EFFECT OF INFILL WALLS ON SOFT STORY BEHAVIOR IN MID-RISE RC BUILDINGS

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ABSTRACT :

Soft story irregularity is one of the main reasons of the building damage during past earthquakes and has been mentioned in almost all reconnaissance reports. Soft story due to increased story height is a well known subject but soft story may also arise due to abrupt changes in amount of infill walls between stories, which are usually not considered as a part of load bearing system. This study investigates soft story behavior due to increased story height, lack of infill amount at ground story and existence of both cases using nonlinear static and dynamic response history analyses for mid-rise reinforced concrete buildings. Displacement capacities at Immediate Occupancy, Life Safety and Collapse Prevention performance levels and story drift demands of the regular and soft story models are determined. Soft story behavior due to change in story height and/or infill amount is evaluated in view of these displacement capacities, drift demands and structural behavior. It is observed that, soft story due to infill walls may be as damaging as soft story due to increased story height.

KEYWORDS: Infill wall, Mid-rise, Nonlinear, Performance evaluation, Reinforced concrete, Soft story.

1. INTRODUCTION

Soft story irregularity is one of the main reasons of building damages during recent earthquakes in the world as mentioned in almost all reconnaissance reports and studies (Adalier and Aydingun, 2001; Dogangun, 2004; Kaplan et al., 2004; Ozcebe, 2004; Sezen et al., 2003, Sucuoglu and Yilmaz, 2000). Soft story may arise not only because of sudden changes in structural system (like height of the stories) but also due to abrupt changes in amount of infill walls between stories which are usually not considered as a part of load bearing system. This study aims to investigate soft story behavior using nonlinear static and dynamic response history analyses for mid-rise RC buildings which are thought to be the most vulnerable in existing building stock. The 4- and 7-storey 3-D building models are designed per pre-modern earthquake code to reflect existing mid-rise building stock (TEC 1975). Soft story models of the reference buildings are obtained considering increased floor story height, less amount of infill at floor story and both cases. Capacity curves are obtained using nonlinear static analyses. Displacement capacities of the reference and soft story models are determined at Immediate Occupancy, Life Safety and Collapse Prevention performance levels according to 2006 Turkish Earthquake Code (TEC 2006). Building models are reduced to “Equivalent” Single-Degree-of-Freedom systems. These models are subjected to 83 different earthquake records and then inter-story drift demands at the ground story (soft story) are determined by using mode shape of the buildings. Nonlinear static analyses are performed using SAP2000. Beam and column elements are modeled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of beams and columns. Effect of infill walls is modeled through diagonal struts as suggested in FEMA-356 (FEMA 2000). Shear hinges take into account possible shear failures in existing reinforced concrete buildings. All buildings are modeled with two different transverse steel amounts to investigate the effect of transverse steel on the behavior. Soft story behavior due to change in story height and/or infill amount is evaluated in view of displacement demands, capacities and structural behavior. The outcomes are useful to better understand soft story damages during past earthquakes and to emphasize the effect of infill walls on the behavior.

2. AIM AND SCOPE

Soft story behavior due to increased story height is a well known subject among civil engineering professionals. But soft story may arise due to many different reasons like changes in load carrying (Watanabe, 1997) and slab system (Dogangun, 2004) between stories. Among others, one of the most frequent reasons of the soft story behavior is the abrupt change in the amount of the infill walls between stories. As the infill walls are not regarded as a part of load carrying system, generally civil engineers do not consider their effects on the structural behavior. Therefore, many civil engineers are not conscious enough about soft story occurrence because of infill walls, and required attention is not provided. In this study, effect of infill walls on structural behavior, especially for the soft story, is investigated in order to increase the level of knowledge and awareness on the subject.

The major portion of the building stock of many developing countries are consists of deficient mid-rise reinforced concrete buildings. In scope of the study, soft story behavior in existing mid-rise reinforced concrete buildings below code requirements are investigated. Two sets of RC buildings 4-story and 7-story are selected to represent mid-rise buildings located in the high seismicity region of Turkey, five buildings in each set. The selected buildings are typical beam-column RC frame buildings with no shear walls. Since in Turkey still the majority of buildings were constructed according to 1975 Turkish Earthquake Code, the 4- and 7-story buildings are designed according this code considering both gravity and seismic loads (a design ground acceleration of 0.4 g and soil class Z3 that is similar to class C soil of FEMA-356 is assumed (FEMA 2000). Material properties are assumed to be 16 MPa for the concrete compressive strength and 220 MPa for the yield strength of both longitudinal and transverse reinforcement. Strain-hardening of longitudinal reinforcement has been taken into account and the ultimate strength of the reinforcement is taken as 330 MPa (TS 500). One of the important deficiencies in the existing building stock is insufficient amount of transverse reinforcement. The transverse reinforcement amount may be considered to represent construction and workmanship. Two different spacings are considered as 100 mm and 200 mm to investigate soft story behavior with different ductility.

3. BUILDING MODELS

The selected 4- and 7-story buildings a have the same plan view as shown in Fig. 1, with 4 bays in X and Y direction as 4 m and 3 m, respectively. Regular story height is 2.8 m. In the figure, the infill walls that meet the requirements of FEMA 356 to form diagonal struts are shown with shaded areas. The other infill walls with openings that prevent diagonal strut formation are considered as dead loads, only. The 4- and 7-story buildings have symmetrical floor plans to avoid any irregularity effects.

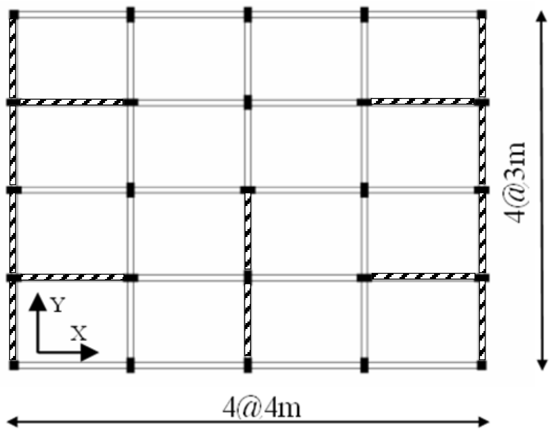

Figure 1 Plan view of the selected 4- and 7-story buildings

Soft story effect in this study is considered increased story height (4 m instead of 2.8 m) , less amount of infill walls and both at ground story due to commercial reasons. Source of soft story, model identifier, period of first mode considering cracked section stiffness (T), ratio of yield lateral strength to the seismic weight of building (C_y) values of the building models is given in Table 3.1. Note that RefNW buildings (reference buildings with no infill effect) are modeled to better understand the effect of neglecting walls as load carrying elements on the building behavior. The last letters in the model identifier express the considered principal direction.

Table 3.1 Properties of building models

		4-story		7-story	
Source of Soft Story	**Model**	**T (s)**	**C_y**	**T (s)**	**C_y**
Reference regular building	Ref-X	0.57	0.17	0.89	0.15
	Ref-Y	0.47	0.25	0.75	0.18
Reference regular building without diagonal struts at any story	RefNW-X	0.84	0.14	1.12	0.12
	RefNW-Y	0.81	0.15	1.1	0.13
Soft story due to increased ground story **h**eight (2.8 m to 4 m)	SSH-X	0.67	0.16	0.97	0.13
	SSH-Y	0.54	0.21	0.83	0.16
Soft story due to absence of **w**alls at ground story	SSW-X	0.63	0.17	0.91	0.14
	SSW-Y	0.55	0.2	0.79	0.17
Soft story due to increased **h**eight and absence of **w**alls at ground story	SSHW-X	0.84	0.13	1.05	0.12
	SSHW-Y	0.77	0.14	0.94	0.13

3.1. Modeling Approach

Nonlinear static analyses have been performed using SAP2000 Nonlinear Version 8 that is a general-purpose structural analysis program (SAP2000). Three-dimensional model of each structure is created in SAP2000 to carry out nonlinear static analysis. Beam and column elements are modeled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of beams and columns. SAP2000 implements the plastic hinge properties described in FEMA-356 (or ATC-40) (FEMA, 2000; ATC-40, 1996). As shown in Figure 2, five points labeled A, B, C, D, and E define force-deformation behavior of a plastic hinge.

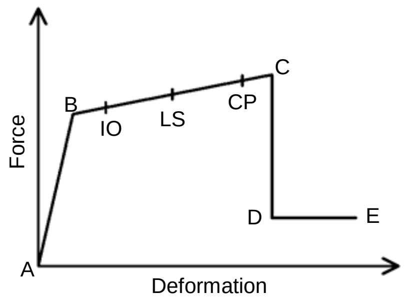

Figure 2 Force-Deformation relationship of a typical plastic hinge

The definition of user-defined hinge properties requires moment–curvature analysis of each element. Modified Kent and Park model (Scott et al., 1982) for unconfined and confined concrete and typical steel stress–strain model with strain hardening (Mander, 1984) for steel are implemented in moment–curvature analyses. The points B and C on Fig. 2 are related to yield and ultimate curvatures. The point B is obtained from SAP2000 using approximate component initial effective stiffness values as per TEC-2006; 0.4EI for beams and values depending on axial load level for columns: 0.4EI for $N/(A_c f_c) \leq 0.1$ and 0.8EI for $N/(A_c f_c) \geq 0.4$. f_c is concrete compressive strength, N is axial load, A_c is area of section. For the $N/(A_c f_c)$ values between 0.1 and 0.4 linear interpolation is made.

The ultimate curvature is defined as the smallest of the curvatures corresponding to (1) a reduced moment equal to 80% of maximum moment, determined from the moment-curvature analysis, (2) the extreme compression fiber reaching the ultimate concrete compressive strain as determined using the simple relation provided by Priestley et al. (Priestley et al., 1996), given in Eqn. 3.1, and (3) the longitudinal steel reaching a tensile strain of 50% of ultimate strain capacity that corresponds to the monotonic fracture strain. Ultimate concrete compressive strain is given as:

$$\varepsilon_{cu} = 0.004 + \frac{1.4\rho_s f_{yh}\varepsilon_{su}}{f_{cc}} \tag{3.1}$$

where ε_{cu} is the ultimate concrete compressive strain, ε_{su} is the steel strain at maximum tensile stress, ρ_s is the volumetric ratio of confining steel, f_{yh} is the yield strength of transverse reinforcement, and f_{cc} is the peak confined concrete compressive strength.

The input required for SAP2000 is moment-rotation relationship instead of moment-curvature. Also, moment rotation data have been reduced to five-point input that brings some inevitable simplifications. Plastic hinge length is used to obtain ultimate rotation values from the ultimate curvatures. Several plastic hinge lengths have been proposed in the literature (Park and Paulay, 1975; Priestley et al, 1996). In this study plastic hinge length definition given in Eqn. 3.2 which is proposed by Priestley et al. is used.

$$L_p = 0.08L + 0.022 f_{yh} d_{bl} \geq 0.044 f_{yh} d_{bl} \tag{3.2}$$

In Eqn. 3.2, L_p is the plastic hinge length, L is the distance from the critical section of the plastic hinge to the point of contraflexure, d_{bl} is the diameter of longitudinal reinforcement.

Following the calculation of the ultimate rotation capacity of an element, acceptance criteria are defined as labeled IO, LS, and CP on Fig. 2. IO, LS, and CP stand for Immediate Occupancy, Life Safety, and Collapse Prevention, respectively. This study defines these three points corresponding to 10%, 60%, and 90% use of plastic hinge deformation capacity. In existing reinforced concrete buildings, especially with low concrete strength and/or insufficient amount of transverse steel, shear failures of members should be taken into consideration. For this purpose, shear hinges are introduced for beams and columns. Because of brittle failure of concrete in shear, no ductility is considered for this type of hinges. Shear hinge properties are defined such that when the shear force in the member reaches its strength, member fails immediately. The shear strength of each member is calculated according to TS 500 that is similar to UBC (TS 500, 2000; Uniform Building Code, 1997).

Effect of infill walls are modeled through diagonal struts as suggested in TEC-2006 and FEMA-356. Nonlinear behavior of infill walls is reflected by assigned axial load hinges on diagonal struts whose characteristics are determined as given in FEMA-356. Material properties are taken from TEC-2006 to reflect characteristics of infill walls in Turkey; 1000 MPa, 1 MPa and 0.15 MPa were assumed as modulus of elasticity, compressive strength and shear strength values, respectively.

4. NONLINEAR STATIC ANALYSIS AND PERFORMANCE EVALUATION

In order to obtain capacity curves and displacement capacity values of the building models for different performance levels, nonlinear static analyses are carried out using SAP2000. The lateral forces applied at center of mass were proportional to the product of mass and the first mode shape amplitude at each story level under consideration. P-Delta effects were taken into account. Performance evaluation of the investigated buildings is conducted using Turkish Earthquake Code (2006). Three levels, Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) are considered as specified in this code and several other international guidelines such as FEMA-356, ATC-40.

5. NONLINEAR RESPONSE HISTORY ANALYSES

In order to investigate the soft story behavior on the drift demands nonlinear response history analyses are carried out. The capacity curve of each building obtained from pushover analysis was approximated with a bilinear curve using guidelines given in ATC-40 and FEMA-440 and reduced to equivalent SDOF systems (ATC-40, 1996; FEMA, 2005). Then these SDOF systems are subjected to nonlinear response history analysis by using ground motion record sets. USGS site classification based on the average shear wave velocity to a depth of 30 m is used for soil site classification of the selected records. Four site classifications include 83 different records, approximately 20 records for each soil type. Soil type A is the stiffest soil type with highest shear wave velocity and D is the weakest soil with the lowest shear wave velocity. All earthquake records are taken from PEER website (http://peer.berkeley.edu/smcat/search.html). Average values for some properties of selected ground motion records are given in Table 5.1.

Table 5.1 Average values for some properties of used ground motion records

Soil Type	Number of records	Magnitude	PGA (g)	PGV (m/s)	PGD (m)
A	20	7.00	0.40	0.30	0.11
B	23	6.71	0.39	0.36	0.11
C	20	7.02	0.40	0.43	0.19
D	20	7.05	0.26	0.36	0.20

Table 6.1 Global drift capacities (%) at given performance levels for the building models for 4-story buildings

	IO				LS				CP			
Model	GD	/Ref	C	/Ref	GD	/Ref	C	/Ref	GD	/Ref	C	/Ref
Refs100-X	0.53	1.00	0.18	1.00	1.08	1.00	0.17	1.00	1.45	1.00	0.17	1.00
Refs100-Y	0.23	1.00	0.20	1.00	0.59	1.00	0.22	1.00	0.84	1.00	0.17	1.00
Refs200-X	0.50	1.00	0.18	1.00	0.68	1.00	0.18	1.00	1.15	1.00	0.17	1.00
Refs200-Y	0.20	1.00	0.18	1.00	0.40	1.00	0.25	1.00	0.63	1.00	0.22	1.00
RefNWs100-X	0.51	0.96	0.14	0.76	0.90	0.83	0.14	0.84	1.36	0.94	0.14	0.85
RefNWs100-Y	0.30	1.32	0.12	0.58	0.78	1.33	0.15	0.70	1.21	1.44	0.15	0.89
RefNWs200-X	0.44	0.89	0.13	0.74	0.68	1.00	0.14	0.75	0.99	0.86	0.14	0.83
RefNWs200-Y	0.25	1.28	0.10	0.56	0.57	1.42	0.15	0.59	0.86	1.36	0.15	0.69
SSHs100-X	0.33	0.62	0.16	0.87	0.81	0.74	0.16	0.97	1.22	0.84	0.12	0.73
SSHs100-Y	0.22	0.96	0.17	0.85	0.49	0.84	0.16	0.73	0.69	0.82	0.15	0.85
SSHs200-X	0.30	0.61	0.15	0.85	0.46	0.68	0.17	0.91	0.82	0.72	0.16	0.97
SSHs200-Y	0.19	0.98	0.16	0.86	0.37	0.94	0.22	0.86	0.47	0.74	0.22	1.00
SSWs100-X	0.28	0.52	0.16	0.87	0.68	0.63	0.17	0.99	1.15	0.79	0.15	0.90
SSWs100-Y	0.16	0.71	0.13	0.66	0.38	0.64	0.20	0.94	0.69	0.82	0.20	1.17
SSWs200-X	0.24	0.48	0.15	0.81	0.37	0.54	0.17	0.92	0.83	0.72	0.15	0.88
SSWs200-Y	0.13	0.67	0.11	0.61	0.24	0.61	0.18	0.72	0.44	0.69	0.21	0.93
SSHWs100-X	0.26	0.48	0.12	0.64	0.55	0.50	0.14	0.82	0.88	0.60	0.14	0.86
SSHWs100-Y	0.17	0.74	0.10	0.47	0.42	0.72	0.15	0.69	0.65	0.78	0.15	0.84
SSHWs200-X	0.23	0.46	0.11	0.61	0.37	0.54	0.13	0.71	0.61	0.53	0.14	0.84
SSHWs200-Y	0.15	0.73	0.08	0.46	0.28	0.70	0.14	0.54	0.45	0.71	0.15	0.68

6. ANALYSES RESULTS

The global drift (GD) capacities (roof displacement/building height) of the building models for Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) performance levels are listed in Table 6.1 and 6.2 for 4- and 7-story buildings, respectively. The "s100" and "s200" terms in the model name express the spacing of the transverse reinforcement in mm. The ratio of the given values in tables to the corresponding value for the reference building is presented in the "/Ref" column. The ratio of lateral strength of the building to the weight of the building at the given capacity is provided in the column denoted by "C". For the evaluation of the soft story behavior on the drift demands, results of nonlinear response analyses are used. The ratio of average drift demands of the soft story models to the corresponding reference model demands at the ground story for each soil type is given in Table 6.3. Since post-yield stiffness of the buildings was considerably small, the effect of transverse reinforcement amount only changes the ultimate displacement point and don't affect the SDOF idealization. Thus, drift demand evaluation is carried out regardless of transverse reinforcement spacing.

Table 6.2 Global drift capacities (%) at given performance levels for the building models for 7-story buildings

	IO				LS				CP			
Model	**GD**	**/Ref**	**C**	**/Ref**	**GD**	**/Ref**	**C**	**/Ref**	**GD**	**/Ref**	**C**	**/Ref**
Refs100-X	0.43	1.00	0.15	1.00	0.65	1.00	0.15	1.00	1.40	1.00	0.13	1.00
Refs100-Y	0.36	1.00	0.18	1.00	0.48	1.00	0.19	1.00	0.68	1.00	0.19	1.00
Refs200-X	0.38	1.00	0.15	1.00	0.59	1.00	0.15	1.00	0.83	1.00	0.14	1.00
Refs200-Y	0.31	1.00	0.17	1.00	0.46	1.00	0.18	1.00	0.58	1.00	0.19	1.00
RefNWs100-X	0.52	1.19	0.12	0.82	0.95	1.45	0.13	0.87	1.25	0.89	0.13	0.97
RefNWs100-Y	0.51	1.40	0.13	0.73	0.89	1.86	0.14	0.74	1.28	1.87	0.14	0.73
RefNWs200-X	0.48	1.25	0.12	0.83	0.81	1.36	0.13	0.83	1.02	1.24	0.13	0.91
RefNWs200-Y	0.43	1.40	0.13	0.75	0.62	1.35	0.13	0.72	0.74	1.26	0.13	0.71
SSHs100-X	0.30	0.69	0.12	0.83	0.48	0.73	0.14	0.93	0.61	0.44	0.13	0.95
SSHs100-Y	0.27	0.74	0.15	0.83	0.41	0.87	0.17	0.88	0.60	0.88	0.17	0.88
SSHs200-X	0.27	0.70	0.11	0.79	0.37	0.63	0.13	0.87	0.49	0.59	0.14	0.97
SSHs200-Y	0.24	0.79	0.14	0.81	0.36	0.78	0.16	0.85	0.46	0.79	0.15	0.82
SSWs100-X	0.33	0.77	0.14	0.92	0.54	0.83	0.15	1.01	0.66	0.47	0.15	1.12
SSWs100-Y	0.25	0.68	0.14	0.81	0.38	0.80	0.17	0.91	0.54	0.80	0.18	0.92
SSWs200-X	0.30	0.78	0.13	0.89	0.43	0.72	0.15	0.95	0.57	0.69	0.15	1.05
SSWs200-Y	0.22	0.71	0.13	0.77	0.31	0.69	0.16	0.85	0.39	0.66	0.16	0.87
SSHWs100-X	0.25	0.58	0.11	0.71	0.40	0.61	0.12	0.85	0.60	0.43	0.13	0.96
SSHWs100-Y	0.19	0.52	0.10	0.57	0.32	0.67	0.14	0.72	0.47	0.69	0.14	0.76
SSHWs200-X	0.23	0.60	0.10	0.69	0.32	0.54	0.12	0.78	0.44	0.54	0.12	0.87
SSHWs200-Y	0.18	0.58	0.10	0.57	0.25	0.54	0.12	0.66	0.36	0.62	0.12	0.66

Table 6.3 Ratio of average story drift demands at ground story for the building models subjected to ground motion record sets

	4-story					7-story				
	Drift Demand Ratio					Drift Demand Ratio				
	A	**B**	**C**	**D**	**Ave.**	**A**	**B**	**C**	**D**	**Ave.**
Ref-X	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ref-Y	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SSH-X	1.34	1.17	1.26	1.35	1.28	1.34	1.33	1.37	1.41	1.33
SSH-Y	1.14	1.26	1.23	1.34	1.28	1.41	1.43	1.32	1.45	1.41
SSW-X	1.60	1.59	1.55	1.63	1.58	1.24	1.21	1.22	1.25	1.23
SSW-Y	1.69	1.89	1.83	2.00	1.90	1.55	1.55	1.43	1.55	1.51
SSHW-X	1.95	1.78	1.91	2.02	1.93	1.78	1.75	1.86	1.78	1.75
SSHW-Y	2.23	2.21	2.21	2.66	2.38	2.05	2.07	2.04	2.18	2.06
Average	1.49	1.49	1.50	1.63		1.42	1.42	1.41	1.45	

7. DISCUSSION OF RESULTS

In this study, soft story behavior due to increased story height, lack of infill wall amount at ground story and existence of both cases is investigated using nonlinear static and dynamic response history analyses for mid-rise reinforced concrete buildings. Based on 40 nonlinear static analyses and 1328 nonlinear response history analyses the following observations are made:

1- Although, transverse steel amount has limited effect on lateral strength, it significantly affects the displacement capacities (Table 6.1 and 6.2). Even though s100 and s200 models have the same yield strength, the displacement capacities of the s200 models are considerably lower.
2- Consideration of infill walls in the building model as diagonal struts increases the yield strength of the 4- and 7-story models by 45% and %32, respectively (Table 3.1). Modeling of infill walls seems to be more effective on the lateral strength of the buildings with less number of stories, because the properties of the walls are not affected by the number of stories but the floor plan. Structural elements with larger dimension and strength in the buildings with more number of stories decrease the affect of walls.
3- In general the lateral strength of the building increases, and displacement capacity decreases when walls are regarded as load carrying elements (Table 6.1 and 6.2).
4- When Table 6.1 is examined, it is observed that for some instances, the displacement capacities of the Soft Story due to Height and Wall (SSHW) model is higher than that of Soft Story due to Wall (SSW) ones on the contrary of the expectations. This is due to the increase in plastic hinge length, hence rotation capacity, because of increased column length at ground story (Eqn. 3.2). In view of the values used in the study, elongation of column length from 2.8 m to 4 m increases plastic rotation capacity of the columns by 35% on the average. Even though this increase, no such instance is encountered in the 7-story models.
5- In order to determine which soft story case has the most negative effect on the displacement capacity, the ratio of the irregular model capacities to the regular ones ("/Ref" column) is considered. For Life Safety performance level: average values are 0.80 for SSH, 0.60 for SSW, 0.62 for SSHW models. Therefore, the most detrimental case for the 4-story buildings is the SSW with slight difference with SSHW due to the above explained reasons. These figures for the 7-story buildings are, SSH: 0.75, SSW: 0.76, SSHW: 0.59. Therefore SSHW case is the most unfavorable one (Table 6.1 and 6.2).
6- SSHW case is the most unfavorable one for both 4- and 7-story buildings for Collapse Prevention level (Table 6.1 and 6.2). The average values are; SSH: 0.78, SSW: 0.76, SSHW: 0.66 for 4-story, and SSH: 0.67, SSW: 0.66, SSHW: 0.57 for 7-story, for the Collapse Prevention level.
7- Considerable increase in story drift demands due to soft story is obvious as listed in Table 6.3. The demands due to soft story may increase up to 100%.
8- Although there is no obvious effect of ground motion records on different soil types in story drift demands for 7-story buildings, the demands of the 4-story buildings are observed to be affected for soil type D.

When the obtained displacement capacity and drift demand results are evaluated, in scope of the values considered in the study, it is observed that soft story due to increased height (SSH) and due to lack of infill walls (SSW) have close values to each other. As a result, it should be kept in mind that soft story may arise not only because of increased story height, but because of abrupt changes in amount of infill walls which are not thought to be a part of structural system. As observed in this study, soft story due to both increased height and lack of infill wall at ground story is the most detrimental case in view of drift capacities and demands.

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