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EFFECT OF SETBACK IRREGULARITY LOCATION ON THE PERFORMANCE OF RC BUILDING FRAMES UNDER SEISMIC EXCITATION

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The setback is a frequent type of irregularity expected in complex-shaped buildings. The main purpose of the present paper is to emphasize the influence of setback location on the performance of reinforced concrete building structures under seismic excitation. In this research study, 68 building models with setback values vary from 0.1L to 0.5L, located at various levels, are studied. Non-linear static (pushover) analyses were conducted. All building models are analyzed using a finite element calculation code. The outcomes show that setback irregularity location has a significant effect on the seismic behavior of the structure. Based on the regression analysis of the results obtained in the current study, a mathematical formula is proposed to quantify the effect of setback location on the performance of building structures. The results of this study would aid all professionals in the building sector to anticipate the response of these types of structures during the design phase.

Keywords: Performance Point, Setback Irregularity, Pushover Analysis, Reinforced Concrete Buildings, Structure Behavior.

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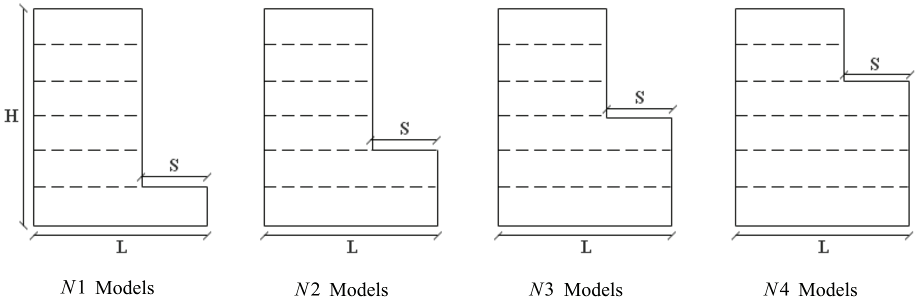
1. INTRODUCTION

Nowadays, modern design increasingly uses irregular structures, in plan or elevation, because of their functional and aesthetic characteristics, this has encouraged researchers and engineers to study the behavior and the performance of these structures during earthquakes.

To take into account the effect of setback irregularity in buildings subjected to seismic action and to improve the seismic behavior of these structures, several research studies have been conducted. Azad et al. [1] studied the effect of setback percentage on the seismic response of buildings. The study was carried out by considering three different shapes of six-storey buildings with setback percentages of 33.33% and 66.67% along with the height of the building. The results show that the setback percentages significantly govern the seismic response of the structures. Also, Bhosale et al. [2] investigated the seismic performance, in terms of inter-storey drift ratio (IDR) and fragility curves, for buildings with three different types of vertical irregularities, including two models with setback were considered, one with a single setback (SB) and the other with multiple setbacks (ST). These models were subjected to 44 ground motions. The results of this study indicated that the (ST) model is the least vulnerable, but these two models need to be carefully studied to validate the requirements recommended by the design codes. In the same way, Habibi and Asadi [3] conducted a study on the seismic performance of multi-storey frames, designed according to the Iranian seismic code (Standard 2800), with a setback along with the height of the building. 35 reinforced concrete frames were subjected to earthquakes with different intensities. Then, the seismic performance is evaluated in terms of the inter-storey drift ratio of the structure and the maximum rotation of its elements. From the results of their study, it was concluded that irregular buildings designed according to Iranian code seem to need to be improved to define and suggest new indicators to predict seismic behavior for this type of structure. Moreover, Lu X. et al. [4] assessed the seismic behavior of a 58 storey building. Non-linear dynamic time-history analyses were conducted. The most remarkable results in their study indicate that there is an excessive concentration of damage in the floors adjacent to the setbacks. Likewise, Habibi A. et al. [5] assessed the seismic performance of several multistorey reinforced concrete moment resisting frames containing different types of setbacks. From their study, it was shown that the structural failure starts for the elements located in the approximate of the setbacks. So, it is necessary to strengthen these elements by introducing appropriate modifications to the design methodologies of seismic code applicated in Iran. Furthermore, Sarkar P. et al. [6] studied the vertical irregularity for 78 stepped buildings to provide a new approach to quantify the irregularity. Then the authors proposed a correction factor to the empirical formula of the code for the fundamental period to make it applicable to these types of buildings. Recently, Repapis C. C. and Zeris C. A. [7] investigated the performance of existing reinforced concrete buildings with height irregularities using both static and dynamic analyses. In their study, five-building models with irregularities are considered including one model with a setback (K60C59 model). From their results, it is very noticeable that the (K60C59) model regularly shows smaller yield and collapse roof deformations. It also exhibits a slightly smaller behavior factor and ductility capacity. Despite all these efforts performed in this field, more advanced researches are still needed to better understand this topic and to formulate the seismic design methodologies. Therefore, this is the main motivation for the current study. Indeed, the fundamental objective of this paper is to study the seismic response of buildings with setback irregularity, particularly single setback, situated in different levels named respectively $N1$, $N2$, $N3$, and $N4$, and for different setback values (S) varying from $0.1L$ to $0.5L$ as illustrated in figures 1 and 2. Non-linear static analyses have been carried out using a finite element calculation code. Based on the regression analysis of the achieved results, a mathematical formula is proposed to express the variation of the performance points for models with a setback in the upper levels ($N2$), ($N3$), and ($N4$) as a function of that of the models with setback irregularity at the bottom storey ($N1$), to illustrate the impact of setback location on the performance of the building and to minimize the computation time at the modeling stage for this type of structures.



$N1$ Models $N2$ Models $N3$ Models $N4$ Models

Fig. 1. Sketch on building elevation with single setback irregularity in different levels.

2. BUILDINGS MODELS ANALYSIS

2.1. BUILDINGS MODELS DESCRIPTION

In this study, different configurations of reinforced concrete buildings are considered as shown in Figure 2. These models correspond to residential buildings, class (III) according to the Moroccan earthquake regulations [8], situated in Agadir city in the south of Morocco. All selected models have six floors with a total height (H) of 18 meters, i.e. a typical floor height of 3 meters. These buildings have a total plan dimension of 20 m × 15 m with 5 bays in the larger direction and 3 bays in the smaller direction. The lateral force resisting system is constituted by moment resistant frames in both longitudinal and transverse directions. More detailed information about geometry, element dimensions, and reinforcement is given in Figure 3. The earthquake load is assumed to be unidirectional and acts parallel to the setback sense. These reference buildings are chosen based on a concise study of the common types of irregular buildings in this region, considered as a high seismic risk area, with a ground acceleration coefficient equal to 0.18 g, according to the Moroccan seismic code.

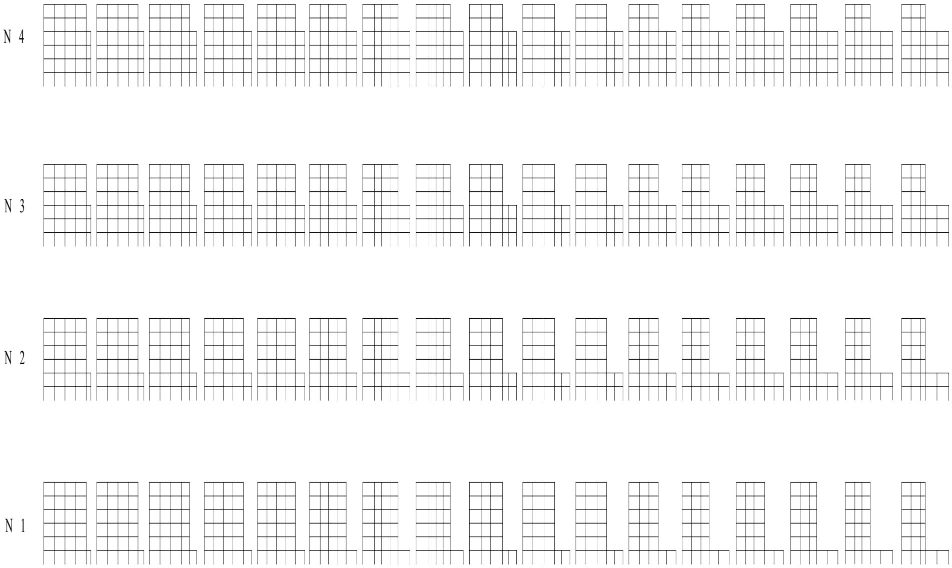


Fig. 2. Explanatory figure for setback irregularity suggested in this study: X-Z view of the studied structures.

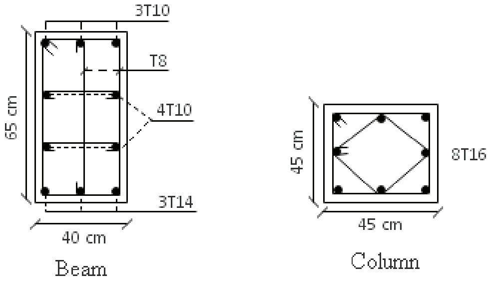


Fig. 3. Typical cross-section of beams and columns.

2.2. STRUCTURAL MODELING AND ASSUMPTIONS

The selected configurations are modeled as three-dimensional models using a finite element calculation code [9]. The modeling of these structures includes the modeling of structural elements like columns, beams, slabs, joint conditions, and base conditions. Columns and beams are modeled as two-nodded rectangular continuous vertical and horizontal line elements, respectively. Slabs are modeled as four-nodded rectangular shell area elements. The joint diaphragms in all the joints of the structure are made as fixed or flexible depending on the condition to make all the joints act as a single unit that contains the nodes of beams, columns, and slabs together in that joint. The boundary conditions at the base are defined by restraining all the degrees of freedom of each joint of the base [10]. Structural components, columns, and beams are designed according to the strong column-weak beam concept to avoid that the columns failed in compression before the yielding of beams [11]. The nonlinearities for various structural elements are taken into account by defining plastic hinges at the extremities of the columns and beams as described in [12, 13]. The set-up of the hinges in columns and beams are considered by the interaction of biaxial bending moments with axial force and pure bending moments, respectively. In this paper, the floors have 25 cm of thickness, assumed to be rigid and support in addition to their self-weight, live loads (Q) of 2.5 KN/m^2 and dead loads (G) of 1.5 KN/m^2, including the weight of the infill walls, applied directly to the beams as a uniform load. The structure weight is taken into account using the combination $G+0.2Q$ according to [8, 18]. For materials used in structural design, the concrete is of class $C25/30$ with a characteristic compressive strength $f_{ck}=25\,MPa$, the tensile strength is given by: $f_{ctm}\,(MPa)=0.3(f_{ck})^{2/3}$, and Young's modulus of concrete is given by the following equation : $E_{cm}\,(GPa)=22(f_{cm}/10)^{0.3}$ [17]. The yield strength for reinforcement bars is $f_{yk} = 400\,MPa$, and the modulus of elasticity is $E_s = 210000\,MPa$. The bar spacing follows the constructive dispositions mentioned in [8, 18]. These structures models are built on dense soil, a site type *S2* according to [8]. The demand spectrum depends on the nature of the site as well as the ground acceleration, the linear interpolation between the values of C_a and C_v given by ATC-40 and Moroccan standard allows determining the seismic coefficients corresponding to the region and the nature of the site. In this study, the acceleration coefficient C_a and the velocity coefficient C_v are equal to 0.256 and 0.2826 respectively. All building models have an effective damping coefficient β_{eff} defined as: $\beta_{eff}(\%) = k\beta_0 + 5$ according to [13], where β_0 represents the ratio between the energy dissipated by damping and the maximum strain energy, and the k-factor depends on the behavior of the building, which in turn depends on the quality of the seismic-resistant system. Furthermore, the studied buildings have a ductility level ($ND1$) according to [8]. To focus on the effect of the setback irregularity, all structural elements were designed to have the same sections for all levels to avoid any variations in mass or stiffness along with the height of the building. Also, bays width remains variable. According to [14] the variation in the width of the bays does not have a great impact on the movement of the structure. Then, a pushover analysis is conducted to assess the response of these buildings models.

2.3. PERFORMANCE POINT COMPUTATION

The performance point is a fundamental parameter to assess the degree of damage to the structure. It reflects the effective behavior of the structure when it is subjected to seismic loading [15]. In this study, the performance points of different structures are computed using the capacity spectrum method described in [13]. The capacity of the structure is given by a force-displacement relationship obtained from a non-linear static (pushover) analysis. The shear forces versus roof displacements are converted into the ADRS (Acceleration-Displacement Response Spectrum) format of an equivalent SDOF (Single Degree of Freedom) system [16]. The transformation of the capacity curve into a capacity spectrum is governed by the following equations:

$$\Gamma_1 = \frac{\sum_{i=1}^{N}(m_i\,\phi_i)}{\sum_{i=1}^{N}(m_i\,\phi_i^{\,2})} \tag{2.1}$$

Where: Γ_1 – modal participation factor for the 1st mode, m_i – mass assigned to level (i), ϕ_i – the amplitude of mode at level (i), N – the uppermost level of the structure.

$$\alpha_1 = \frac{\left(\sum_{i=1}^{N}(W_i\phi_{i1})/g\right)^2}{\left(\sum_{i=1}^{N}W_i/g\right)\left(\sum_{i=1}^{N}(W_i\phi_{i1}{}^2)/g\right)} \tag{2.2}$$

Where: α_1 – the modal mass coefficient for the 1st mode, W_i – building weight, dead load plus a fraction of live load at level (i), ϕ_{i1} – the amplitude of mode 1 at level (i), g – acceleration of gravity.

$$S_a = \frac{(V/W)}{\alpha_1} \tag{2.3}$$

Where: S_a – spectral acceleration, V – base shear, W – building weight, α_1 – the modal mass coefficient for the 1st mode.

$$S_d = \frac{U_n}{\Gamma_1\phi_{1,n}} \tag{2.4}$$

Where: S_d – spectral displacement, U_n – roof displacement at level (n), Γ_1 – modal participation factor for the 1st mode, $\phi_{1,n}$ – the amplitude of mode 1 at level (n).

Indeed, the performance point corresponds to the intersection between the capacity spectrum and the reduced demand spectrum, as shown in Figure 4. Using this method, displacement becomes the main dimensioning parameter, not the force. Then, we will apply this method to calculate the performance point of the various models mentioned above.

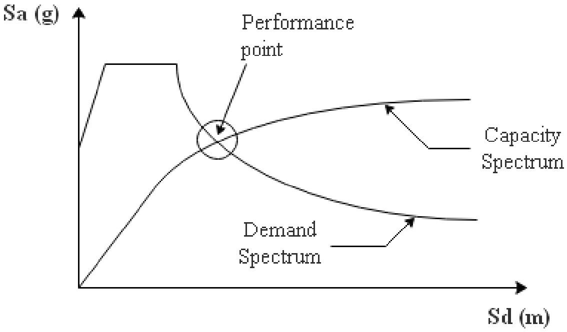


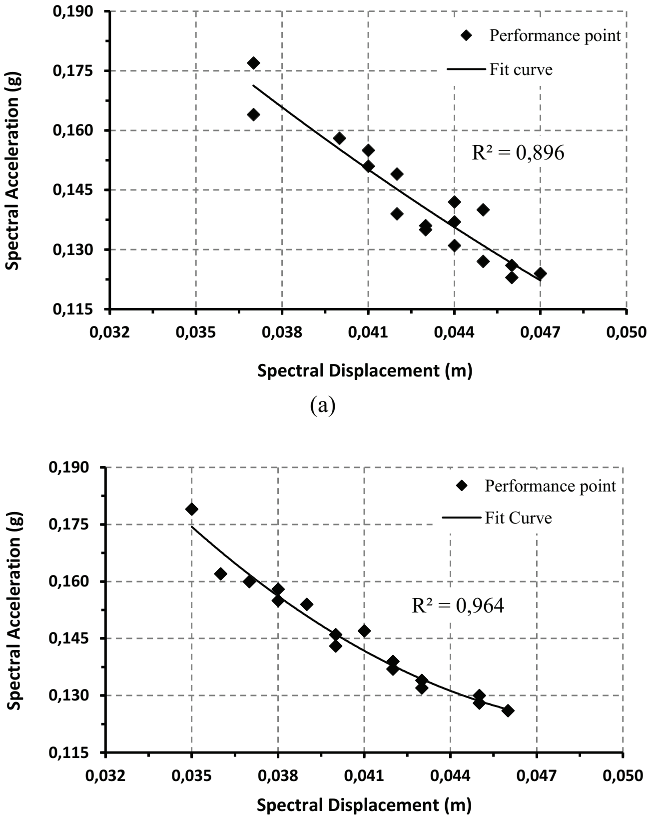
Fig. 4. Performance point determination method [19].

3. RESULTS AND DISCUSSIONS

To emphasize the importance of the setback irregularity phenomenon on the structural behavior of buildings, the following figure shows the results obtained in terms of roof displacement registered from an incremental loading in the longitudinal direction. Figure 5 indicates that the response of structures to the setback location is quite similar for all models and the variation of performance points as a function of the setback value for these models adopts a polynomial form. The results clearly show that the location of the setback irregularity has a significant influence on the structural behavior of the buildings. Therefore, the buildings with the irregularity on the first level have lower seismic performance compared to the other models ($N2$, $N3$, and $N4$), for all setback values. Moreover, this influence of Setback location on the seismic behavior of buildings can be observed from the results of the modal analysis described in table 1. It can be noted that when Setback is at the bottom of the structure (i.e. $N1$ models) the period is great compared to that of the other models. This implies that these structures are less rigid and more vulnerable to seismic shaking. These buildings also exhibit a slightly lower behavior factor and ductility capacity. This effect tends to decrease until we reach the fourth level where the models ($N4$) perform better in terms of seismic performance. This consequence can be explained by the fact that the energy induced by the earthquake is absorbed mainly by the columns. The energy absorption has been evenly distributed in the columns, except at the setback side where the energy distribution was concentrated. This can also be observed during the hinges formation mechanism.

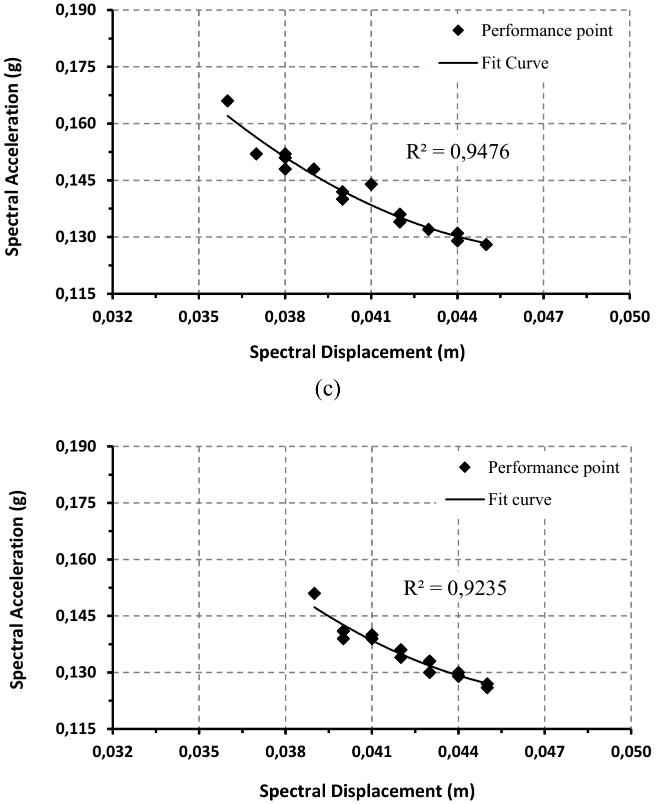
Table 1. Period (s) (or frequency (Hz)) of building structures with Setback at different locations.

Setback value / Setback location	20%	30%	40%	50%
$N1$	$T = 0.83144$ $f = 1.20273$	$T = 0.85047$ $f = 1.17582$	$T = 0.80238$ $f = 1.2463$	$T = 0.7579$ $f = 1.31944$
$N2$	$T = 0.82242$ $f = 1.21592$	$T = 0.83289$ $f = 1.20064$	$T = 0.78765$ $f = 1.2696$	$T = 0.74842$ $f = 1.33615$
$N3$	$T = 0.81961$ $f = 1.22009$	$T = 0.82464$ $f = 1.21264$	$T = 0.78327$ $f = 1.27669$	$T = 0.74855$ $f = 1.33591$
$N4$	$T = 0.82373$ $f = 1.21399$	$T = 0.82657$ $f = 1.20981$	$T = 0.79103$ $f = 1.26417$	$T = 0.76176$ $f = 1.31275$



(a)

(b)



(c)

(d)

Fig. 5. Acceleration-displacement relationship for different models and different Setback values: (a) For $N1$ models, (b) for $N2$ models, (c) for $N3$ models, and (d) for $N4$ models.

From the above curves, it is very noticeable that the setback value has a significant impact on the performance of the studied structures. The results show that the spectral displacement drops by 10 mm from a setback value of $0.1L$ to $0.5L$ for ($N1$), ($N2$), and ($N3$) models. It is also obvious from the results of analyses that the setback irregularity location has an important incidence on the response of the structure. This effect is manifested by the presence of a deviation between the displacement values registered during the transition from the top of the structure to the bottom stories. According to the results, it is highly remarkable that spectral displacement S_d has been reduced from about 40 mm for ($N4$) models to 35 mm in the case of ($N1$) models when the setback value is taken equal to

$0.5L$. Also, the setback effect is noticeable through the dispersion of performance points, it is observed that when the irregularity is at the first level the overall capacity of the structure is more affected and this effect tends to decrease until the fourth storey which seems to be less vulnerable. Therefore, based on regression analysis, the variation in the performance point for the different models is given by the equation described below:

$$S_a = C_{1(N_j)} S_d^2 - C_{2(N_j)} S_d + C_{3(N_j)} \tag{3.1}$$

Where: S_a – spectral acceleration, S_d – spectral displacement, $C_{1(N_j)}, C_{2(N_j)}$ *and* $C_{3(N_j)}$ – the determining coefficients described in the table below.

Table 2. Parameters of the fitting formulas.

Setback location	$C_{1(N_j)}$	$C_{2(N_j)}$	$C_{3(N_j)}$
First Storey	50.756	9.218	0.4431
Second Storey	222.270	22.338	0.6858
Third Storey	231.150	22.440	0.6701
Fourth Storey	310.760	29.460	0.8238

For $N2$ models, the equation (3.1) can be written as a function of the coefficients of $N1$ models as:

$$S_a = \xi\, C_{1(N_1)} S_d^2 - \xi' C_{2(N_1)} S_d + \xi'' C_{3(N_1)} \tag{3.2}$$

Where: $\xi = 4.379$, $\xi' = 2.423$, and $\xi'' = 1.547$

The same applies to the $N3$ models, the equation (3.2) becomes:

$$S_a = \xi.\eta\, C_{1(N_1)} S_d^2 - \xi'.\eta' C_{2(N_1)} S_d + \xi''.\eta'' C_{3(N_1)} \tag{3.3}$$

Where: $\eta = 1.039$, $\eta' = 1.004$, and $\eta'' = 0.977$

Finally, for $N4$ models, the evolution of the performance point, as a function of $N1$ models, is given by the following equation:

$$S_a = \xi.\eta.\zeta\, C_{1(N_1)} S_d^{\,2} - \xi'.\eta'.\zeta' C_{2(N_1)} S_d + \xi''.\eta''.\zeta'' C_{3(N_1)} \tag{3.4}$$

Where: $\zeta = 1.344$, $\zeta' = 1.312$, and $\zeta'' = 1.229$

Therefore, the overall expression of the proposed formula to express the variation of performance points in the case of models $N2$, $N3$, and $N4$ as a function of $N1$ models, is written as:

$$S_a = (\xi)^x.(\eta)^y.(\zeta)^z\, C_{1(N_1)} S_d^{\,2} - (\xi')^x.(\eta')^y.(\zeta')^z C_{2(N_1)} S_d + (\xi'')^x.(\eta'')^y.(\zeta'')^z C_{3(N_1)} \tag{3.5}$$

Where: $\begin{cases} x = \dfrac{j-k}{j-(j-1)} \\ y = (1-k)^{(j-3)} \\ z = 1-k \end{cases}$; $k = \dfrac{(4-j)^{(j-1)}}{(j-1)^{(3-j)} + (3-j)^{(j-1)}}$,

and: $j = \{1,\ \ 2,\ \ 3,\ \ 4\}$ represents the location of the setback.

The suggested formula may be useful to minimize considerably the computation time at the modeling stage. As well, it illustrates the influence of the setback location on the structural behavior of the buildings.

4. CONCLUSION

In this paper, the seismic behavior of buildings with setback irregularity in different locations was studied by non-linear static (pushover) analysis. Based on the results presented in the current paper, the following conclusions can be drawn:

(1) A formula to express the variation in the performance points, adapted to buildings with a single setback, is proposed, taking into account the impact of changes in the setback location along with the height of the building. This is a simple concept that has proven to be more useful than existing measures.

(2) The performance point of the building structures is influenced by the setback irregularity location. In the case of building models with a setback at the bottom stories, the capacity of the structure is more affected as compared to the building models with a setback in the upper levels. This is very noticeable through the registered displacement of the roof which is reduced from 45 mm to 40 mm when the setback value is taken equal to 30 % of the longitudinal dimension of the plane (L).

(3) The performance of the structure decreases with the increase in setback value, as the setback value increases involve an abrupt reduction of the floor, which reduces the mass and stiffness at this location. This results in a reduced capacity and therefore the structure becomes more vulnerable.

(4) The structural elements on the setback side need to be improved in terms of detailing requirements and constructional provisions compared to the current design methodologies.

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LIST OF FIGURES AND TABLES:

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