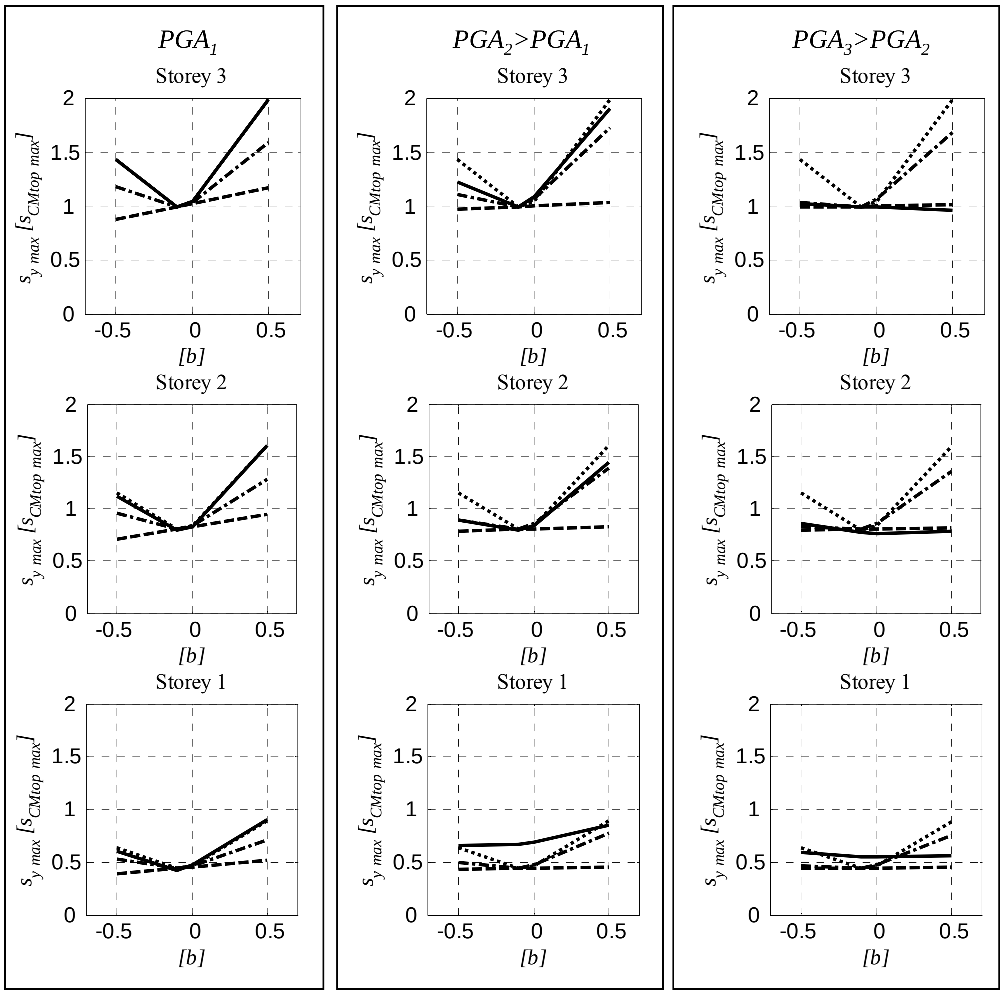

Figure 6 Comparisons between time history analyses (solid line), R-method (dashed line), extended N2-method (dotted line) and Modal Pushover Analysis (dashed/dotted line) for the R_1 building: displacements envelopes for increasing values of the seismic action intensity (i.e. increasing *PGA* values)

The trends that can be observed in the analyses results reported in Figure 6 are representative also of those obtained in the other investigated cases. The Extended N2-method and the Modal Pushover Analysis overestimate in general the torsional effects: such overestimation is significantly more pronounced at the roof than the first floor. In all the studied buildings the effectiveness of the R-method is shown to improve with increasing levels of the inelastic demand, while the Extended N2-method and the Modal Pushover Analysis become less effective. For the case of the Extended N2-method this is probably related to the increase of the error due to the approximation in evaluating the inelastic torsional effects with a linear analysis. As for the Modal Pushover Analysis, the decrease in the effectiveness of the method is probably related to the fact that the application of the modal combination rule (rigorously valid for linear systems only) to inelastic systems leads to increasing error when the system gets deeper into the nonlinear range.

5. CONCLUSIONS

The investigations carried out in this study highlighted some new and interesting properties of the inelastic seismic behavior of asymmetric-plan buildings. In the studied cases it was shown that deep into the nonlinear range the storey shears producing the maximum floor displacement demands in all the different lateral resisting elements of the building are located at the Centers of Resistances *CR* corresponding to the collapse mechanisms which provide the maximum lateral strength of the storeys in the imposed direction of the seismic excitation. Based on this finding, a new evaluation method is proposed to estimate the inelastic demand of asymmetric-plan buildings called the R-method. In the proposed R-method a pushover analysis of the asymmetric-plan building is carried out using a single load vector proportional in elevation to the first mode and located in each floor at *CR*. Since the effectiveness of the method improves with increasing nonlinearity, an a-posteriori evaluation of the requested inelastic demand level could be used to directly measure the validity of the obtained results. It is worth noting that with respect to other improved pushover procedures, proposed in the literature for taking into account the torsional behavior of asymmetric-plan buildings, the R-method keeps the conceptual and computational simplicity of the analysis methods commonly used for symmetric-plan structures.

In order to confirm the effectiveness of the proposed pushover method, additional studies are already underway by the authors for investigating the influence of the considered structural scheme, the influence of an eventual asymmetry in the orthogonal direction of excitation, and the effect of the irregularity in elevation.

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