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Effect of arrangement of masonry infill walls, shear walls and steel bracings on the story drift and stiffness irregularity

Mohammed Gamal Al-Hagri *1, **Abdulhamit Nakipoglu** 1, **Mahmud Sami Döndüren** 1

1Konya Technical University, Department of Civil Engineering, Türkiye, mg.alhagri@gmail.com; anakipoglu@ktun.edu.tr; msdonduren@ktun.edu.tr

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Abstract

Irregularities in structures, such as soft story irregularity, might make them vulnerable under lateral forces such as earthquake. One solution to this problem is a suitable use of infill members. In this study, the effect of masonry infill walls, shear walls and steel bracings on the soft story irregularity and story drift of a 10-story building is evaluated. The building has its first two stories not infilled, and the remaining stories fully infilled with masonry infill walls. Fourteen models of different infill situation divided into three groups were studied. In the first infill group, the 1st and 2nd stories were fully infilled with masonry infill walls, shear walls and steel bracings. In the second infill group, infill members were used in the center of the building. In the third group, infill members were placed in some portions of the exterior surface of the building. Moreover, two more models were developed to overcome the excess of the permissible values of partially infilled models using shear walls by changing the thickness of the shear walls. The models were analyzed using ETABS analyzing software. The results showed that arrangement of infill members has remarkable effect on the soft story irregularity and story drift. They also showed that symmetry in the elevation of the building has great impact on the performance of the building against stiffness irregularity and lateral displacement of the structure. The most applicable solution for the stiffness irregularity and story drift problems in the studied building is partially infilling the exterior surfaces with steel bracings or shear walls. With these infilling methods, the interior parts of the first two stories will be empty and can be used for different purposes since the infilling is only applied in the exterior surfaces of the building.

1. Introduction

Earthquakes are one of the most devastating and unpredictable natural disasters that cause massive economic, property and population losses [1]. When designing a structure to withstand the applied seismic forces, resistance of the elements is the most important factor to be considered. However, structures with strong elements might still fail due to some other effects such as irregularities in the horizontal and vertical directions. One of the most common irregularities is the soft story irregularity.

Soft story is characterized by the sudden change of stiffness between soties. Such irregularity has been the reason of failure of so many structures. It is considered to be one of the main reasons of building failures during recent earthquakes [2]. Due to the sudden change in stiffness between two adjacent stories, the story with the lower stiffness has a higher displacement than the stiffer one. Excessive drift of the vertical elements leads to their failure. Soft story is coupled with P-Δ effect on the failed vertical elements which lead to the collapse of the structure [3]. The behavior of a building with a soft story irregularity under earthquake is shown in Figure 1. As can be seen from the figure, during an earthquake, the infilled stories moved like a single block and have smaller displacements. However, the story with no infill members has bigger displacements. Under earthquake, buildings having a soft first story, which is the most common situation, behave like an inverted pendulum. As a result, columns of the soft story are severely stressed, and plastic hinges might form at the two ends of these columns. If the columns are not able to withstand theses stresses, the building might collapse [4]. Some examples of buildings failed under earthquake because of the formation of soft story are shown in Figure 2.

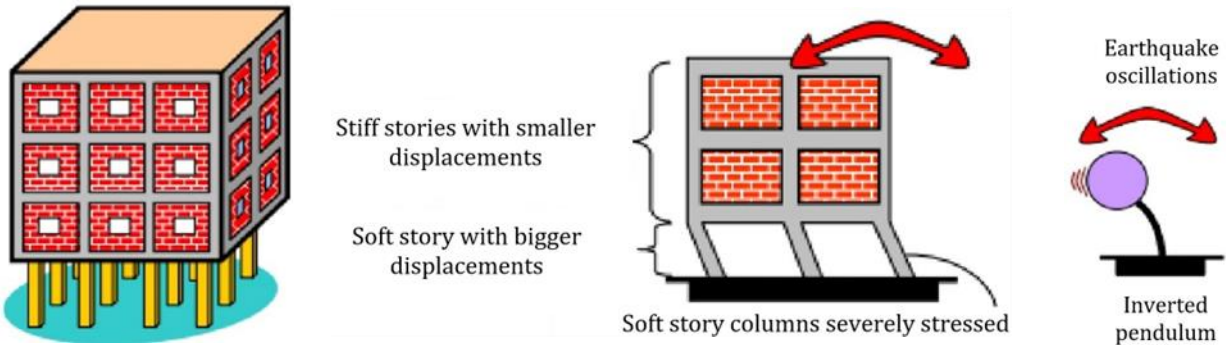


Figure 1. Behavior of buildings with soft story during earthquake (modified from [4])

(a) (b)

Figure 2. Some examples of soft story damages, (a) a building having its first two stories damaged under 1999 Kocaeli earthquake, Türkiye [5], (b) a building damaged under 2011 Van earthquake, Türkiye [6]

There are many conditions that can lead to the creation of the soft story irregularity. Some of these are removing the infill walls from some stories to make them available for different uses, significantly increasing the length of the columns of some stories compared to the adjacent ones, and terminating some columns in some stories to increase the open space on these soties [7,8]. Soft story commonly happens on the ground floor, due to the lack of infill walls in such story. However, this does not mean it is only related to ground floors. Emptying some stories of infill walls has many benefits. However, when it creates a soft story, its casualties are huge. Past earthquakes have revealed that many buildings were failed under the effect of earthquakes because their infill walls were removed from some stories for different purposes resulting in the development of soft story irregularity [9].

Soft story irregularity is commonly found in old structures [10]. Such structures need to be checked for their safety under expected future earthquakes according to the updated recommendations of world standards. If the old structures are not safe, a proper retrofitting method should be carried out. Soft story irregularity might also happen in new structures if the recommendations of the design standards are not properly followed.

During the soft story mechanism tendency to story drift increases rapidly [2]. In general, during lateral forces such as earthquake, a structure might be subjected to big lateral displacements. Such displacements cause discomfort of the people living in such structures and might also lead to the destruction of their valuable possessions and collapse of structures. To limit the harm caused by excessive story drifts, standards give a maximum value for it.

Many studies have been carried out on evaluation of soft story irregularity and story drift of different structures. Döndüren and Nakipoğlu [11] experimentally researched the effect of different retrofitting methods on soft story irregularity. A two-story single span reinforced concrete frame having its 2nd story infilled with masonry infill walls and its 1st story retrofitted with different methods was examined. These methods are, masonry infill walls, K-type (<>) steel bracings, V-type (V) steel bracings and turned sideways V-type (>) steel bracings. Their results showed that K-type steel bracings has the best performance against softy story irregularity. Pavithra and Babulal [12] studied the soft story irregularity in 15 story building. The soft story was evaluated in different stories of the building. The results showed that the earthquake response increases when soft story is found at lower stories and becomes minimum when it is found at the top story. Islam and Shuvo [13] studied the effectiveness of using shear walls, steel bracings, and lateral buttresses and increasing the thickness of the columns in overcoming the soft story irregularity of a frame having a soft story on the ground floor. In the study, the strengthening techniques were applied only to the ground floor. The results of their study showed that use of shear walls, lateral buttresses and diagonal braces increased the lateral strength and stiffness of the studied frame remarkably. In their work, Hejazi et al. [3] evaluated the response of a 12-story reinforced concrete frame building having a soft story at the ground floor under seismic forces using SAP2000 software package. The authors studied the effect of various arrangements of bracings on soft story irregularity. They found that location and number of bracings plays a critical role in retrofitting soft story irregularity. Their results also showed that bracing mainly effect the results of the story they are placed in. Inel and Ozmen [2] investigated the soft story irregularity due to increased story height and lack of infill members at the ground floor of 4-story and 7-story buildings. Their results showed that lack of infill walls may be as dangerous to buildings as increased story height. It is observed from the literature review conducted in this study that the past works concentrated on the soft story of the ground floor. There is a lack of studies on the occurrence of soft story in other stories.

There are many strengthening techniques that can be used in buildings having soft story irregularity. Some examples are addition of shear walls, addition of steel bracing, addition of infill walls, wall or column thickening, base isolation and jacketing of columns [14]. In this study, the effect of masonry infill walls, reinforced concrete shear walls and steel bracings on the stiffness irregularity and maximum story drift of a building is studied. A 10-story building having its first two stories not infilled with any infill member, and its other stories fully infilled with masonry infill walls was examined. Different retrofitting methods to the soft story irregularity found in such building were evaluated. The concentration of this study is the softy story irregularity and maximum story drift. For this reason, strength of elements and other parameters were not evaluated.

2. Project overview and calculation methods

2.1. Details of models

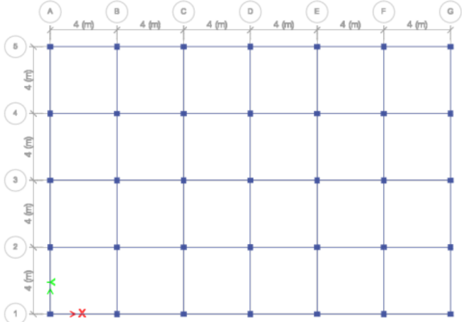
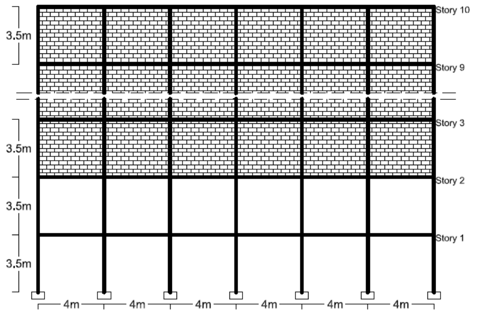
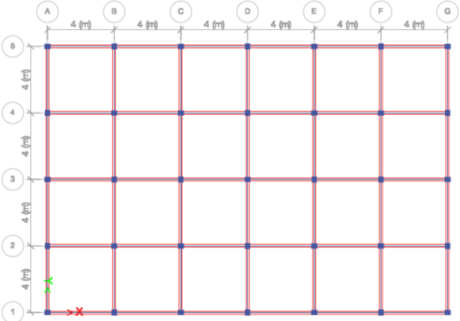
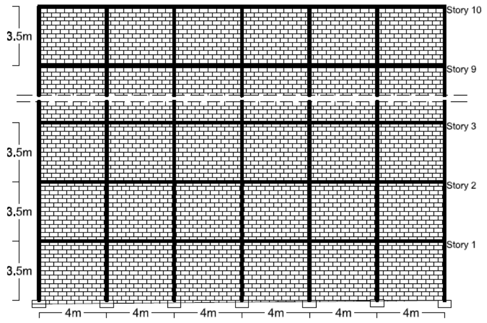
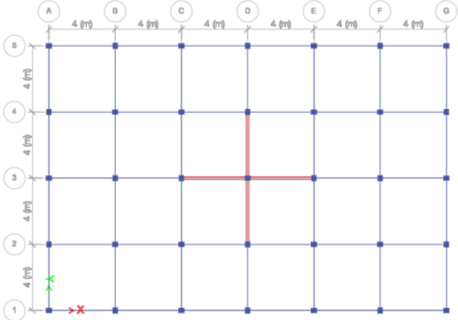
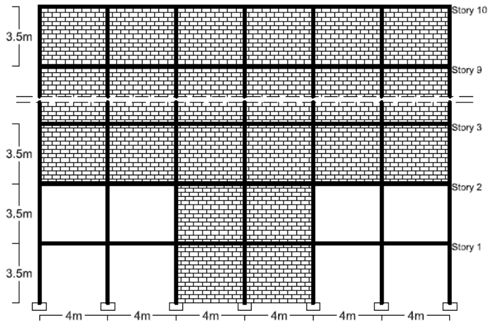
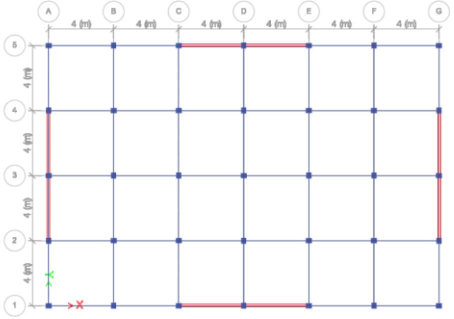
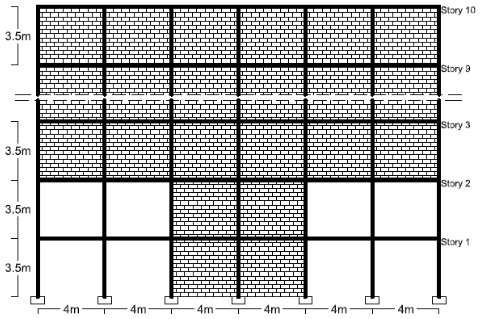
In the current study, a 10-story building of 24 m length, 16 m width, 35 m height and a story height of 3.5 m was analyzed. All the models were designed to be symmetric and have the same materials properties. In All the models, concrete strength is taken as 25 MPa. Reinforcement steel has a yield strength of 420 MPa and a maximum strength of 500 MPa. Slab thickness is 150 mm. Rigid diaphragms were considered in the analysis and were applied to all the slabs. Beams width and height are 250 mm, 350 mm, respectively. Column dimensions are 300×350 mm. Columns orientation was chosen to have a symmetric building plan. When calculating the weight of the building for earthquake excitation, only %30 of live load was considered. Design and analysis were done according to Turkish Building Earthquake Code-2018 (TBEC-2018) [15]. The analyses were performed using ETABS 19.1.0 program.

A total of 14 models were planned in this work. The reference model has infill walls in all the directions in all the stories except the first and second stories. The infill walls were placed under all the beams and between all the columns. The only variable in this study is the retrofitting method. Infill walls, shear walls and steel bracings were used in different situations to evaluate their effect on the maximum story drift and stiffness irregularity. The details of models and their designations are shown in Table 1. The models were divided to four groups: A, B, C and D. In group A, the first two stories are not infilled with any types of infills (Reference model – M1). In group B, the first two stories are fully infilled with infill walls, shear walls or steel bracings. In group C, one of the three infill types (infill walls, shear walls and steel bracings) is placed in the center part of the first and second stories. Since in practice, retrofitting using shear walls is usually applied to the whole height of the building, one model (M8) has its shear walls extended to the whole height of the building, not only the first two stories. Accordingly, for the comparison purpose, one model (M9) having steel bracings on all the stories was also studied. In group D, some portions of the external surface (external facade) are infilled with infill materials. The symmetry in placement of the infill members was considered. Similar to group C, in group D, two models infilled with shear walls and steel bracings throughout the whole height of the building (M13 and M14 respectively) were also investigated. The plan view and elevation view of the model groups are shown in Table 2. Since similar infilling situation is considered in every group of models, in the table, only infill walls situations are shown.

Table 1. Models' details, designations, and groups

Model Detail	Model Designation	Group
First two stories are not infilled (empty)	M1	A
First two stories are fully infilled with infill walls	M2	B
First two stories are fully infilled with shear walls	M3	B
First two stories are fully infilled with steel bracing	M4	B
First two stories have infill walls placed in the center part	M5	C
First two stories have shear walls placed in the center part	M6	C
First two stories have steel bracings placed in the center part	M7	C
All stories have shear walls placed in the center part	M8	C
All stories have steel bracings placed in the center part	M9	C
First two stories have infill walls placed in the exterior surface	M10	D
First two stories have shear walls placed in the exterior surface	M11	D
First two stories have steel bracings placed in the exterior surface	M12	D
All stories have shear walls placed in the exterior surface	M13	D
All stories have steel bracings placed in the exterior surface	M14	D

Table 2. Groups of models and plan and elevation views

Model Group	Plan View	Elevation View
A		
B		
C		 (Along axes no. 3)
D		

2.2. Loads

Beside self-weight of materials, dead load, live loads, and earthquake loads were applied to the structure. A dead load of 5 kN/m^2 and a live load of 2 kN/m^2 were applied to the slabs in all stories except the roof story, in which live load was taken as 1.5 kN/m^2. In addition, a dead load of 6.8 kN/m as weight of walls was applied to all the beams except for the roof story.

The seismic loads were calculated according to TBEC-2018 [15]. The loads are calculated for buildings placed in Bagcilar/Istanbul. It should be emphasized that after the 6th of February earthquakes, that struck Türkiye and Syria, the riskiest place in terms of seismic gap in our country is the Marmara branch of the northern Anatolian fault. For this reason, Istanbul was considered for this study. According to [16], in Bagcilar/Istanbul, the value of V_{S30} (average S wave velocity in the upper 30 meters) is between 150-1392 m/s, most of which lies between 150-400 m/s. This indicates a weak soil condition [17,18]. The range of V_{s30} value for ZD site class is 180-360 m/s [15]. Accordingly in this study, the site class was taken as ZD. Earthquake ground motion level was taken as DD-2 and occupancy importance as 1. The seismic loads were calculated for both direction with an eccentricity ratio of 0.05. Due to the symmetry of the building, seismic loads were only calculated in the positive direction of X axis and Y axis. Load cases and combinations were taken as per recommendations of TBEC-2018 [15].

2.3. Modeling of infill walls, shear walls, and steel bracing in ETABS Software

Shear walls were designed as reinforced concrete walls with a thickness of 180 mm. Steel bracings were chosen as to have a section shape of double angle. The double angle section has a total depth of 200 mm, a width of single angle of 200 mm, a horizontal and a vertical leg thickness of 25 mm, a back-to-back distance of 20 mm and a fillet radius of 0 mm. Steel material used in steel bracings were considered to have a yield strength of 250 MPa and a maximum tensile strength of 373 MPa. Steel bracings were modeled as a pinned ended X bracing. The X bracings were modeled to be pinned to the corners of the openings.

Masonry infill walls have a weight per unit volume of 10 kN/m^3, a modulus of elasticity of 2460 MPa, a Poisson's ratio of 0.18 and a compressive strength of 7.61 MPa. Masonry bricks considered in the infill walls have a length, a thickness and a height of 290 mm, 135 mm, and 190 mm respectively.

Masonry infill walls can be modeled as equivalent diagonal struts or shell elements [19]. In this study, infill walls were modeled as equivalent diagonal struts. When designing the infill walls as equivalent diagonal struts, the infill walls are replaced with a compression brace that have the properties and thickness of the masonry wall and have a width of w (Figure 3). There are many methods for calculating the width of the equivalent diagonal strut. In this study, the results of the research conducted by [19] was taken into account. Amalia and Iranata, [19] evaluated 14 different methods for calculating the width of the equivalent diagonal struts. These are Saneinejad-Hobbs method, Holmes method, Stafford-Smith method, Mainstones method, Mainstones-Weeks method, Bazan-Meli method, Liauw Kwan method, Paulay and Priestley method, FEMA 356 method, Durani Luo method, Hendry method, Al-Chaar method and Papia and Chen-Iranata method. The authors compared the results of the methods with the experimental work results of [20]. In the evaluation process the authors compared the force-deflection diagrams. The evaluation results showed that the method that gives the closest results to the experimental work is Holmes method. In this method, w is calculated as Equation 1:

$$w = \frac{1}{3}\, d_{inf} \tag{1}$$

where: d_{inf} is the diagonal of infill. In this study, d_{inf} = 5 m and w = 1.67 m.

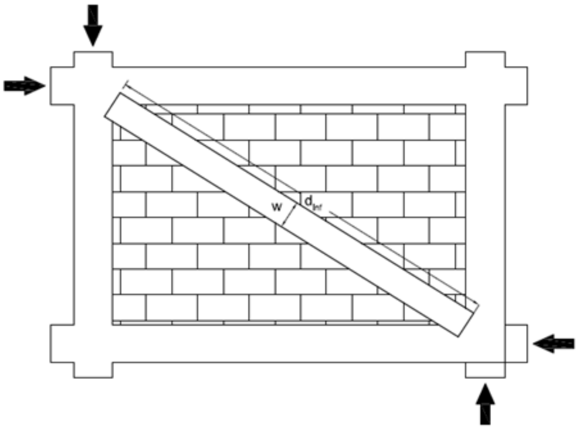


Figure 3. Equivalent diagonal struts method for modeling masonry infill walls

2.4. Calculation of maximum story drift (Δ_{max})

According to TBEC-2018 [15], when infill walls and surface elements are made of brittle material and are completely joined to the frame members without any flexible joints or connections between them, the condition in Equation 2 must be ensured for both the earthquake directions.

$$\lambda^*(\delta_{i,max}(X)/h_i) \leq 0.008^*\kappa \tag{2}$$

where

$$\delta_{i,max}(X) = (R/I)^*\Delta_{i,max}(X) \tag{3}$$

δi,max(X) is the effective relative story drift in the studied direction, the bearing system behavior coefficient R = 8, the occupancy importance factor of the structure I = 1. h_i is the story height and is equal to 3500 mm. κ = 1 for reinforced concrete structures. λ is calculated using the Equation 4:

$$\lambda = S_{ae}(T)(DD3)/S_{ae}(T)(DD2) \tag{4}$$

Sae(T)(DD3) and S_{ae}(T)(DD2) are the elastic design spectral acceleration of the DD-3, and DD-2 earthquake ground motion respectively. There values are related to the natural period of the structure (T) and are calculated according to Equation 5 when TB ≤ T ≤ 6 sec. Here TB is the horizontal design spectrum bigger corner period and was calculated to be 0.44 and 0.52 for DD-3 and DD-2 respectively. The natural periods of all the models in both the directions were found to be between TB and 6 sec.

$$S_{ae}(T) = SD1/T \tag{5}$$

SD1 is the design spectral acceleration coefficients. It is directly taken from Türkiye Earthquake Hazard Maps and is equal to 0.264 and 0.597 for DD-3 and DD-2 respectively.

Using the upper values and equations, $\Delta_{i,max}(X)$ and $\Delta_{i,max}(Y)$ were found to be equal to 7.92 mm for all the studied models.

2.5. Coefficient of stiffness irregularity

Stiffness irregularity coefficient (η_{ki}) is an indicator of soft story irregularity. It is defined as the ratio of the average story drift of i_{th} story and the average story drift of the upper or lower story, excluding basements. It is calculated according to Equation 6. If the value of coefficient of stiffness irregularity is more than 2 for either of two the perpendicular seismic directions, then the structure is considered to have a soft story irregularity [15].

$$\eta ki = \frac{\left(\frac{\Delta_i^x}{h_i}\right)_{avg}}{\left(\frac{\Delta_{i+1}^x}{h_{i+1}}\right)_{avg}} \text{ or } \frac{\left(\frac{\Delta_i^x}{h_i}\right)_{avg}}{\left(\frac{\Delta_{i-1}^x}{h_{i-1}}\right)_{avg}} \tag{6}$$

It should be noted that in some other standards such as [21,22], only the stories above the studied story are considered, the stories under the studied story are not taken into consideration. Some other standards use different approaches to check the soft story irregularity [23].

3. Results and Discussion

3.1. Soft story irregularity

For the calculations of coefficient of stiffness irregularity, the average story drifts were calculated for all the stories in all the models. Table 3 and Table 4 present the values of average story drift and coefficient of stiffness irregularity in X and Y directions respectively. Since the sudden change in stiffness happens between the 2nd and 3rd stories, results of η_{ki} of only these two stories are shown in the tables. ΔS2, and ΔS3 refer to the average story drift of 2nd and 3rd stories, respectively.

Table 3. Average story drift and soft story irregularity check for X direction

Model Designation	Story										Coefficient of Stiffness Irregularity (η_{ki})	
	1	2	3	4	5	6	7	8	9	10		
	Average story drift (ΔX_{avg}) (mm)										$\Delta S2/\Delta S3$	$\Delta S3/\Delta S2$
M1	26.54	30.50	2.85	2.49	2.47	2.35	2.17	1.94	1.66	1.33	10.72	0.09
M2	3.25	3.58	3.70	3.73	3.66	3.49	3.23	2.88	2.46	1.97	0.97	1.04
M3	0.15	0.20	4.21	4.38	4.28	4.06	3.71	3.25	2.67	2.01	0.05	21.29
M4	0.46	0.66	4.07	4.16	4.07	3.87	3.56	3.15	2.64	2.05	0.16	6.18
M5	14.74	16.35	2.65	2.48	2.45	2.34	2.17	1.94	1.65	1.33	6.17	0.16
M6	2.19	2.89	3.82	3.86	3.79	3.62	3.34	2.98	2.54	2.02	0.76	1.32
M7	4.59	5.74	3.32	3.32	3.26	3.12	2.89	2.58	2.20	1.76	1.73	0.58
M8	2.54	3.60	3.07	3.17	3.17	3.09	2.93	2.72	2.47	2.22	1.17	0.85
M9	4.81	6.20	3.11	2.99	2.89	2.75	2.57	2.32	2.04	1.72	1.99	0.50
M10	10.29	11.25	2.57	2.48	2.45	2.34	2.16	1.94	1.65	1.33	4.37	0.23
M11	1.12	1.61	3.83	3.93	3.86	3.68	3.39	2.99	2.51	1.95	0.42	2.38
M12	2.81	3.63	3.59	3.64	3.58	3.41	3.16	2.81	2.39	1.90	1.01	0.99
M13	1.63	2.66	2.65	2.78	2.79	2.70	2.53	2.31	2.08	1.87	1.00	1.00
M14	3.18	4.37	3.03	3.00	2.93	2.80	2.61	2.37	2.10	1.81	1.44	0.69

Table 4. Average story drift and soft story irregularity check for Y direction

Model Designation	Story										Coefficient of Stiffness Irregularity (η_{ki})	
	1	2	3	4	5	6	7	8	9	10		
	Average story drift (ΔY_{avg}) (mm)										$\Delta S2/\Delta S3$	$\Delta S3/\Delta S2$
M1	27.46	31.78	3.42	3.14	3.20	3.14	3.00	2.78	2.50	2.16	9.29	0.11
M2	3.20	3.72	4.01	4.18	4.22	4.14	3.96	3.67	3.29	2.84	0.93	1.08
M3	0.16	0.24	4.23	4.58	4.64	4.54	4.29	3.89	3.37	2.74	0.06	18.01
M4	0.51	0.83	4.21	4.46	4.51	4.42	4.19	3.85	3.40	2.86	0.20	5.06
M5	15.06	16.87	3.20	3.13	3.19	3.13	3.00	2.78	2.50	2.16	5.28	0.19
M6	2.93	3.70	4.11	4.31	4.36	4.28	4.09	3.79	3.39	2.91	0.90	1.11
M7	4.83	6.15	3.68	3.92	3.95	3.87	3.69	3.41	3.06	2.63	1.67	0.60
M8	3.33	4.45	3.31	3.56	3.71	3.77	3.68	3.53	3.33	3.13	1.34	0.74
M9	4.58	6.01	3.45	3.58	3.59	3.53	3.39	3.19	2.93	2.64	1.74	0.57
M10	10.49	11.62	3.11	3.13	3.18	3.13	2.99	2.78	2.50	2.16	3.74	0.27
M11	1.05	1.58	4.05	4.30	4.35	4.28	4.07	3.74	3.31	2.79	0.39	2.56
M12	2.62	3.55	3.90	4.09	4.15	4.09	3.90	3.62	3.24	2.78	0.91	1.10
M13	1.55	2.63	2.81	3.06	3.18	3.18	3.09	2.94	2.75	2.57	0.94	1.06
M14	2.96	4.25	3.31	3.44	3.50	3.48	3.38	3.21	2.98	2.73	1.29	0.78

As can be observed from the Tables 3 and 4, the η_{ki} value for the reference model M1 is much larger than that of the permissible value (i.e., 2) in both the directions. This shows the condition of a soft story irregularity under the studied earthquake. This is expected due to the emptiness of first and second stories from infill walls. This leaded to a sudden change in the stiffness between the second and third stories.

By fully infilling the first and second stories with masonry infill walls a homogeneity was provided to the building and vertical symmetry was established. As a result, the soft story problem was eliminated perfectly, as can be seen in M2. As can be seen that the value of η_{ki} is close to 1. When replacing the masonry infill walls in the first two stories with reinforced concrete walls or steel bracings the stiffness of these stories was enormously increased and became much higher than that of the third story. This can be observed from the value of $\Delta S3/\Delta S2$ which is much higher than 2. This also led to a soft story irregularity according to TBEC-2018 [15]. It can also be observed that shear walls effect on stiffness is much higher than steel bracings. As stated before, while TBEC-2018 [15] takes the stiffness of the lower story into consideration when calculating η_{ki}, some other standards only take the upper stories into consideration.

When the first two stories were partially infilled, the situation completely changed. When having a masonry infill walls in the center part (Group C) or in the exterior surface (Group D), the stiffness of the first and second stories remarkably decreased which led to a soft story situation. However, when compared to the reference model, they showed a better performance especially when the infill walls were placed in the exterior surface. On the other hand, except for Model M11, models partially infilled with shear walls and steel bracings don't have a soft story irregularity. Placing shear walls in the exterior surface as in M11, increased the stiffness of the first two stories leading to a value of η_{ki} slightly higher than 2. This irregularity might be dealt with by some approaches such as reduction of the thickness or length of the shear walls. It can be seen that this irregularity was overcome when the shear walls were extended the whole height of the building (M13 model).

It can be seen from the figures that extending the steel bracing placed in the center part of the building to the whole height of the building (M9 model) increased the difference between the stiffness of the second and third stories. This can be seen from the value of ΔS2/ΔS3 in the X direction which is very close to 2. This situation was not observed in the case of shear walls. This situation can be attributed to the fact that stiffness of shear walls is much higher than infill walls, which makes them dominants. As a result, the effect of absence of infill walls in some portions of the first two storis on soft story irregularity negligible. This can be clearly seen from the values of η_{ki} of M8 and M13 models, which are close to 1 in both the directions.

By comparing the values of group C and D, it is observed that placing the infill members in the exterior surface has a bigger effect than placing them in the center part of the building. This can be observed by comparing the results of the groups with the results of the reference model M1. It can be also observed that use of partial infill can solve the soft story problem more effectively than full infill. This will also be remarkably reflected on the financial cost of the building. Another observed point is that although first story is not infilled with any infilling members in M1, soft story irregularity was not observed between the first and second stories due to the unchanged in the stiffness between the two stories. The same was also observed for the rest of the models.

3.2. Maximum story drift

Table 5 and Table 6 show the maximum story drift values in X and Y directions. As can been seen from the tables, the reference model M1, showed story drifts much higher than the allowable one for the first two stories. This is related to the reduction in lateral stiffness in these stories. On the other hand, all models in group B have less story drift than the permissible value. It is seen that shear walls have the highest effect on the maximum story drift values of the first two stories, depending on their higher stiffness, followed by the effect of steel braces and finally infill walls.

When masonry infill walls were placed in the center part or in the exterior surface of the building, they reduced the story drift compared to M1 model, but not enough to be under the permissible value. It can be seen from the figures that partially infilling the building in the center part has a bad effect on the maximum story drift. All the models in C group have a value of maximum story drift higher than the permissible one. It is observed that when shear walls were used in the center part of building (M6 and M8 models), the value of maximum story drift is higher than the permissible one only in the Y direction. This problem is thought to be solved by increasing the thickness or length of the shear walls. When steel bracings were used instead of shear walls, they showed a worse performance.

The results showed that placing shear walls or steel bracings in the exterior surface of the building increased the stiffness sufficiently and reduced the story drift to be under the permissible values. All models with shear walls and steel bracings in D group have a value of maximum story drift much lower than the permissible one.

It can be observed from the table that shear walls then steel bracings performed better than infill walls. Similar results have been found in the literature [24]. It can also be seen that displacement in Y direction is higher than in X direction. This is logical since the building is longer and stiffer in X direction than in Y direction.

3.3. Investigation on changing the thickness of the shear walls in M6 and M11 models

In this section, the authors tried to solve the problem of slightly exceeding the permissible values of ΔY_{max}, and ΔS3/ΔS2 for models M6 and M11 respectively. The authors evaluated the change of only the thickness of shear walls without changing the other parameters. It should be noted that other parameters of the members can be tried in another work. This solution can also be tried to solve the excess of ΔY_{max} in M8 model.

Since M6 was found to have a maximum story drift of 9.2 mm which is 16.16% higher than the permissible value. This problem can be solved by increasing the resistance to lateral displacement. The stiffness can be increased by increasing the thickness of the shear walls. For this purpose, another model was developed and was designated as M15. In this model the thickness of the shear walls used in M6 was increased from 180 mm to 400 mm. The authors tried many thicknesses and found that 400 mm is the least thickness to overcome the excess of the permissible story drift. The results of the model M15 are presented in Table 7. As can be seen from the table, 400 mm thickness reduced the maximum story drift of the second story to be %1.39 less than the allowable value.

This percentage can be increased by further increasing the thickness of the shear walls. However, an attention should be given to the soft story irregularity not to happen.

Table 5. Values of maximum story drift in X direction

Model designation	**Story**										**Δ_{max} as per TBEC-2018** [15]
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	
	Maximum story drift (ΔX_{avg}) (mm)										
M1	28.41	32.64	3.17	2.75	2.70	2.54	2.33	2.06	1.74	1.38	7.92
M2	3.80	4.10	4.17	4.14	4.01	3.78	3.47	3.06	2.59	2.05	
M3	0.16	0.21	4.81	4.92	4.75	4.45	4.02	3.48	2.84	2.11	
M4	0.49	0.69	4.61	4.64	4.48	4.21	3.84	3.36	2.79	2.14	
M5	16.62	18.49	2.98	2.75	2.68	2.53	2.32	2.05	1.74	1.38	
M6	4.86	6.06	4.33	4.28	4.15	3.92	3.59	3.17	2.67	2.10	
M7	7.09	8.59	3.76	3.67	3.57	3.37	3.09	2.74	2.31	1.83	
M8	5.50	7.19	3.63	3.62	3.57	3.43	3.20	2.92	2.61	2.31	
M9	7.36	9.10	3.56	3.35	3.21	3.02	2.78	2.49	2.15	1.80	
M10	10.90	11.87	2.90	2.76	2.69	2.54	2.33	2.06	1.74	1.38	
M11	1.16	1.66	4.36	4.40	4.26	4.01	3.65	3.19	2.65	2.03	
M12	2.91	3.75	4.05	4.04	3.92	3.70	3.39	2.99	2.51	1.97	
M13	1.69	2.76	2.77	2.91	2.92	2.82	2.64	2.41	2.16	1.94	
M14	3.29	4.53	3.21	3.17	3.09	2.94	2.73	2.47	2.17	1.87	

Table 6. Values of maximum story drift in Y direction

Model Designation	**Story**										**Δ_{max} as per TBEC-2018** [15]
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	
	Maximum story drift (ΔY_{avg}) (mm)										
M1	31.64	36.54	4.09	3.69	3.69	3.56	3.35	3.06	2.71	2.30	7.92
M2	4.13	4.63	4.85	4.94	4.90	4.73	4.45	4.07	3.60	3.06	
M3	0.18	0.26	5.29	5.57	5.52	5.30	4.91	4.39	3.74	2.99	
M4	0.56	0.90	5.15	5.33	5.27	5.08	4.75	4.29	3.73	3.08	
M5	19.25	21.64	3.86	3.69	3.68	3.56	3.35	3.07	2.71	2.31	
M6	7.57	9.20	5.04	5.08	5.05	4.88	4.58	4.18	3.69	3.12	
M7	9.40	11.35	4.50	4.50	4.48	4.33	4.08	3.73	3.30	2.80	
M8	8.51	10.72	4.31	4.40	4.46	4.57	4.22	3.96	3.65	3.34	
M9	9.73	11.94	4.29	4.18	4.13	4.00	3.79	3.51	3.18	2.81	
M10	11.64	12.83	3.75	3.70	3.69	3.57	3.37	3.08	2.73	2.32	
M11	1.12	1.68	4.97	5.16	5.12	4.94	4.62	4.19	3.65	3.02	
M12	2.80	3.76	4.72	4.85	4.82	4.67	4.39	4.01	3.53	2.98	
M13	1.67	2.84	3.07	3.35	3.47	3.46	3.36	3.18	2.98	2.78	
M14	3.18	4.59	3.67	3.81	3.86	3.80	3.66	3.45	3.19	2.91	

For M11, $\Delta S3/\Delta S2$ was higher than 2 in both the directions. This means that the stiffness of the 2nd story is much higher than the 3rd story. For this reason, the authors created a new model with a reduced thickness. This model was designated as M16. M16 model has the same properties as M11 except for the thickness of the shear walls, which was reduced from 180 mm to 120 mm. Many attempts were done for other thickness. However, the maximum thickness that eliminated the soft story problem was found to be 120 mm. Table 8 presents the results for model M16. It can be observed from the table that 120 mm thickness overcame the soft story irregularity by 10%.

It should be mentioned that the authors tried to solve the problem of excess of maximum allowable story drift of M7 model by following the same approach, i.e., by increasing the thickness of the double angle steel section. However, by increasing the thickness of the section to larger values, the problem was not solved. Since M5 and M10 have values much greater than the permissible ones, no attempt was done to increase the thicknesses of the masonry infill walls. Shear walls and steel bracings in group B have very large difference in stiffness between 2nd and 3rd stories. For this reason, change of thickness might not be an applicable solution for their soft story irregularity.

Table 7. Results for model M15

Story	1	2	3	4	5	6	7	8	9	10	
ΔX_{max} (mm)	3.78	4.77	4.57	4.54	4.40	4.15	3.80	3.35	2.82	2.22	≤ 7.92 mm
ΔY_{max} (mm)	6.35	7.81	5.26	5.33	5.29	5.10	4.79	4.37	3.85	3.25	
ΔX_{avg} (mm)	1.77	2.23	4.03	4.10	4.02	3.83	3.54	3.15	2.68	2.13	
ΔY_{avg} (mm)	2.37	3.17	4.29	4.51	4.56	4.48	4.27	3.95	3.53	3.03	
Soft Story Irregularity Check											
Coefficient of Stiffness Irregularity (η_{ki})	X direction	ΔS2/ΔS3	0.55	< 2							
		ΔS3/ΔS2	1.80	< 2							
	Y direction	ΔS2/ΔS3	0.74	< 2							
		ΔS3/ΔS2	1.35	< 2							

Table 8. Results for model M16

Story	1	2	3	4	5	6	7	8	9	10	
ΔX_{max} (mm)	1.58	2.18	4.27	4.29	4.16	3.92	3.57	3.13	2.60	2.00	≤ 7.92 mm
ΔY_{max} (mm)	1.52	2.18	4.89	5.06	5.03	4.85	4.55	4.12	3.60	3.00	
ΔX_{avg} (mm)	1.53	2.11	3.76	3.84	3.77	3.60	3.31	2.93	2.47	1.92	
ΔY_{avg} (mm)	1.43	2.06	3.99	4.23	4.28	4.21	4.01	3.69	3.27	2.77	
Soft Story Irregularity Check											
Coefficient of Stiffness Irregularity (η_{ki})	X direction	ΔS2/ΔS3	0.56	< 2							
		ΔS3/ΔS2	1.78	< 2							
	Y direction	ΔS2/ΔS3	0.52	< 2							
		ΔS3/ΔS2	1.94	< 2							

3.4. Comparison of the performance of different models

3.4.1. Maximum excess of Δ_{max} and η_{ki}

To compare the performance of the different models, the maximum excess of both maximum story drift (Δ_{max}) and stiffness irregularity coefficient (η_{ki}) in comparison to the permissible values for all the models were evaluated and presented in Figure 4. Here, the maximum story drift for each model in all the stories and for both the direction was compared to the permissible maximum story drift. The maximum value was chosen for the comparison. The same approach was followed for η_{ki}.

The figure shows that M1 has the worst performance for both Δ_{max} and η_{ki} as expected. It also shows the best performance was found in M2, M12, M13 and M14 models. From η_{ki} values point of view, M3 model showed the highest value, due to the remarkable increase in stiffness of the first two stories. It can be also observed that partial use of masonry infill walls (M5 and M10 models) did not perform well in both the story drift and the stiffness irregularity. It can also be seen that when steel bracings are partially used in the center part of the building (M7 and M9 models) they didn't perform well. However, putting the steel bracing in the exterior surface (M12 and M14 models) has great effect.

Partially infilling using shear walls in the center part (M6 and M8 models) didn't show a good performance from Δ_{max} and η_{ki} point of view. Placing shear walls in the exterior surface of the building in only the first two stories (M11 model) also didn't have a good performance. However, when the shear walls were extended to all the stories (M13 Model), the maximum story drift was highly limited, and the stiffness irregularity was efficiently overcome.

It can be seen from the results that type, arrangement and number of infill members have high effect on the softy story irregularity. The farer the infill members are placed from the center of the building the better the performance of the building is. As can be seen from the figure that M15 and M16 have one or the two values close to the limit values. This is because their purpose was to find the thicknesses that lies closest to the limits but on the safe side.

3.4.2. Displacement-height relationship

The relationship between the average story displacement and the height were also studied to evaluate the performance of different models. Figure 5a and 5b presents the displacement-height relationship of the models in X and Y directions respectively. The displacement was calculated according to the average values of the story drifts. As can be observed from the figure, M1 has the highest displacement followed by M5 and M10. This indicates that masonry infill walls improve the performance of the building when a symmetry or a close situation to symmetry in the elevation is found between the stories. When no symmetry is found their effect might got remarkably decreased. The figure also shows that the remaining models have close displacement-height relationship to each other. It can be seen that all the models show similar behavior starting from the 3rd story and above. When comparing the results of this study with the results found in the literature, a consistence was observed [3,8,13].

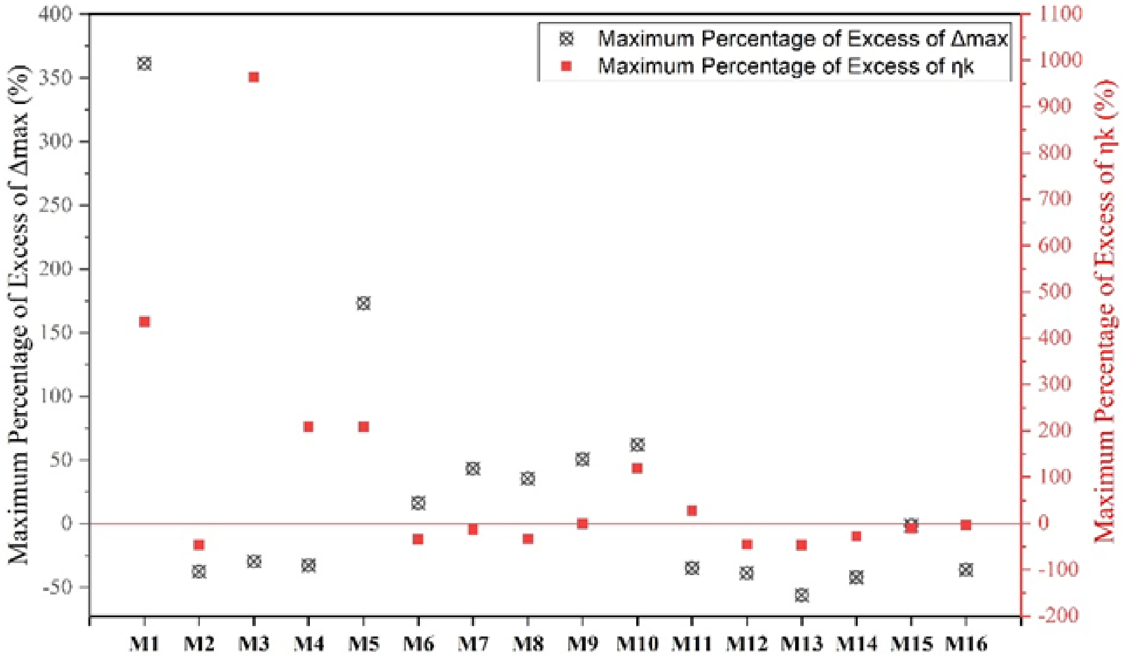
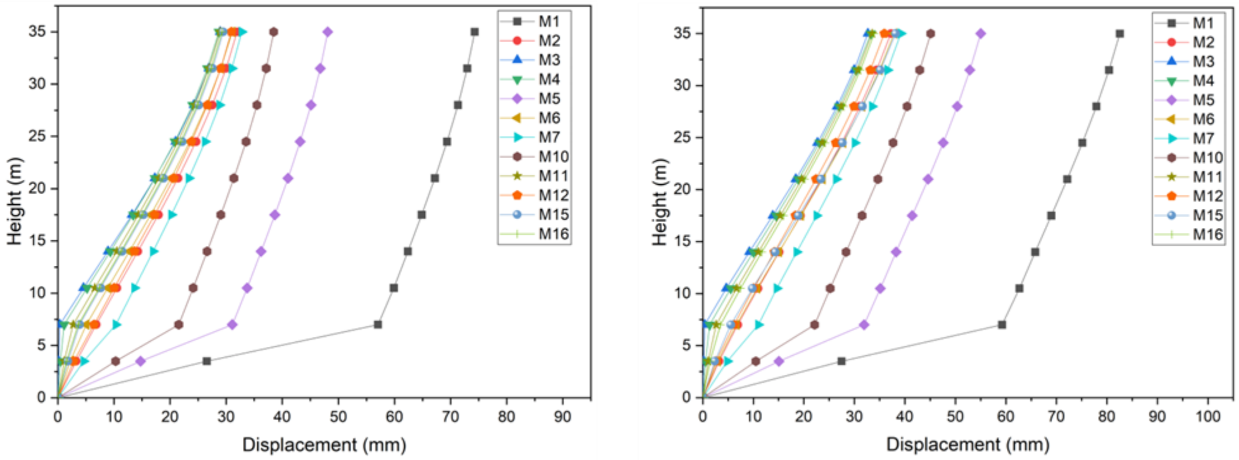


Figure 4. Performance of different models



(a)

(b)

Figure 5. Displacement-height relationship for different models: (a) X direction, (b) Y direction

4. Conclusion

This study evaluates the effect of masonry infill walls, shear walls and steel bracings on the story drift and soft story irregularity. The reference model has its first two stories with no infill members and the remaining 8 stories fully infilled with masonry infill walls. First two stories were infilled with different situations. These are fully infilled, partially infilled in the center part of the building and partially infilled in the exterior surface. In some of the models the infill members were extended to the whole height of the building. The following main conclusions can be drawn from the present study:

- Arrangement of infill members plays a very important role in soft story irregularity and maximum story drift. The stiffness of the story increases with increasing the number of the infill members. When the infill members are placed in the exterior surface, they show better effect on the soft story irregularity and story drift than when placed in the center.
- Fully infilling the first two stories does not always solve the soft story irregularity. It might still cause a soft story irregularity when the stiffness of the first two stories is highly increased.

- Besides being economically preferable, use of partially infilled situation might show much better performance than the fully infilled situation.
- Due to their higher stiffness, reinforced concrete shear walls have higher effect on soft story irregularity and story drift than steel bracings and infill walls.
- The best performance was found in M2, M12, M13 and M14 models. However, since M2 model has its first two stories fully infilled with masonry infill walls, M12 and M14 models, in which only the exterior surface is partially infilled with steel bracings, provide better solutions. The best performance was found in M13 model, which has shear walls as infill members in some parts of the exterior surface throughout the whole height of the building. For M12 model, the maximum percentage of excess of maximum displacement and maximum percentage of excess of coefficient of stiffness irregularity are -38.76% and -45.04% respectively. For M14 model, they are -42.10% and -27.87%, respectively. For M13 model, their values are -56.19% and -46.76%, respectively. This situation indicates a better performance in the case of M13 model.
- Changing the thickness of the shear walls might be a viable soliton to overcome the soft story irregularity and excess of maximum story drift. This option might not be suitable for steel bracings and masonry infill walls.
- The effect of length of infill members on the stiffness irregularity and story drift might be investigated in the future. The use of different situations of partial infill members, such as use of infill members on the corner of the building and as elevator cores, might also be evaluated.

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Author contributions

Mohammed Gamal Al-Hagri: Conceptualization, Methodology, Software, Analysis, Writing-Reviewing. **Abdulhamit Nakipoglu:** Conceptualization, Methodology, Software, Analysis, Data curation. **Mahmud Sami Döndüren:** Reviewing, Editing and Supervising.

Conflicts of interest

The authors declare no conflicts of interest.

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