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Estimation of Seismic Deformation Demands of Tall Buildings with Symmetric Setbacks

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Abstract**—**This study estimates the seismic demands of tall buildings with central symmetric setbacks by using nonlinear time history analysis. Three setback structures, all 60-story high with setback in three levels, are used for evaluation. The effects of irregularities occurred by setback are evaluated by determination of global-drift, story-displacement and story drift. Story-displacement is modified by roof displacement and first story displacement and story drift is modified by global drift. All results are calculated at the center of mass and in x and y direction. Also the absolute values of these quantities are determined. The results show that increasing of vertical irregularities increases the global drift of the structure and enlarges the deformations in the height of the structure. It is also observed that the effects of geometry irregularity in the seismic deformations of setback structures are higher than those of mass irregularity.

Keywords**—**Deformation demand, drift, setback, tall building.

I. Introduction

BECAUSE of structural and architectural reasons, the seismic response of setback structures has been a subject of active research for many years. Pekau and Green [1] and Humar and Wright [2] investigated seismic response of setback structures and observed that inter-story drift demands were increased near the location of the setback level. Aranda [3] concluded that the ductility demands in setback structures are higher than those of regular structures. Shahrooz and Moehle [4] observed concentration of inelastic behavior in members near setback. The seismic response of buildings with vertical irregularities in mass, stiffness and lateral strength was studied by [5]. They concluded that the effects of lateral strength irregularity are higher than stiffness and mass irregularities. The study of Chintanapakdee and Chopra also agrees with this observation [6]. Some other analytical and experimental studies were carried out on the linear and nonlinear response of setback structures, as in [7]-[13] and etc. Although numerous studies have been conducted in this field, the studies have conflicting conclusions regarding the seismic response of setback structures.

Current design codes contain criteria for classification of “irregular” structures. The most influential types of vertical irregularities are irregularity in mass, stiffness, geometry and lateral strength [14]. For structures with vertical irregularities in stiffness, mass or geometry, current guidelines require using dynamic analysis (seismic response history procedure or modal response spectrum analysis) to come up with a lateral force distribution [14].

In buildings with sudden changes in geometry, i.e. setback buildings; stiffness, mass and lateral strength vary with geometric changes. It should be mentioned here that structures with setbacks in their height have vertical irregularities at specific levels.

In this paper, deformation demands of tall buildings with setbacks are evaluated by using nonlinear time history analysis. In addition, the influence of the amount of irregularities caused by geometrical changes is studied. Deformations that are studied in this paper are as follows: (1) roof displacement which is an important factor in seismic behavior of structures [15], (2) story displacement which is lateral displacement at the center of mass and (3) story drift that its distribution depends on ductility, mass and stiffness of structures.

II. Modelling

A. Description of Models

The seismic behavior and response evaluations are carried out for three 60-story special moment frames. The models have been extracted from [16]. The structures have setbacks in three levels above; 15th, 30th and 45th story. Moreover, the plan geometry of these structures is centrally symmetric. In other words, all models contain 4 parts and each part is a 15-story regular structure and the total height of the structures is 210 meters. Model specifications including the effective mass ratio of the story below setback levels to the story above and the irregularity type of each model, are shown in Table I. Fig. 1 shows the effective mass distribution of the structures. As can be seen in Table I and Fig. 1, S1 is an approximately regular structure due to the vertical irregularity limits defined in ASCE/SEI 7-10 [14], S2 is an irregular structure with mass irregularity, and S3 is regular in lower parts of the structure and irregular in upper part. Furthermore, first and second period of all models are approximately equal.

B. Input Ground Motions

This study focuses on evaluating the effects of setbacks on the seismic response of structures subjected to ground motions of D type soil [14]. The three pairs of ground motion records used in this study are selected from FEMA-P695 [18]. The magnitude of selected ground motions is greater than 6.5. Furthermore peak ground acceleration and peak ground velocity are greater than 0.2g and 15 centimeters per second respectively. Each pair of motions is scaled [16] based on

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ASCE/SEI 7-10 [14] at the design based earthquake (DBE). The MCE (Maximum Considered Earthquake) spectral response acceleration parameter for short periods is determined by selecting S_1=0.7 and S_s=1.5.

TABLE I
MODELS SPECIFICATIONS

Models	W_i [a]/W_{i+1} [b]			Period	Modal participation mass ratio	
	15th floor	30th floor	45th floor	Sec	X	Y
S1	1.46	1.45	1.55	7.58	1%	61%
				7.32	64%	1%
S2	1.92	2.12	1.95	7.79	47%	1%
				7.17	1%	56%
S3	1.27	1.37	2.41	7.54	16%	50%
				7.40	50%	16%

[a] The weight of ith story
[b] The weight of i+1th story

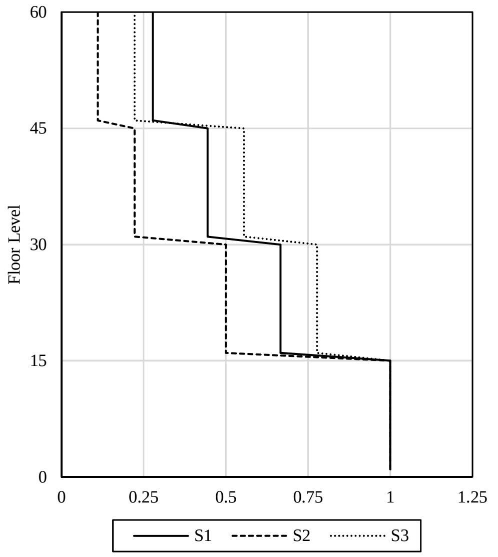

Fig. 1 Effective mass distribution of the structures [16]

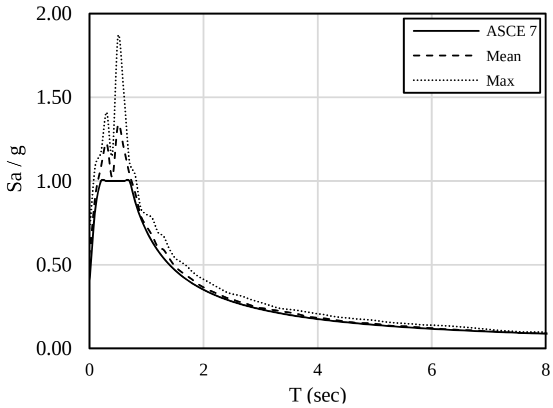

Fig. 2 Comparison between spectra of ASCE/SEI 7-10 [14], mean and max spectra of modified ground motions [16]

III. ANALYSES AND RESULTS

The seismic demands of the structures are evaluated by using nonlinear time history analysis method. In time history analyses, three pairs of horizontal ground motion acceleration components are used. Each orthogonal pairs of ground motion acceleration histories is applied to the structures simultaneously. Median of maximum story displacements and drifts is calculated at the center of mass for each pair of ground motions. Moreover plastic hinge method is used for nonlinear modeling of structures and plastic hinges are defined based on ASCE/SEI 41-06 [17].

Table II presents the global drift of the structure (d G.), which is the roof displacement at the center of mass per height of the structure in models with symmetric setbacks (S). Global drifts are determined by nonlinear time history analysis (NL.THA). In this Table II, d G.x. and d G.y. indicate the global drift in x and y directions respectively, and d G.abs. is the absolute global drift of the structure. As seen in Table II, the absolute global drift of S2 is greater than that of S3, and the absolute global drift of S3 greater than that of S1; and increasing the amount of irregularities causes increasing of global drift. It can also be seen that the amounts of d G.x. and d G.y. are approximately equal in S1 but are different in S2 and S3, since S1 is more regular than the other two. In addition, increasing the changes in plan geometry from 50% to 100%, increases roof displacement about 35%.

TABLE II
GLOBAL DRIFTS

Models	d G.x. [a]	d G.y. [b]	d G.abs. [c]
S1	0.91%	0.92%	1.28%
S2	1.26%	1.17%	1.72%
S3	1.09%	0.95%	1.45%

Global drifts of the structures calculated by nonlinear time history analysis.
[a] Global drift in x direction
[b] Global drift in y direction
[c] Absolute global drift

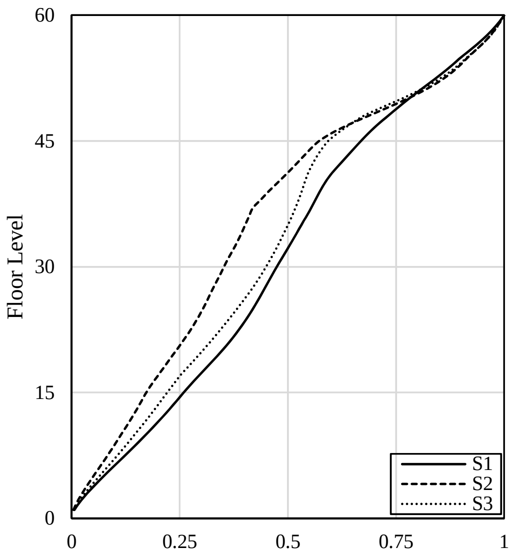

Fig. 3 Absolute story-displacement at center of mass modified by absolute roof displacement

Absolute values of median story-displacement are demonstrated in Fig. 3 and values of median story displacement in x and y directions are shown in Fig. 4. It should be noted that the values are modified by roof displacement. As can be seen in Fig. 3, the distribution of story displacement in S1 (with lower irregularity) is more uniform than S2 and S3. Also the increase of irregularity enlarges the effects of changes in plan geometry (Fig. 4).

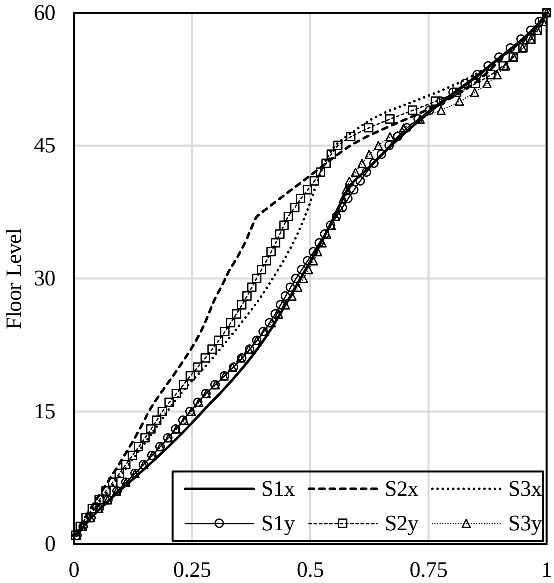

Fig. 4 Story-displacement at center of mass modified by roof displacement

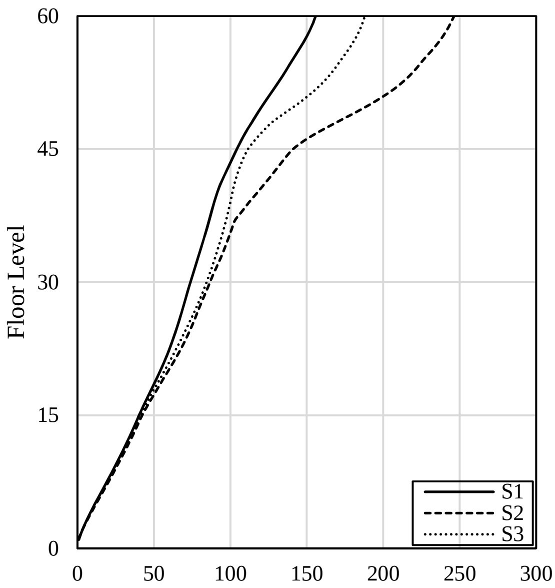

Fig. 5 Absolute story-displacement at center of mass modified by absolute first story displacement

The absolute values of median story-displacement and its values in x and y direction are presented in Figs. 5 and 6 respectively. The values are modified by first story displacement. It can be seen that, the distribution of displacement in lower parts of all models is approximately equal, but story-displacement above setback levels is higher for S2 and S3. Fig. 5 and Fig. 6 also indicate sudden change in graph gradient at setback levels in irregular models. The roof displacement of S2, modified by first story displacement, is 60% higher than that of S1. As seen in Fig. 6, the distribution of displacement is affected by changes of plan geometry. The values of displacement in upper parts of S2 in x direction are higher than those in y direction. It can be concluded that the effects of mass irregularity are lower than the effects of irregularity in geometry.

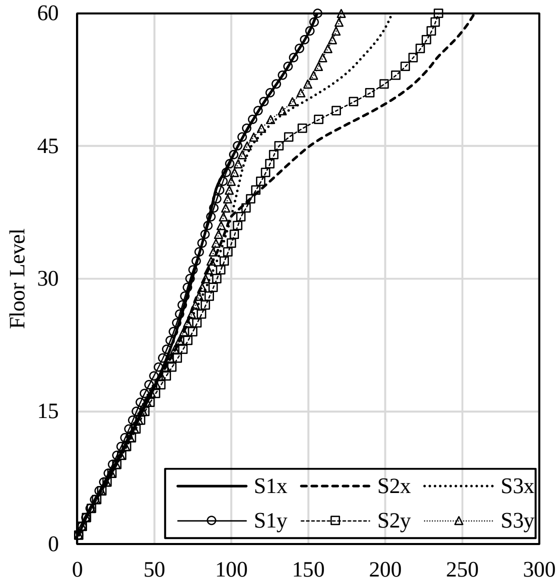

Fig. 6 Story-displacement at center of mass modified by first story displacement

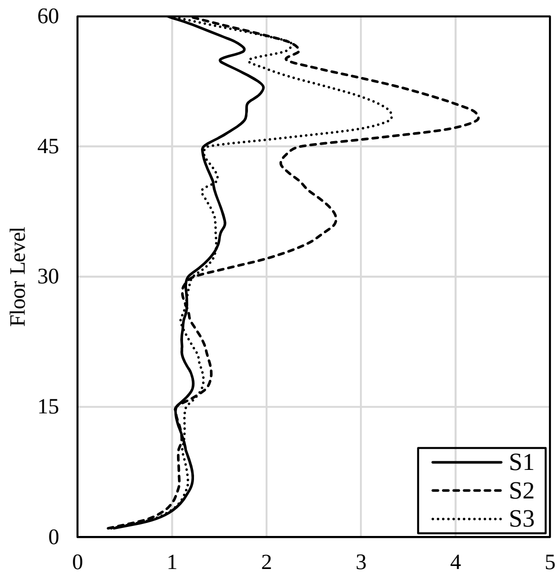

Fig. 7 Absolute story-drift at center of mass modified by absolute global drift

Figs. 7 and 8 show the distribution of median story drift modified by global drift. It can be observed in Fig. 7 that the modified story-drift increases above setback levels. Also, the distribution of modified story-drift increases in the upper levels of the structures and is enlarged by increasing vertical irregularity. As observed in Fig. 8 the effects of vertical irregularity in geometry is higher than the effects of mass irregularity. In addition, increasing the amount of vertical irregularity in mass and geometry enlarges the story drifts in some parts of the structures about 4.5 times.

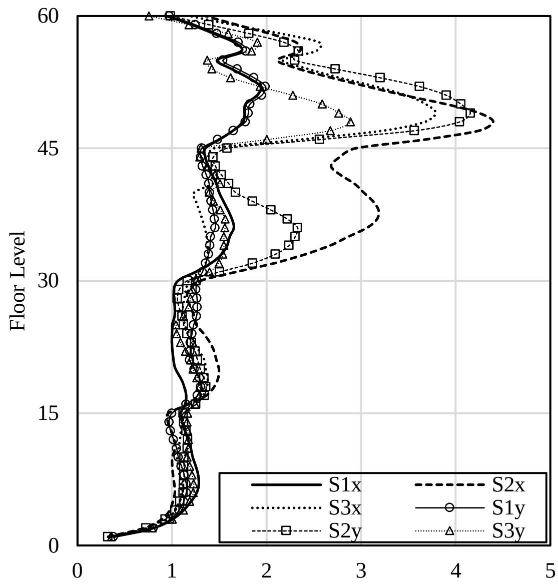

Fig. 8 Story-drift at center of mass modified by absolute global drift

IV. Conclusions

With the use of nonlinear time history analysis and using three pairs of horizontal ground motions, the seismic response of three tall buildings with setbacks in three levels have been evaluated. The main conclusions of this study are: (1) The effects of vertical irregularity in geometry are higher than the effects of mass irregularity in deformation demands; (2) increasing vertical irregularities, increases the deformation demands of the upper parts more than the lower parts of the structures.

Moreover, by increasing vertical irregularities, the following conclusions were reached:

1) Increasing the geometrical irregularity by 50 percent, enlarges the global drift of the structures by about 35 percent, and the roof displacement modified by first story displacement is enlarged by 60 percent.
2) The story-displacement distribution of the structures becomes non-uniform and this non-uniformity enlarges by increasing the irregularities.
3) The distribution of story-drift modified by global drift is non-uniform and it increases in the upper parts of the structures.
4) Lower parts of the structures were not affected by increasing of vertical irregularities.

It was also concluded that, the story drift increases above setback levels which agrees with conclusions of previous researches.

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