The Nonlinear Effect of Infill Walls Stiffness to Prevent Soft Story Collapse of RC Structures

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Abstract: Experimental or theoretical tests show that dramatically changes of infill area causes soft story mechanism. "Soft story" mechanism is the most frequent failure mode of reinforced concrete (R.C.) structures. This phenomenon is caused by the fact that the overall shear force applied to the building by an earthquake is higher at the base floor. If the lower story is not originally weakened, it is however there that infill are the most stressed, so that they fail first and create the weak story and finally leads collapse of structures. This kind of collapse was observed many times in Turkey caused by earthquake. The aim of this paper is to show the contribution of infill walls to the building response during earthquake. Different type of configuration of infill walls are modeled and analyzed by the Finite Element Method. These models also have soft story risk. The nonlinear force-displacement behavior is used for structural analysis. El Centro N-S component is used for time-history analysis.

INTRODUCTION

The most frequent failure mode of reinforced concrete frame buildings caused by earthquake is called "soft storey" mechanism. It consists in a localization of buildings' seismic deformations and rupture in the bottom story of the building (Fig. **1**). This phenomenon is caused by the fact that the overall shear force applied to the building by an earthquake is higher at the base due to the following factors:

- wide openings are present in the bottom story and not present at upper levels and weaken the structure - ground level is often used for offices, shops, lobby in hotels, etc.

- Columns are at ground level are too slender.

- If the lower story is weakened, it is however there those infills are the most stressed, so that they fail first and create the weak story.

In many applications, architectural considerations result in a taller first story, which causes a soft-story formation due to sudden change in the vertical stiffness between following stories. The presence of a soft story results in a localized excessive drift that causes heavy damage or collapse of the story during a severe earthquake. Another typical case of soft story arises when the first floor is left open to serve a commercial function (stores) or as a parking garage (very common in Turkey), while upper floors are infilled with unreinforced masonry walls. A relatively rare case results when the strength of the two adjacent stories is significantly different (weak story) leading to localized deformations similar to the soft-story mechanism. In this paper, the second reason has been analyzed.

Existence of infill walls in the frame is very important not only to prevent soft story mechanism but also lateral rigidity of the frame. The behavior of empty frames and infilled frames is very different. The contribution of masonry infills to the global capacity of the structure constitutes the structural strength to the 80% and stiffness to the 85%. The main reason of their beneficial behavior is that the amount of increase in earthquake inertia force appears to be relatively small, comparatively with the increase in the strength of masonry infills [1].

Widely used masonry infill elements in the reinforced concrete frame building design are adobe blocks, hallow bricks, solid bricks, clay bricks, aerated concrete blocks, briquette blocks etc. Although there is no general acceptance of the contribution of infill walls in the earthquake resistant design many researches point out that negative effects are often associated with irregularities in the distribution of infills in plan and/or in the evaluation. The main problem in the design process is mostly that masonry infills have as-built properties and it is almost impossible to take into account reliably [2]. Due to the design and methodological complexity incorporation of infill walls in the numerical analysis as structural elements is not common. Nevertheless, infill walls increase lateral stiffness and minimize P-Δ effect [3]. The main problem of analyzing the infill frame reinforced concrete buildings is that mostly it is impossible to estimate reliably as built properties in the design procedure. Standardization of masonry units and mortar is not enough for characterization of the inelastic cyclic behavior of masonry infills [4]. A simple modification of the diagonal strut model is proposed in order to include some coupling between the two bars. The coupling is done by the introduction of a concept that the authors have called ``plastic concentrator''. A plastic concentrator can be compared with a plastic hinge in the sense that both may be imagined as zero length

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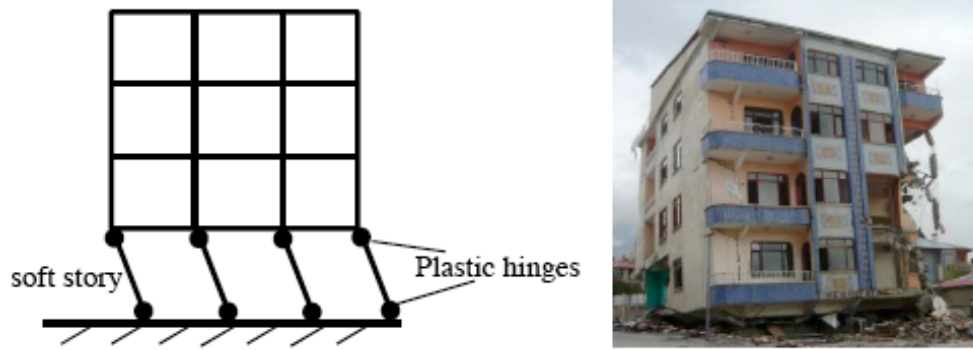E-mails: deguney@yildiz.edu.tr; dguney@gmail.com

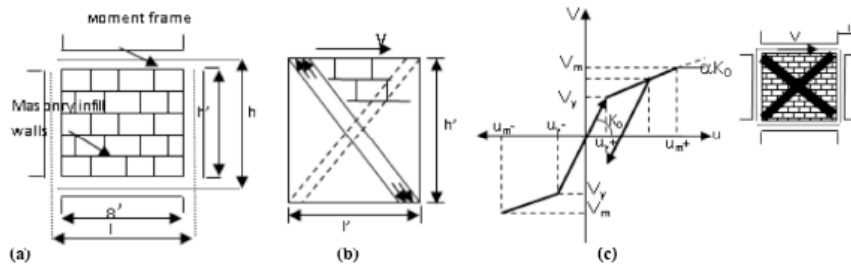**Fig. (1).** The soft storey mechanism and collapsed building example

Fig. (2). Equivalent Strut Model for Masonry Infill Walls in Frame Structures: (a) Masonry Infill Frame Geometry, (b) Masonry Infill Walls and Strut [16] (c) Strength Envelope for Infill Walls.

inelastic springs [5, 6]. Another concept is the Applied Element Method (AEM) can track the structural collapse behavior during early stages of loading and can account for nonlinear behavior of structures including element separation [7]. A comprehensive overview of the analytical modelling techniques of infilled frame structures was prepared by Moghaddam and Dowling [8] and more recently by Crisafulli, *et al.,* [9]. The most commonly used technique to model infill panels is that of single or multiple compressive equivalent diagonal struts [10]. Plumier et. all. investigated soft story mechanism of RC frames using by steel profiles in the columns of the lower levels the structure both theoretical and experimentally [11].

The experimental results indicate that the failure modes of the infilled frames can be classified into distinct modes. Such a classification of the failure modes (crack patterns) enhances considerably the understanding of the earthquake resistant behavior of infilled frames and leads to improved comprehension of their modeling, analysis and design [12]. The infill walls in multistory buildings have a considerable contribution to the stiffness and lateral resistance of frame. In particular, the case of infilled frame with infill walls in all three stories contributes to up to a 77% decrease of the lateral displacements [13]. The knowledge of the elastic response of composite structure will be very critical for a thorough understanding of its response under reversed cyclic loading [14, 15].

Soft story collapse was observed many times in Turkey caused by earthquake. The most important reason for soft story is irregular distribution of infill walls. Especially many buildings close to main road were renovated to get show-

room. In order to do this transform in building function, many infill walls at ground floor were demolished. Many of those structures either collapsed or heavily damaged during the earthquake in 1999. The aim of this paper is to show the importance of infill walls to the building response during earthquake. Different type of configuration of infill walls are modeled and analyzed by the Finite Element Method using by real earthquake acceleration record. The behavior of infill walls are assumed as nonlinear.

THE THEORETICAL MODEL

The behavior of infill walls is assumed as bilinear force-displacement model as shown in Fig. (**2**). The equivalent strut model for masonry infill walls in frame structures is used. The size of strut is related with stiffness and geometry of the infill.

The maximum lateral force V_m and corresponding displacement u_m in the infill panel are shown in Eqs. 1 and 2. In the equation, t is thickness of the infill wall, l' is lateral dimension of the infill panel, f'_m is masonry prism strength, ε_m is corresponding strain, θ is inclination of the diagonal strut, V is basic shear strength of masonry and A_d and l_d are area and length of the equivalent diagonal strut respectively.

$$V^+{}_m(V^-{}_m) \le A_d \cdot f'_m \cdot \cos\theta \le \frac{V \cdot t \cdot l'}{(1-0.45\tan\theta')\cos\theta} \le \frac{0.83 \cdot t \cdot l'}{\cos\theta} \quad (1)$$

$$u^+{}_m(u^-{}_m) = \frac{\varepsilon'_m \cdot l_d}{\cos\theta} \quad (2)$$

The monotonic lateral force-displacement curve is completely defined by the maximum force V_m, corresponding

displacement u_m, the initial stiffness K_0 and the ratio α of the post-yield to initial stiffness. The initial stiffness K_0 of the infill masonry wall may be estimated from the Eq. (3). The lateral yield force V_y and displacement u_y of the infill wall may be calculated from geometry Eq. (4). For practical purposes, the elastictiy modulus of the infill wall can be taken as 500-700 f_{ckd} . f_{ckd} is characteristic shear strength which is taken about 2000-4000 kN/m^2.

$$K_o = \frac{Ed \cdot Ad}{l'}$$

$$(3)$$

$$V_y^+(V_y^-) = \frac{V_m - \alpha K_o u_m}{(1-\alpha)} , u_y^+(u_y^-) = \frac{V_m - \alpha K_o u_m}{K_o(1-\alpha)}$$

$$(4)$$

Using these degrees of freedom, the dynamic response of the system to earthquake acceleration record $a_g(t)$ in the x and y direction, $a_{g\theta}(t)$ in the z-direction and are described by the following equation of motion in Eq. (5, 6).

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = F_e(t)$$

$$(5)$$

Eq. (7) shows lateral stiffness in x- and y- directions. Eq. (8) represents the lateral torsional coupling in the system. Eq. (9) gives torsional stiffness of the system.

$$C = \alpha M + \beta K$$

$$(6)$$

$$\alpha = \xi \frac{\omega_i \omega_j}{\omega_i + \omega_j}$$

$$(7)$$

$$\beta = \xi \frac{2}{\omega_i + \omega_j}$$

$$(8)$$

In this paper, proportional damping is considered where the damping matrix is a combination of the mass and stiffness matrices as shown in Eq. (10). α and β are proportionality constants can be solved using Eqs. (6, 7, 8). ω_i and ω_j are taken as first and second mode frequencies. For practical

purposes, the elasticity modulus of the infill wall can be taken as 500 f_{ckd} . f_{ckd} is characteristic shear strength which is taken about 2000kN/m^2 [17]. Kanit and Donduren modeled masonry walls with similar geometrical properties using software and they compared numerical results with experimental results [18]. The general infill wall material characteristics of the building stock in Turkey are presented in Table **1** [19].

Table 1.   Material Properties of Infill Walls

Parameter	Lower Bound	Upper Bound
Mod.of elasticity E (MPa)	1500	5000
Comp. strength, (MPa)	1.90	3.2
Tensile strength,(MPa)	1.1	1.3

The analyzed structural frame models are shown in Fig. (**3**). The location of infill walls are changed in every frame model therefore location of soft story is changed in every frame model. In addition to this the ratio between infill walls modulus of elasticity to frame modulus of elasticity is not constant as given in Table **2**. There are four type of ratio (between wall and frame) has been used for analysis. The schematic view of equivalent strut model for infill walls is shown in Fig. (**4**). The section of the beam is 25x50cm, the section of the column is 40x40cm. The floor height is 3m and the span is taken as 6m as shown in Fig. (**4**).

Table 2.   The Ratio Between infill Walls Material Mod. of Elasticity to Frame Material mod. of el.

Model	Model 1	Model 2	Model 3	Model 4
E_w/E_f	1/16	1/4	1/2	1/1

Model a   Model b   Model c   Model d   Model e

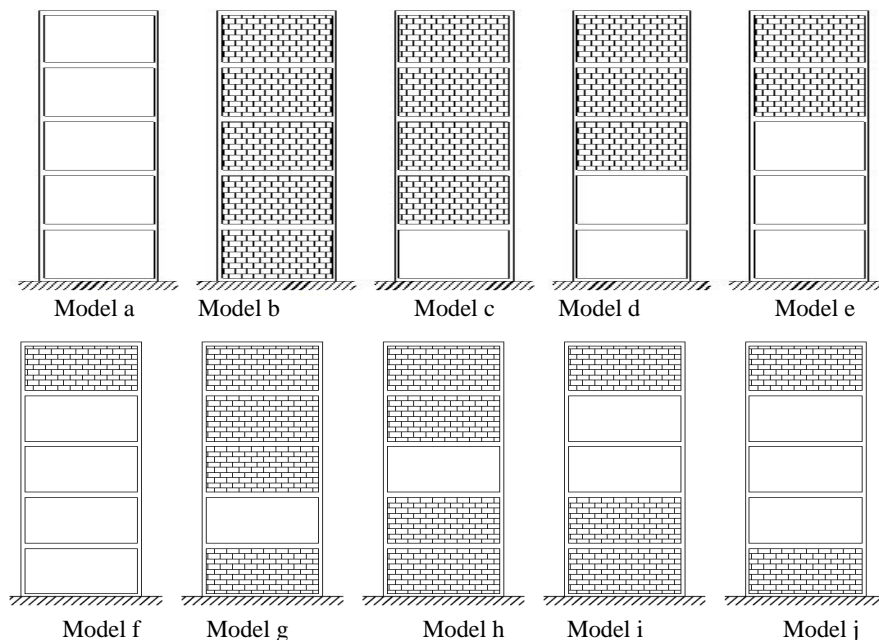Model f   Model g   Model h   Model i   Model j

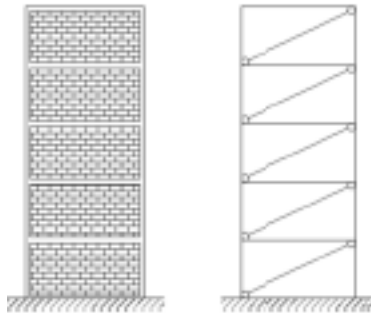**Fig. (3).** Analyzed structural models (different configurations).

Fig. (4). Equivalent strut model for infill walls.

Ten different models are developed to investigate contribution of infill walls to the response of frame. The properties of analyzed models are given in Table **3**. All models (a-j) are analyzed four times according to ratio of modulus of elasticity. All analyses are performed using by SAP2000 (FEM software) [20].

Table 3.   Infill Wall Configuration Between Floors

Model Name	Explanation	Model Name	Explanation
Model a	Bare frame	**Model f**	5th floors has infill wall
Model b	All floors have infill wall	**Model g**	1st, 3rd, 4th and 5th floors have infill wall
Model c	2nd, 3rd, 4th and 5th floors have infill wall	**Model h**	1st, 2nd, 4th and 5th floors have infill wall
Model d	3rd, 4th and 5th floors have infill wall	**Model i**	1st, 2nd and 5th floors have infill wall
Model e	4th and 5th floors have infill wall	**Model j**	1st, and 5th floors have infill wall

All models are analyzed using by El Centro earthquake record. Fig. (**5**) shows El Centro earthquake N-S ground acceleration data. El Centro earthquake was in May 1940 in Imperial Valley (USA) and the Richter magnitude of the earthquake was recorded as 7.1. The epicenter of the earthquake was 70 km from the ground and max acceleration was 0,341 m/s^2.
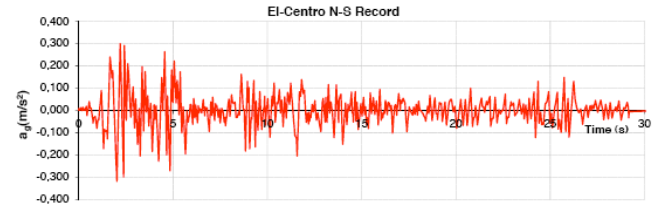

Fig. (5). The N-S component of El Centro earthquake (1940).

The natural vibration periods (three modes) of Model 1 is given in Table **4**. The ratio of modulus of elasticity is 1/16 as shown in Table **3**.

The natural vibration periods of Model 2 is given in Table **5**. The ratio of modulus of elasticity is 1/4 as shown in Table **3**.

The natural vibration periods of Model 3 is given in Table **6**. The ratio of modulus of elasticity is 1/2 as shown in Table **3**.

The natural vibration periods of Model 4 is given in Table **7**. The ratio of modulus of elasticity is 1/2 as shown in Table **3**.

The maximum displacement response for first ratio (Model 1) is given in Fig. (**6**). As shown in the figure, the maximum displacement is calculated for Model 1a (bare frame).

The maximum displacement response for second ratio (Model 2) is given in Fig. (**7**). As shown in the figure, the max. interstorey drift is calculated between Model 2h and Model 2d..

The displacement results of analyzed models are given in Figs. (**6-9**) based on modulus of elasticity ratio (Table **3**). As

Table 4.   The Natural Vibration Periods of Model 1

Mode	Model1a	Model1b	Model1c	Model1d	Model1e	Model1f	Model1g	Model1h	Model1ı	Model1j
1	0,6526	0,374	0,4299	0,5348	0,6067	0,6418	0,4628	0,4364	0,483	0,582
2	0,2037	0,123	0,138	0,139	0,1549	0,1854	0,1282	0,1307	0,152	0,165
3	0,1116	0,073	0,0774	0,0839	0,0897	0,0966	0,0756	0,0836	0,087	0,088

Table 5. The natural vibration periods of Model 2

Mode	Model2a	Model2b	Model2c	Model2d	Model2e	Model2f	Model2g	Model2h	Model2ı	Model2j
1	0,6526	0,2436	0,3445	0,4958	0,5912	0,637	0,3676	0,3342	0,411	0,542
2	0,2036	0,0801	0,1026	0,1033	0,1388	0,179	0,0872	0,0890	0,113	0,144
3	0,1164	0,0467	0,0519	0,0725	0,0725	0,091	0,0527	0,0615	0,074	0,074

Table 6. **The Natural Vibration Periods of Model 3**

Mode	Model3a	Model3b	Model3c	Model3d	Model3e	Model3f	Model3g	Model3h	Model3ı	Model3j
1	0,6526	0,2021	0,3228	0,486	0,5875	0,636	0,3393	0,3057	0,393	0,530
2	0,2036	0,0649	0,0906	0,0939	0,1355	0,178	0,0746	0,0728	0,099	0,139
3	0,1164	0,0369	0,0422	0,0672	0,0693	0,090	0,0428	0,5346	0,067	0,071

Table 7. **The Natural Vibration Periods of Model 3**

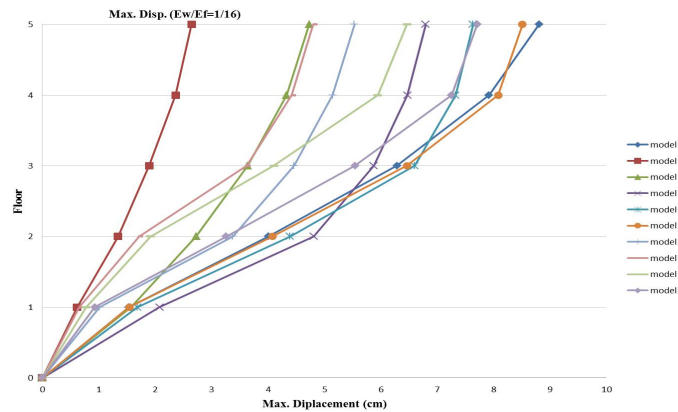| Mode	Model4a	Model4b	Model4c	Model4d	Model4e	Model4f	Model4g	Model4h	Model4ı	Model4j
1	0,6526	0,1758	0,3106	0,4814	0,5854	0,636	0,322	0,289	0,383	0,524
2	0,2036	0,0544	0,0827	0,0894	0,1338	0,177	0,066	0,06	0,092	0,136
3	0,1116	0,0302	0,0356	0,0633	0,0681	0,090	0,034	0,047	0,059	0,069

Fig. (6). Maximum displacement of Model 1.

shown in Fig. (**6**), the displacement of Model a (bare frame structure) gives the largest displacement compared with the other models with infill. Model b gives the smallest displacement compared with other infill wall configurations. This result means infill walls increases lateral stiffness of the structure which leads decrease in lateral displacement of frame. In addition to this, frame can absorb more energy and if the infill is configured in regular mode. The interstorey displacement of floors without infill walls are much more than infilled frame. If all structural configurations are compared, Model 4 gives minimum displacement compared with other models have smaller modulus of elasticity. This result means increasing modulus of elasticity leads larger structural stiffness and less displacement response. Infill walls give additional lateral stiffness to the frame. If infill wall does not exist in any floor, this floor becomes soft story.

The base shear results of Model 1 analysis is given in Fig. (**10**). As shown in the figure Model 1d and Model 1g gives the largest base shear force for Model 1.

CONCLUSIONS

In many applications, architectural considerations result in a taller first story, which causes a soft-story formation due to sudden change in the stiffness between following stories. If infill walls are not exist in any floor level means that floor is under risk of soft story collapse. The presence of a soft story results in a localized excessive drift that causes heavy damage or collapse of the story during a severe earthquake. In this paper, a detailed parametric study of the influence of
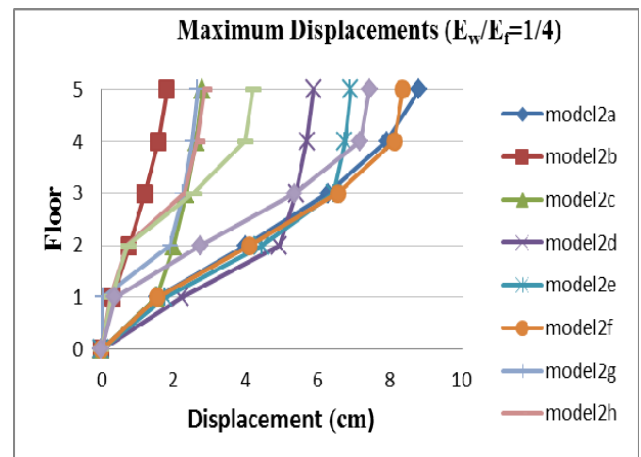

Fig. (7). Maximum displacement of Model 2.

masonry infill on the behavior of frames subjected to earthquake forces using the finite element method for the analysis has shown the following consequences:
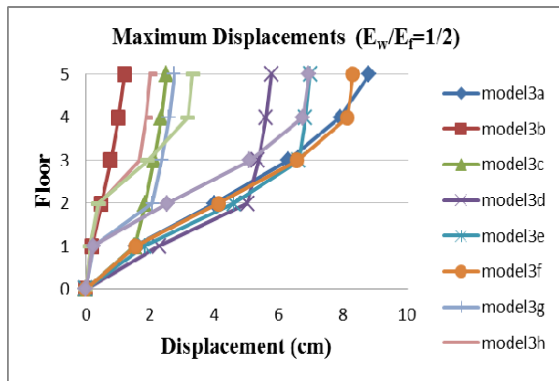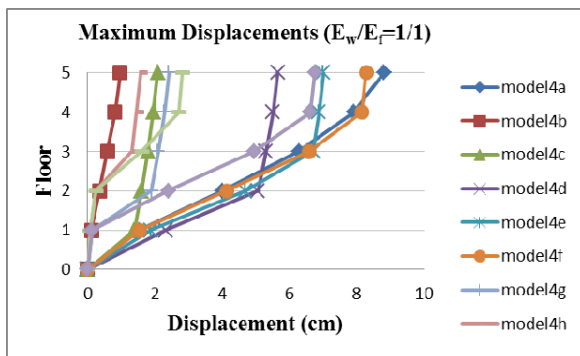

Fig. (8). Maximum displacement of Model 3
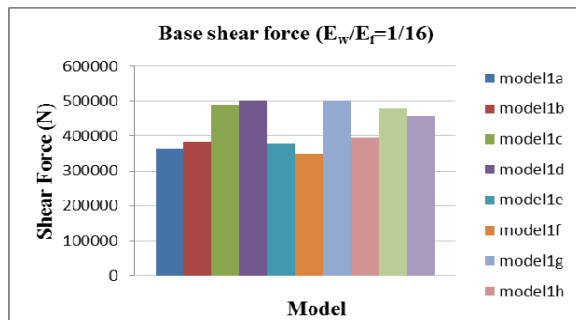

Fig. (9). Maximum displacement of Model 4.

Fig. (10). Base shear of Model 1.

- The infill walls in multistory buildings have a considerable contribution to the stiffness and lateral resistance of frame. However those infills should be distributed in regular manner in the frame structure. In this case, infill walls decrease period of the structure and story displacements decrease. Otherwise (irregular distributed) infilled frame becomes much more rigid than bare frame which leads soft story collapse.

- The existence of infills walls causes, less shear forces on the frame columns. However, in the case of infilled frame with a soft ground story, the shear forces acting on columns are considerably higher than bare frame shear forces.

- The material quality of the infill frame (based on ratio between infill wall material and frame material modulus

of elasticity) directly affect seismic response of the frame. Because modulus of elasticity of infill wall frame is directly proportional to the stiffness of the frame.

As a result of this study, the distribution of infill walls is very important for formation of soft story effect caused by earthquake. In order to prevent soft story collapse, the inter-story drifts should be controlled and limited changing by stiffness of columns.

CONFLICT OF INTEREST

None declared.

ACKNOWLEDGEMENT

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