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PREVENTING IRREGULARITY EFFECTS OF INFILLS THROUGH MODIFYING ARCHITECTURAL DRAWINGS

Azadeh NOORIFARD [a*], Mohammad Reza TABESHPOUR [b], Fatemeh Mehdizadeh SARADJ [c],

[a] PhD Candidate; Department of Architecture and Environmental Design, Iran University of Science and Technology, Tehran, Iran
*E-mail address: *anoorifard@iust.ac.ir*

[b] Assistant Prof.; Department of Mechanical Engineering, Sharif University of Technology, Tehran, Iran

[c] Associate Prof.; Department of Architecture and Environmental Design, Iran University of Science and Technology, Tehran, Iran

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Abstract

Experiences of past earthquakes show that some designed and constructed buildings by engineers have been damaged during earthquakes because of negative effects of infill walls. The main aim of this paper is to prevent the amount of overall detrimental effects of infill walls such as torsion and soft story in a conventional residential building based on seismic codes of some countries and to use the maximum potential of walls. The results show that building in construction condition may suffer torsion because infills which are not modelled in design process are attached to the structure in construction phase. Contrary to the initial impression that there is a soft story in municipal buildings because of parking on ground floor, in buildings with architectural plan similar to the analyzed one, soft story would not happen. Furthermore, this case study proves that it is possible to prevent irregularity effects of infills through modifying architectural drawings without fundamental changes in concept, functional and aesthetic aspects. For modifying architectural drawings an algorithm is proposed in this research.

Streszczenie

Doświadczenia ostatnich trzęsień ziemi pokazują, że niektóre budynki zaprojektowane i skonstruowane przez inżynierów zostały zniszczone podczas trzęsienia ziemi na skutek negatywnego wpływu ścian wypełniających. Głównym celem tego artykułu jest zapobieżenie tym szkodliwym wpływom takim jak skręcanie i wiotkie kondygnacje w tradycyjnych budynkach mieszkalnych w oparciu o normy sejsmiczne niektórych krajów oraz przy wykorzystaniu maksymalnego potencjału ścian. Wyniki pokazują, że budynki w trakcie budowy mogą cierpieć na skutek skręcenia z powodu wypełnień, które nie są modelowane w procesie projektowania, a dopiero dołączone do konstrukcji na etapie realizacji. Wbrew początkowemu wrażeniu, że ze względu na zlokalizowanie parkingu na parterze w budynkach komunalnych istnieje wiotka kondygnacja, w budynkach o rzucie zbliżonym do analizowanego do powstania wiotkiej kondygnacji nie dojdzie. Ponadto, ta analiza przypadku dowodzi, że jest możliwe, aby zapobiec wpływom wynikającym z nieregularności wypełnień poprzez modyfikację rysunków architektonicznych bez zasadniczych zmian w koncepcji oraz aspektów funkcjonalnych i estetycznych. W artykule przedstawiono propozycję algorytmu do modyfikowania rysunków architektonicznych.

Keywords: **Architectural drawings; Conventional residential building; Infill walls; Seismic design; Soft Story; Torsion.**

1. INTRODUCTION

Nowadays structural engineers usually consider masonry infill walls as non-structural elements during analysis and design process of buildings [1, 2, 3, 4, 5, 6, 7] and only calculate their weight. Consequently, analysis and design of the structures are based on the bare frames without the effects of infills [5, 6, 7, 8]. On the other hand, architects do not consider seismic behavior of walls in arrangement of spaces in plan and elevation, in selecting materials and designing construction details. So, in numerous projects, one of the most important non-structural elements with destructive effects in earthquake is usually neglected, while earthquake-resistant design includes two inseparable parts, namely earthquake-resistant structural design and earthquake-resistant architectural design, both of them are equally important in the entire design process [9]. For reducing seismic vulnerability and cost of project, close collaboration between the architect and the engineer from the earliest planning stage is essential [10]. But in developing countries, especially in design and construction process of conventional residential buildings, there is no collaboration between architects and structural engineers and they design the building separately. In these countries the quality of construction is poor and masonry walls are usually used in medium-rise buildings, so it is important to study the behavior of infilled frame in the context of engineering and construction practices of these countries.

It should be noted that there were buildings without sufficient lateral resistance elements which remained stable during earthquake because of lateral strength and stiffness of masonry infill walls. Contrary, there were designed and constructed buildings by engineers which have been damaged during earthquakes because of negative effects of walls [4, 11]. In fact, despite special attention to seismic resistant design of structures, disregarding the infill walls will cause the loss of life and property [12]. It also confirms that it is necessity to study infills.

Structures with simple and regular geometry perform well during earthquakes, while in many cases, despite designing regular structure, asymmetrical infill walls cause irregularity in plan and discontinuous infill walls in elevation cause irregularity in height [1, 12, 13]. Unfortunately these irregular buildings constitute a large portion of the modern municipal buildings [14] and experiences of past earthquakes show these buildings are vulnerable. Several studies of structural damages during past earthquakes reveal that torsion is the most critical factor leading to major damage or complete collapse of buildings [14]. A significant part of torsional effects created by inappropriate distribution of stiffness in buildings is the result of arrangement of walls [11, 15, 16, 17, 18, 19, 20] (Fig. 1). Sometimes, in spite of designing regular structures in elevation, due to reducing or eliminating infill walls in adjacent floors, vertical irregularity occurs [12, 20, 21, 22, 23, 24, 25] and soft story is formed in an earthquake (Fig. 2).

Figure 1.
Torsional fracture due to arrangement of walls in the 1995 Kobe earthquake [13]

Figure 2.
Soft story fracture due to elimination of masonry infill wall in ground floor in the 2006 L'Aquila earthquake [26]

The main aims of this paper are to evaluate the amount of two detrimental effects of infill walls including torsion and soft story in conventional buildings based on provisions of seismic codes, to use the maximum potential of walls and to prevent irregularitiy effects of infills through modifying architectural drawings. Since there is poor collaboration between architects and structural engineers in design and construction of conventional residential buildings and on the other hand, location, material and detail of infill walls are determined in architectural drawings and these drawings are usually changed several times in design and construction process due to comments of client and problems during implementation, so it is more reliable and easier that overall seismic behavior of infill walls to be checked by architects without any fundamental change in common culture of construction.

Since the probability of torsion in the buildings located in corner or northern urban lots due to urban regulation, natural light, solid and perforated walls layout are high [7], a 5-story residential building in a

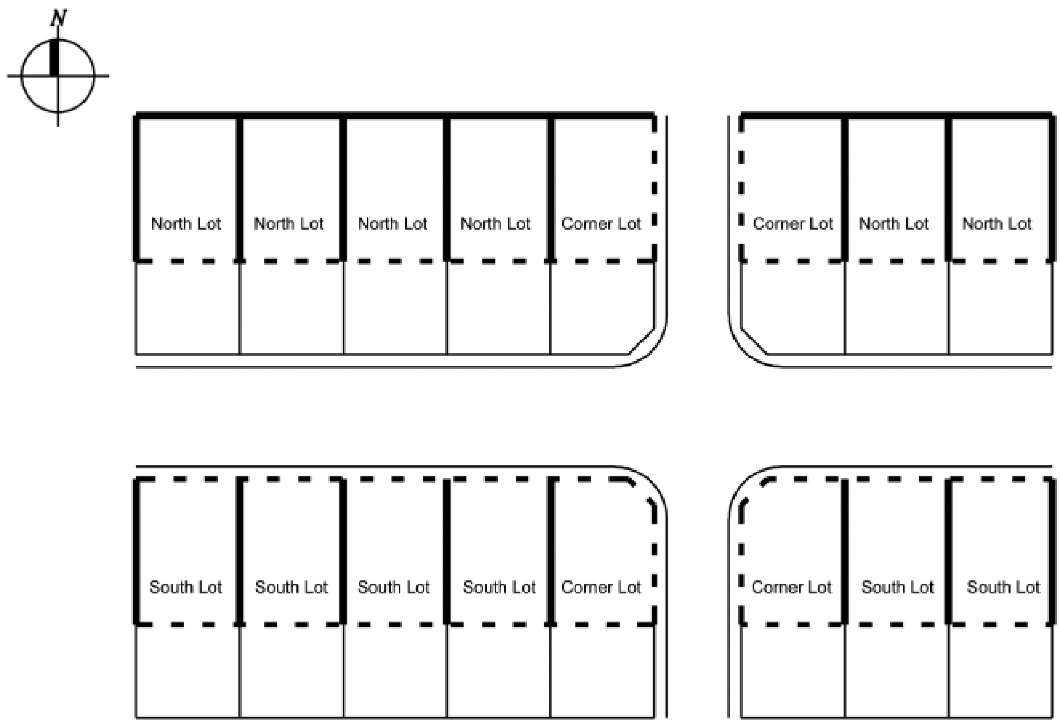

Figure 3.
Arrangement of solid and perforated walls in different urban lots

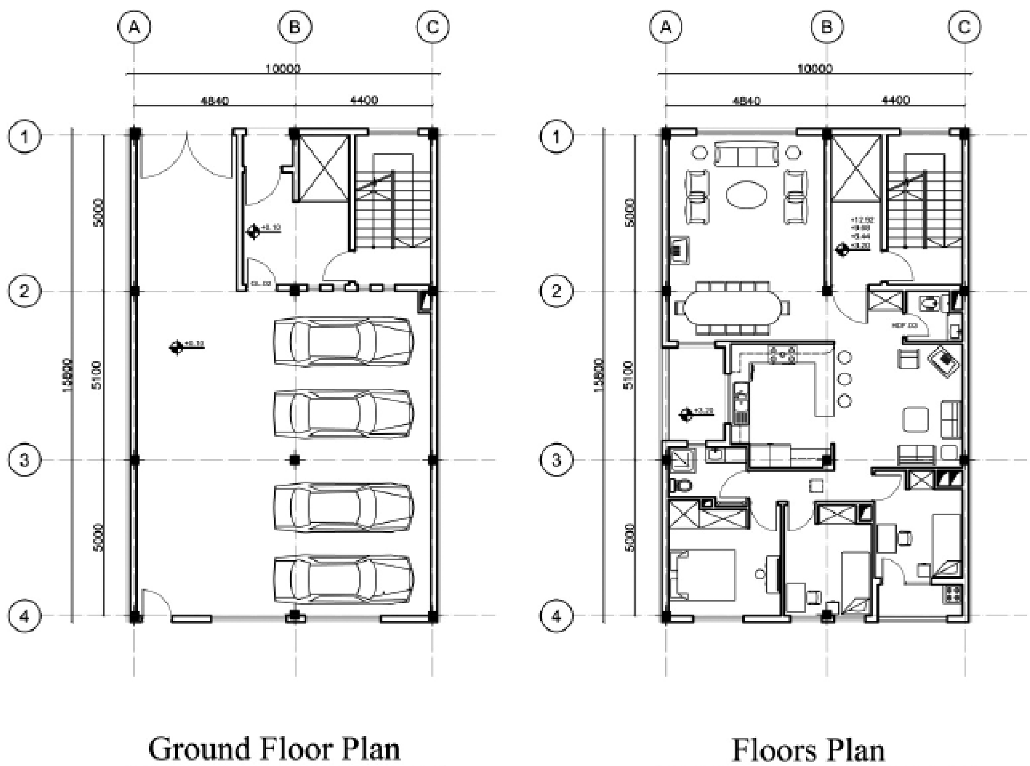

Figure 4.
Architectural Plans of selected case

south lot with a width of 10 m in Tehran has been selected as a case study (Fig. 3). In selected building, parking is located on the ground floor and four upper floors are residential. Each floor contains a set residential unit with three bedrooms. Bedrooms located on the south side and stairs and a living room on the north side of the building. Due to the separation of public, semi-private and private zones, a skylight for lighting and ventilation of the kitchen is designed in the middle of the west side (Fig. 4).

2. ANALYTICAL MODELLING

For studying the effects of infill walls in seismic behavior of structures, simulations are performed by a structural analysis and design software for two cases of design condition and construction condition. In developing countries structural engineers usually assume that dividing walls are separated from the frames and they design bare frames, while this assumption is not true in construction and all dividing walls and partitions are attached to the frames, so for comparing design condition with construction condition, behavior of bare frame and infilled frame will be studied. As a safer condition, some structural engineers assume that walls will be attached to the frames and according to seismic design codes increase the applied forces. For example in standard No. 2800 of Iran, these forces shall be calculated by assuming 80% of empirical period of bare frame. In this condition only the applied force to the bare frame is increased, but infill walls are not modelled and wall distribution in plan and elevation are not checked. In this research one architectural plan with the lowest risk which have the symmetrical arrangement of walls and is located in a south lot as mentioned before and one of the safest condition of structural design with applied force based on 80% of empirical period will be studied. In order to ensure the structural design of bare frame and control the variables, first based on Iranian national building code-part 6 and standard No. 2800 the structure without walls has been designed and then infill walls has been added to the model to study behavior of structure in two aforementioned conditions. Since linear static method is used in structural calculation of conventional buildings, this method is selected for analytical modelling.

2.1. Material Properties and Design Gravity Forces

Since infill walls have the greatest influences on seismic behavior of reinforced concrete moment frames [7], the structural system of the selected building is a reinforced-concrete intermediate-moment resisting frame in two directions. Concrete and rebar properties are summarized in Table 1. Floors have been constructed by joist and block and covered by ceramic tiles. Peripheral walls have been constructed with the use of hollow clay block with a thickness of 20 cm and interior walls with hollow clay block with a thickness of 10 cm. Building cladding and inner layer of stair walls are granite tiles and inside walls and ceilings are coated by 2-cm-thick gypsum and clay plaster and 1-cm-thick gypsum plaster. According to these introduced materials, design forces have been determined based on provisions of the Iranian national building code – part 6.

2.2. Seismic Forces

Seismic forces have been calculated based on Iranian standard No. 2800. The data used in calculation of seismic coefficient are as follows: It is residential building and classified to moderate important group, the building is located in Tehran and design base acceleration ratio is 0.35, soil type is II, structural system is reinforced concrete intermediate moment resisting frame with building response factor of 7. In calculation of fundamental period of vibration of the structure, building height is assumed 16.56 m and it is considered that infill wall impose resistant on frame displacement. In structural design, empirical formula presented in standard No. 2800 has been used to determine period of structure.

2.3. Modelling of Infill Walls

As it has been attempted to study detrimental overall effects of walls such as torsion and soft story, so simulation is based on macro model. In this method infill

Table 1.
Concrete and rebar properties

Weight per unit volume	Modulus of Elasticity	Poisson's Ratio	Coefficient of Thermal Expansion	f'_c Concrete compressive Strength	f_y Bending Reinforcement Yield Stress	f_{ys} Shear Reinforcement Yield Stress
kg/m^3	N/mm^2	-	1/°c	N/mm^2	N/mm^2	N/mm^2
2500	24516	0.15	1E-5	24.5	392	392

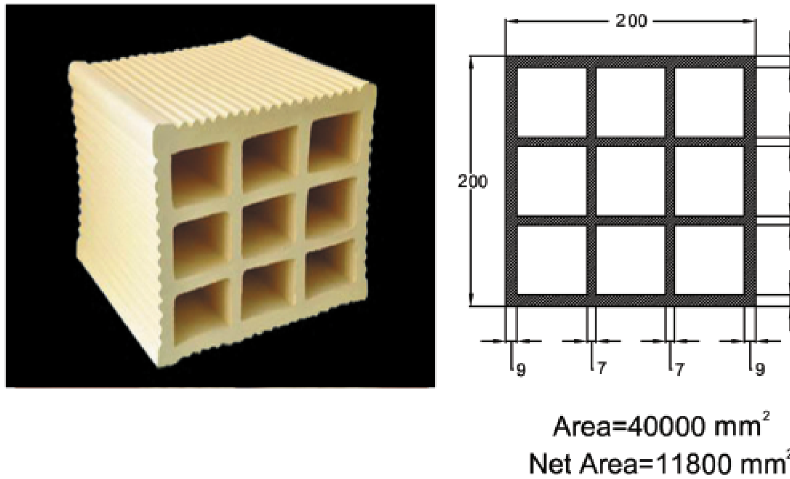

Figure 5.
Dimensions of 9 holes hollow clay blocks

walls are modelled with an equivalent compression diagonal strut. Modulus of elasticity has been assumed 800 times of compressive strength of wall, the effective width of equivalent strut, 0.2 times of wall diameter [13, 27] and thickness of strut, the same as wall.

Dimensions of 9 holes hollow clay blocks used in the building are 20×20×20 cm, thickness of external shell is 9 mm and inner divider walls are 7 mm (Fig. 5). Since the assumptions presented in top paragraph are based on previous researches about solid brick, so in order to simulate the real condition, β factor that is the ratio of net area to total cross section of block, proposed to determine the section of equivalent as a hollow box. Based on performed experiences, the compressive strength of wall with hollow clay blocks and cement mortar is 3.8 MPa [28]. For considering the effect of opening on strength and stiffness of walls, Equation 1 recommended by the New Zealand Society for Earthquake Engineering, has been used [29]. In this equation, $\lambda_{Opening}$ is the reduction factor for strength and stiffness of the infill wall, $L_{Opening}$ is the length of opening and L_{inf} is the length of infill wall. It should be noted that effects of short column which may increase torsional vulnerability are neglected in simulation. In Fig. 6, an arrangement of bare frame, infilled frame and perforated infilled frame are presented, location of short column created by perforated infill walls cause center of rigidity shift to upper right corner.

$$\lambda_{Opening} = 1 - \frac{1.5\, L_{Opening}}{L_{inf}} \qquad (1)$$

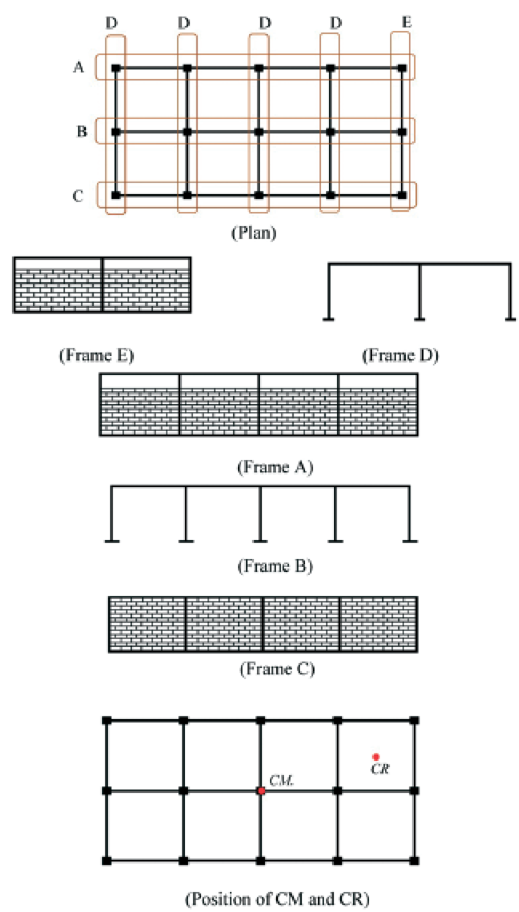

Figure 6.
Effect of short columns on center of rigidity location [27]

3. EVALUATION CRITERIA

Since the main goal of this paper is to investigate the influence of infill walls on creating the torsion and soft story in buildings, the seismic codes of six countries have been reviewed to extract evaluation criteria of these two phenomena for assessing the outputs of analyses. It should be indicated that various national codes can be broadly grouped in two categories of those considering or not considering the role of masonry infill walls while designing RC frame [1]. In this paper it has been attempted to select countries with similar construction condition of Iran and countries that have done researches on infilled frames. In the following provisions of seismic code of Iran, USA, India, Turkey, New Zealand and Nepal are discussed. Most of these criteria are the provisions of torsional and stiffness irregularity in general, in other word, by modelling infill walls it will be checked how much irregularity criteria change.

3.1. Evaluation Criteria of Torsion

For evaluating torsion, three criteria given below are considered. Although, national codes mention torsional irregularity, only a few address the problem in the context of masonry infill walls [1]. The accidental eccentricity and summarized provisions of torsional irregularity of the investigated standards are presented in Table 2 and 3.

1. **The first three modes of modal analysis**: If the torsional mode of the structure occurs in first or second mode of modal analysis instead of third mode, the structure will be susceptible to torsion.
2. **The distance between center of mass and center of rigidity**: According to the section 1-5-5 of standard No. 2800 of Iran, lateral load resisting elements shall be configured in a manner that the torsion resulting from earthquake loading is minimized. For this purpose it is recommended that the eccentricity between the center of mass and center of stiffness, at each floor level, is less than 5% of the building dimension in that level and in the direction under consideration [30]. In this standard there is no mandatory for the maximum allowable amount of eccentricity, but in Nepal National Building Code about mandatory rules of reinforced concrete buildings with masonry infill walls [31], the distance between center of mass and center of rigidity including the effects of infill wall shall be less than 10% of building dimension at the same direction [31]. Based on seismic design code of Nepal [32], if the eccentricity is less than $0.1b$ (building dimension) and the building is 4 stories or less, the design eccentricity may be taken as equal to 0, for eccentricity between 0.1 and $0.3b$ and higher building, the design eccentricity shall be taken as eccentricity $\pm 0.1b$, whichever is the most severe and for greater eccentricity, special provisions should be considered [32], So if the infill walls change the eccentricity of the building, not only applied torsional moment change, but also design assumptions may change too.
3. **The ratio of the maximum relative story drift to the average relative story drift**: In Table 12.3.1 of ASCE 7-10, section 1-7-1-b of standard No. 2800, Table 4 of IS 1893 (Indian Standard) and Table 2.1 of seismic code of Turkey as a condition of plan regularity, in each story the maximum drift, including accidental torsion, at one end of the structure shall not exceed 20% of the average of the story drift of the two ends of the structure. It should be indicated that in these codes, accidental eccentricity is 5% [30, 33, 34, 35] (Fig. 7). In section 4.5.2.3 of NZS 1170.5.2004 (New Zealand Standard) there is a similar provision, but instead of 1.2, the ratio of 1.4 is presented and accidental eccentricity of 10% should be used in calculations instead of 5% [36].

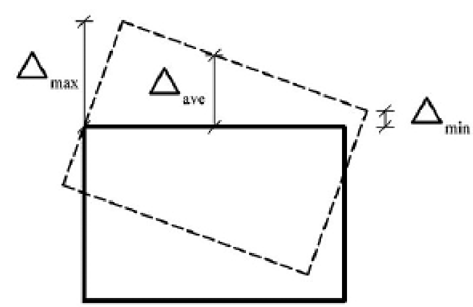

Figure 7.
Maximum relative story drift and average relative story drift

In the following, it is tried to find the relation between second and third criterion by an approximate calculation. The calculations have been performed based on the simple idea shown in Fig. 8. Calculations show that the eccentricity of 10% causes the ratio of the maximum relative story drift to the average relative story drift to be 1.2. In other words, the eccentricity which is allowable in NBC 201 is equivalent to the third criterion.

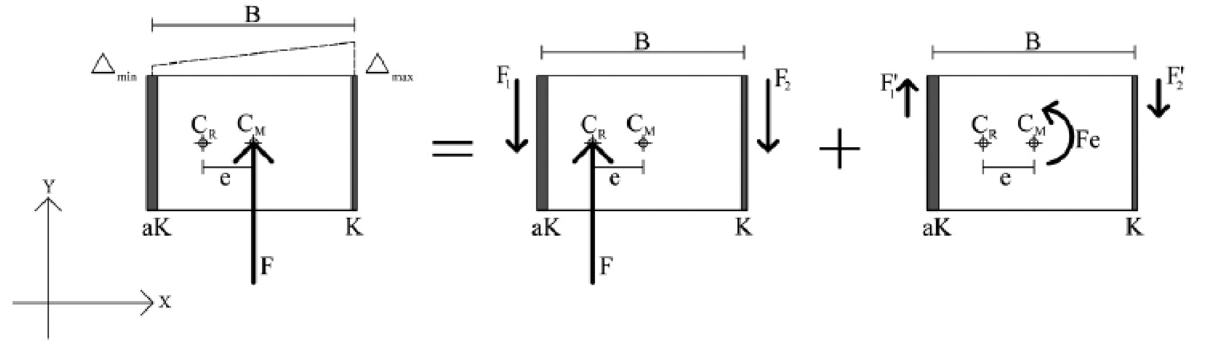

Figure 8.
Simple idea for calculation of the eccentricity of third criterion

1. Load distribution based on the ratio of rigidity with assumption that load is applied to the center of rigidity:

$$\frac{aK}{(1+a)\times K}=\frac{F_1}{F}\longrightarrow F_1=\frac{aF}{1+a}$$

$$\frac{K}{(1+a)\times K}=\frac{F_2}{F}\longrightarrow F_2=\frac{F}{1+a}$$

2. Center of Rigidity:

$$BK=(1+a)\times Kx\longrightarrow x=\frac{B}{1+a}\longrightarrow$$

$$\longrightarrow e=\frac{B}{2}-\frac{B}{1+a}$$

3. Forces due to moment of $F\cdot e$:

$$F_1'=F_2'$$

4. Equilibrium Equation:

$$F_1'\left(\frac{B}{1+a}\right)+F_2'\left(B-\frac{B}{1+a}\right)=F\left(\frac{B}{2}-\frac{B}{1+a}\right)$$

$$F_1'B=F\left(\frac{B}{2}-\frac{B}{1+a}\right)\longrightarrow F_1'=F\left(\frac{a-1}{2(a+1)}\right)$$

5. Criteria of $\frac{\Delta_{max}}{\Delta_{ave}}$:

$$\frac{\Delta_{max}}{\Delta_{ave}}\leq 1.2\longrightarrow \Delta_{max}\leq 1.2\left(\frac{\Delta_{min}+\Delta_{max}}{2}\right)\longrightarrow$$

$$\longrightarrow 0.4\Delta_{max}\leq 0.6\Delta_{min}\longrightarrow \Delta_{max}\leq 1.5\Delta_{min}$$

$$\Delta_{max}=\frac{F_2+F_2'}{K}=\frac{F\left(\frac{1}{1+a}+\frac{a-1}{2(a+1)}\right)}{K}=\frac{F}{2K}$$

$$\Delta_{min}=\frac{F_1-F_1'}{aK}=\frac{F\left(\frac{a}{1+a}-\frac{a-1}{2(a+1)}\right)}{K}=\frac{F}{2aK}$$

$$1.5\times\frac{F}{2aK}=\frac{F}{2K}\longrightarrow a=1.5$$

6. The amount of eccentricity (Distance between center of mass and center of rigidity):

$$e=\frac{B}{2}-\frac{B}{1+a}=\frac{B}{2}-\frac{B}{2.5}=0.1B$$

$\boldsymbol{e=0.1B}$

Table 2.
The accidental eccentricity in six seismic codes

Standard No. 2800 of Iran	ASCE 7-10	IS 1893 of India	Seismic code of Turkey	NBC 105, 201 of Nepal	NZS 1170.5 of New Zealand
5%	5%	5%	5%	0 (*) 10% (*)	10%

*: According to what is described in second criteria of section 3.1.

Table 3.
Summarized provisions of torsional irregularity of six seismic codes

	Standard No. 2800 of Iran	ASCE 7-10	IS 1893 of India	Seismic code of Turkey	NBC 105, 201 of Nepal	NZS 1170.5 of New Zealand
The distance between center of mass and center of stiffness	5% (*) 20% (*)	-	-	-	10%	-
The ratio of the maximum relative story drift to the average relative story drift	1.2	1.2	1.2	1.2	-	1.4

*: According to what is described in second criteria of section 3.1.

3.2. Evaluation Criteria of Soft Story

For evaluating soft story, two criteria are considered as below. Summarized provisions of stiffness irregularity of the investigated standards are presented in Table 4.

1. **The ratio of lateral stiffness of each story to the story above**: In Table 12.3.2 of ASCE 7-10, section 1-7-2-e of standard No. 2800, Table 5 of IS 1893 and section 4.5.1.2 of NZS 1170.5 as a condition of vertical regularity, the lateral stiffness of each story shall not be less than 70% of that in the story above or 80% of the average stiffness of the three stories above [30, 33, 34, 36].
2. **The ratio of the average relative story drift at any story to the story immediately above or below**: In Table 2.1 of seismic code of Turkey as a condition of inter story stiffness irregularity (soft story) it has been indicated that Stiffness Irregularity Factor which is defined as the ratio of the average relative story drift at any story to the average relative story drift at the story immediately above or below, is greater than 2 in each of the two orthogonal directions, ±%5 additional eccentricities shall be considered in calculation [35].

4. RESULTS

In calculating the fundamental period, the effective stiffness of the cracked section has been considered. This is done by considering the moment of inertia for beam equal to 0.5 Ig and for columns equal to Ig. These values are 1.5 times of moment of inertia for cracked sections. In the following, the outputs of analysis are presented and the vulnerability of structure in terms of torsion and soft story is also evaluated.

4.1. Results of Torsion Evaluation

First three modes of modal analysis are presented in Tab. 5, and structure movements illustrated in Fig. 9. According to these results of simulation, torsion occurs at second mode of modal analysis for infilled frame, while this is not expected for bare frame. The results in Tab. 6 and Fig. 10 show that the distance between CM and CR along Y axis is greater than 10% of building dimension, it also confirms torsion of the structure in construction conditions. Comparison of eccentricity in bare frame with infilled frame in Table 6 shows that structure in construction condition has to resist greater moment of torsion than that is considered in design process. This is variable from 1.25 of design amount in first floor to 2.4 of design amount in fifth floor along Y axis.

The ratios of the maximum relative story drift to the average relative story drift with accidental eccentricity of 5% are summarized in Tab. 7 and Fig. 11. In case of infilled frame, the ratios along X axis with negative accidental eccentricity in first to fourth story are close to 1.2 and in fifth story is more than 1.2, this means torsional irregularity. Same ratios for accidental eccentricity of 10% are summarized in Tab. 8. The results along X axis with negative accidental eccentricity are more than 1.2 but less than 1.4 and based on provision of NZS. 1170.5.2004, they are acceptable. The symbols in Tab. 7, 8 and Fig. 11 are described in the following:

EQX: Earthquake load in X direction

EQXP: Earthquake load in X direction with positive eccentricity

EQXN: Earthquake load in X direction with negative eccentricity

EQY: Earthquake load in Y direction

EQYP: Earthquake load in Y direction with positive eccentricity

EQYN: Earthquake load in Y direction with negative eccentricity

Table 4.
Summarized provisions of stiffness irregularity of six seismic codes

	Standard No. 2800 of Iran	ASCE 7-10	IS 1893 of India	Seismic code of Turkey	NBC 105 of Nepal	NZS 1170.5 of New Zealand
The ratio of lateral stiffness of each story to the story above	70%	70%	70%	-	-	70%
The ratio of lateral stiffness of each story to the average of the three stories above	80%	80%	80%	-	-	80%
The ratio of the average relative story drift at any story to the story immediately above or below	-	-	-	2	-	-

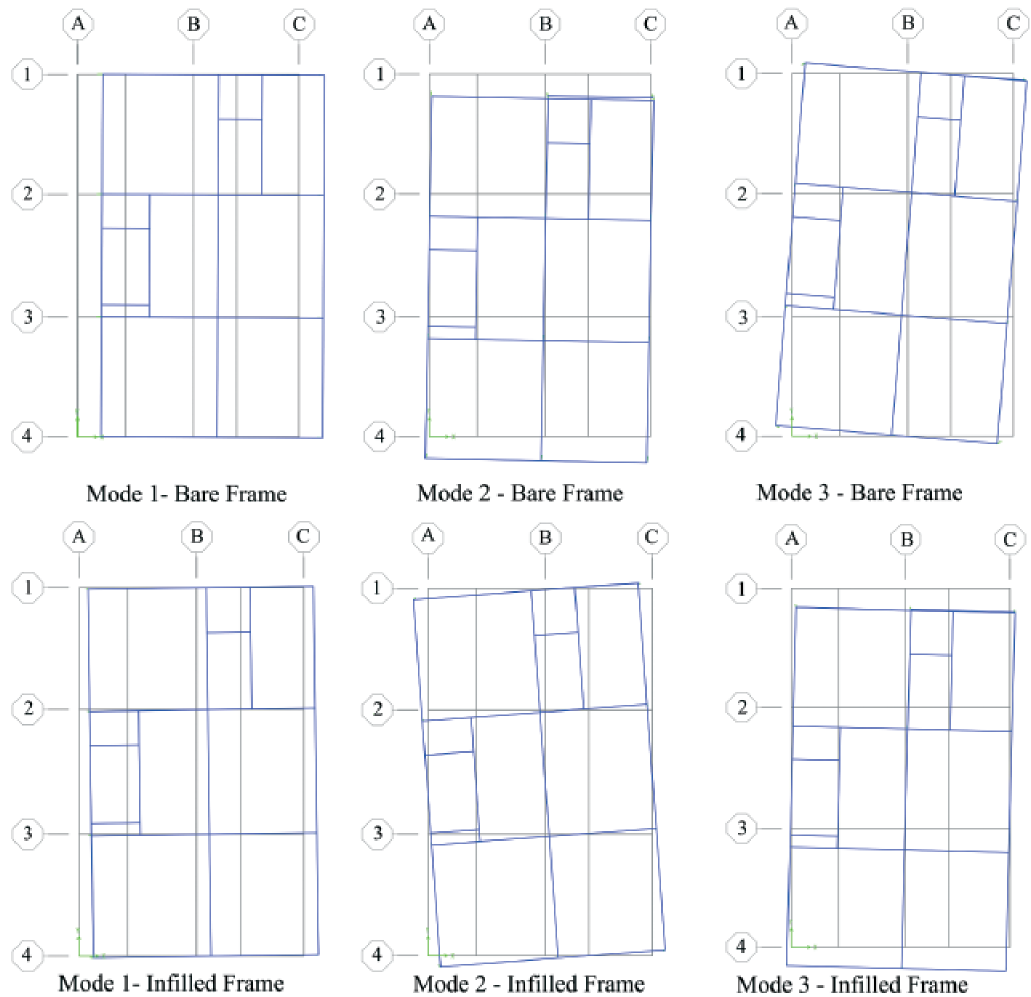

Figure 9.
The first three modes of modal analysis

Table 5.
The fundamental vibration periods of building in first three modes of modal analysis

	Mode 1				Mode 2				Mode 3			
	Period[s]	Dir.	UX	UY	Period [s]	Dir.	UX	UY	Period[s]	Dir.	UX	UY
Bare Frame	1.015	X	73.75	0.002	0.965	Y	0.008	73.43	0.823	T	0.188	1.044
Infilled Frame	0.890	X	74.93	0.000	0.620	T	1.360	3.372	0.589	Y	0.049	77.04

Table 6.
The distance between CM and CR to building dimension at two directions

	STORY 1		STORY 2		STORY 3		STORY 4		STORY 5	
	%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey
Bare Frame	4.264	6.609	2.652	6.497	2.316	5.583	1.883	5.007	-1.461	2.285
Infilled Frame	4.026	9.490	2.511	11.470	4.524	12.570	6.190	13.483	6.017	12.477

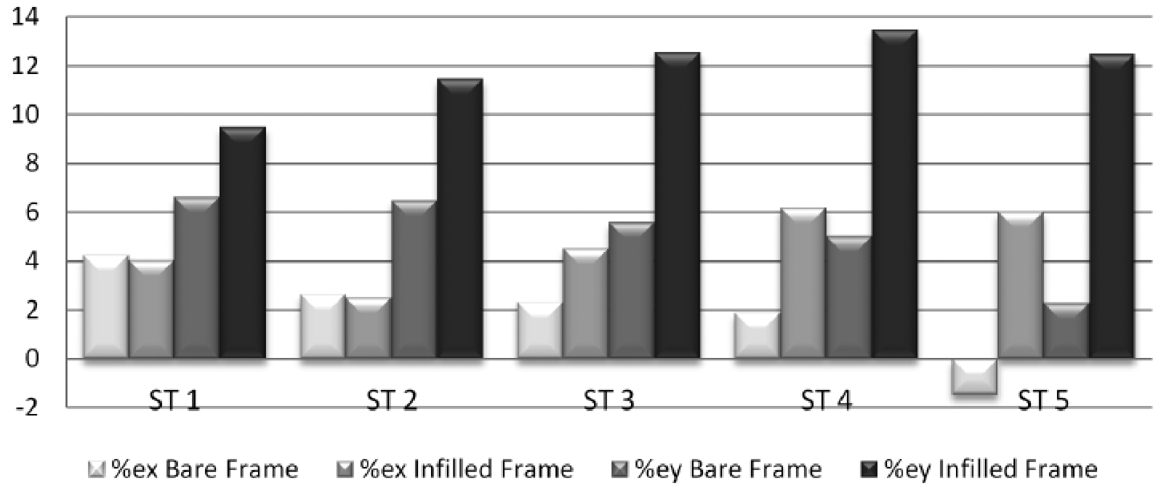

Figure 10.
The distance between CM and CR to building dimension at two directions

Table 7.
Ratio of the maximum relative story drift to the average relative story drift with accidental eccentricity of 5%

	EQX	EQXP	EQXN	EQY	EQYP	EQYN
STORY 1						
Bared Frame	1.0220	1.0667	1.1196	1.0114	1.0455	1.0227
Infilled Frame	1.0933	1.0135	1.1579	1.0000	1.0526	1.0263
STORY 2						
Bared Frame	1.0000	1.0952	1.0872	1.0139	1.0486	1.0208
Infilled Frame	1.0982	1.0364	1.1681	1.0217	1.0870	1.0652
STORY 3						
Bared Frame	1.0000	1.1146	1.0667	1.0223	1.0615	1.0223
Infilled Frame	1.1203	1.0611	1.1765	1.0000	1.0208	1.1020
STORY 4						
Bared Frame	1.0326	1.1257	1.0598	1.0237	1.0651	1.0059
Infilled Frame	1.1282	1.0696	1.1849	1.0769	0.9744	1.1500
STORY 5						
Bared Frame	1.0307	1.1173	1.0671	1.0667	1.1067	0.9664
Infilled Frame	1.1596	1.1087	1.2105	1.0741	1.0385	1.1111

Table 8.
Ratio of the maximum relative story drift to the average relative story drift with accidental eccentricity of 10%

	EQX	EQXP	EQXN	EQY	EQYP	EQYN
STORY 1						
Bared Frame	1.0220	1.1685	1.2043	1.0114	1.0909	1.0682
Infilled Frame	1.0933	1.0411	1.2208	1.0000	1.1053	1.0789
STORY 2						
Bared Frame	1.0000	1.1849	1.1800	1.0139	1.0764	1.0556
Infilled Frame	1.0982	1.0370	1.2261	1.0217	1.1304	1.1304
STORY 3						
Bared Frame	1.0000	1.2094	1.1582	1.0223	1.1006	1.0559
Infilled Frame	1.1203	1.0078	1.2391	1.0000	1.0833	1.1600
STORY 4						
Bared Frame	1.0326	1.2143	1.1576	1.0237	1.1006	1.0414
Infilled Frame	1.1282	0.9912	1.2500	1.0769	1.0789	1.2000
STORY 5						
Bared Frame	1.0307	1.2174	1.1506	1.0667	1.1391	1.0068
Infilled Frame	1.1596	0.9560	1.2449	1.0741	1.0769	1.2222

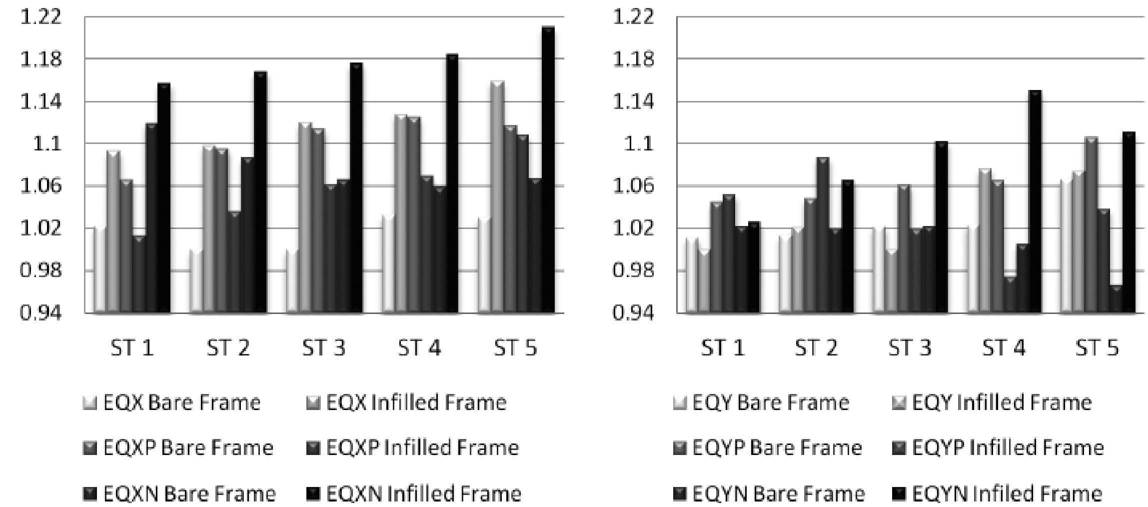

Figure 11.
Ratio of the maximum relative story drift to the average relative story drift with accidental eccentricity of 5%

Table 9.
The ratio of story stiffness at two directions for controlling soft story

Unit: N/mm	STORY 1					
	K_x	K_{x1}/K_{x2}	$K_{x1}/((K_{X2}+K_{x3}+K_{x4}))/3)$	K_y	K_{y1}/K_{y2}	$K_{y1}/((K_{y2}+K_{y3}+K_{y4}))/3)$
Bare Frame	122951	1.76	2.41	126404	1.76	2.34
Infilled Frame	151515	1.62	2.07	312500	1.34	1.56

Unit: N/mm	STORY 2					
	K_x	K_{x2}/K_{x3}	$K_{x2}/((K_{X3}+K_{x4}+K_{x5}))/3)$	K_y	K_{y2}/K_{y3}	$K_{y2}/((K_{y3}+K_{y4}+K_{y5}))/3)$
Bare Frame	69876	1.54	1.84	71885	1.47	1.72
Infilled Frame	93555	1.40	1.58	233161	1.23	1.30

Unit: N/mm	STORY 3				STORY 4				STORY 5	
	K_x	K_{x3}/K_{x4}	K_y	K_{y3}/K_{y4}	K_x	K_{x4}/K_{x5}	K_y	K_{y4}/K_{y5}	K_x	K_y
Bare Frame	45409	1.21	48966	1.18	37594	1.21	41436	1.18	31163	35019
Infilled Frame	66667	1.13	189076	1.06	58901	1.12	178571	1.04	52570	171103

Table 10.
The ratio of the average relative story drift for controlling soft story

	EQX		EQXP		EQXN		EQY		EQYP		EQYN	
	Drift x S_i/S_{i+1}	Drift x S_i/S_{i-1}	Drift x S_i/S_{i+1}	Drift x S_i/S_{i-1}	Drift x S_i/S_{i+1}	Drift x S_i/S_{i-1}	Drift x S_i/S_{i+1}	Drift x S_i/S_{i-1}	Drift x S_i/S_{i+1}	Drift x S_i/S_{i-1}	Drift x S_i/S_{i+1}	Drift x S_i/S_{i-1}
STORY 1												
Bare Frame	0.55	-	0.55	-	0.56	-	0.55	-	0.55	-	0.55	-
Infilled Frame	0.60	-	0.61	-	0.61	-	0.74	-	0.74	-	0.74	-
STORY 2												
Bare Frame	0.77	1.81	0.77	1.81	0.76	1.80	0.80	1.82	0.80	1.82	0.80	1.82
Infilled Frame	0.84	1.66	0.84	1.65	0.83	1.65	0.94	1.35	0.96	1.35	0.94	1.35
STORY 3												
Bare Frame	1.05	1.30	1.05	1.31	1.06	1.31	1.06	1.24	1.06	1.24	1.06	1.24
Infilled Frame	1.14	1.19	1.14	1.19	1.14	1.20	1.26	1.07	1.23	1.04	1.23	1.07
STORY 4												
Bare Frame	1.13	0.95	1.13	0.95	1.12	0.94	1.13	0.94	1.13	0.94	1.13	0.94
Infilled Frame	1.24	0.88	1.25	0.88	1.25	0.88	1.44	0.80	1.50	0.81	1.48	0.82
STORY 5												
Bare Frame	-	0.89	-	0.89	-	0.89	-	0.89	-	0.89	-	0.88
Infilled Frame	-	0.80	-	0.80	-	0.80	-	0.69	-	0.67	-	0.68

4.2. Results of Soft Story Evaluation

To control the soft story, a point in center of mass of upper floor has been defined and connected to the diaphragm. To calculate the story stiffness, the force of 5% of building weight, equal to 45 KN in each direction applied to the point and displacement has been calculated [7]. The story stiffness in each direction is calculated by dividing the force by relative displacement in the same direction. K_x is the story stiffness in X direction and K_y is the story stiffness in Y direction. The results presented in Tab. 9 show there is no soft story neither in infilled frame nor in bare frame. To control the provision of seismic code of Turkey, the ratio of the average relative story drift at any story to the story immediately above and below have been calculated and results are presented in Tab. 10. All the results are less than 2 and it also confirms that the soft story does not occur.

5. MODIFYING ARCHITECTURAL DRAWINGS

As mentioned in introduction, it is tried to reduce irregularity effects of infill walls through architectural design. Accordingly, to achieve symmetrical arrangement of walls in plan and continuous walls in elevation, in order to prevent torsion and soft story, five main measures are possible in architectural design. For maximum use of walls potential, first measures 2 to 4 should be done with the aim of increasing infill walls in low density part of plan and elevation and then they should be done with the aim of decreasing infill walls in high density part of plan and elevation:

1. The first measure is to consider continuous and symmetrical arrangement of infill walls in concept design and in arrangement and adjacency of spaces in initial stages of architectural design. If it is not achieved in this stage, without fundamental changes in functional and aesthetic aspects and the sense of space, following modifications can be done.
2. Slight movement of structural axes to increase or decrease infill walls where it is required.
3. Slight change in the size of spaces to increase or decrease infill walls where it is required.
4. According to a simple but practical approach in New Zealand assessment code, if an infill is pierced with either a door or window opening, then the strength and stiffness may be reduced by the factor $\lambda_{Opening}$ given by Eq. (1). If the opening length exceeds two-thirds of the bay length, it may be assumed that the infill has no influence on the system performance. In this paper, the minimum reduction factor is assumed 0.25 to consider the stiffness of infill walls in arrangement of walls in plan and elevation, so the maximum length of opening shall be half of the wall length. In architectural design, it is possible to reduce the opening length of walls which are located in low density part of the plan and the opening length of discontinuous walls in soft story to the extent that natural lighting and ventilation and landscape view are not lost. On the contrary, it is possible to increase length of opening to reduce infill walls where it is useful.
5. As a final action in architectural design, separating infill walls from frames in high density part of the plan and separating discontinuous infill walls from frames in upper floors of soft story is recommended.

Based on the results of analysis, there is no risk of torsion for bare frame, but infilled frame may suffer torsion in the earthquake. Soft story will occur neither in infilled frame nor in bare frame. So in Fig. 12 an algorithm for modifying architectural drawings in order to prevent torsion caused by asymmetric distribution of infill walls is proposed, this is based on 5 measures that are discussed above. Red parts of the chart are related to increasing infill walls and blue parts are related to decrease infill walls.

In the following, four modifications are recommended for the studied case. It is assumed that the concept, arrangement and adjacency of spaces are finalized and could not be changed, so architectural drawings could be modified to the extent that functional and aesthetic aspects are not lost. In this way, the regular plan will be achieved and only the potential of three walls will be lost by separating from frame (Fig. 13):

1. Moving axis 2 to 20 cm upward. In this way, wall 2-BC will not be located on axis 2 of the structure.
2. Changing two windows with a width of 2.4 m which are located on axis 4 of parking in ground floor to three windows with a width of 1.2 m. This is sufficient for lighting and ventilation based on Iranian national building code-part 4.
3. Eliminating left window of middle bedroom in residential floors. This is sufficient for lighting and ventilation based on Iranian national building code – Part 4, too.
4. Separating wall C-23 from the structure in three upper floors.

After modifying architectural drawings, a new infilled frame was modelled in structural analysis software. The results which are not passed for infilled frame

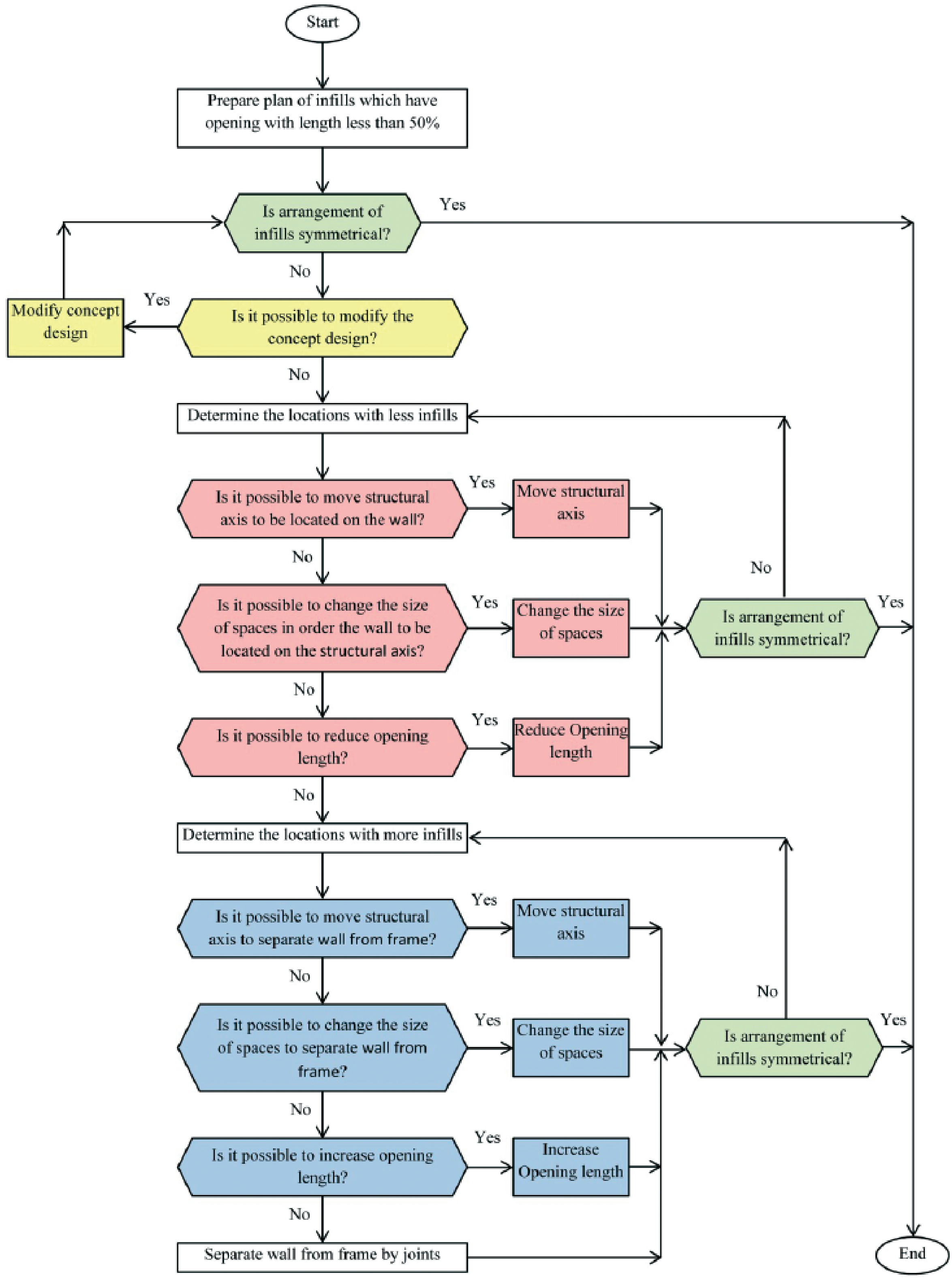

Figure 12.
Algorithm for modifying architectural drawings in order to prevent torsion caused by asymmetric distribution of infill walls

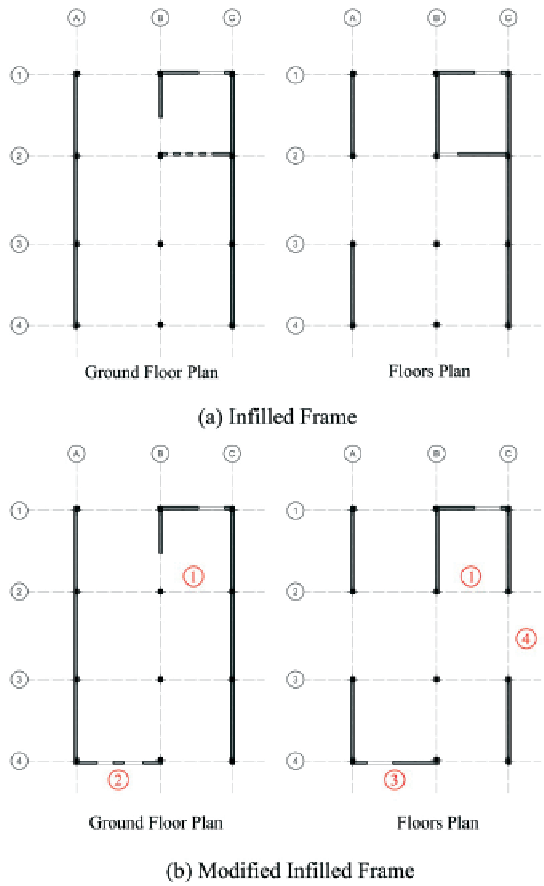

Figure 13.
Arrangement of infills

are presented as follows. Based on first three modes of modal analysis which are presented in Table 11 and structure movements illustrated in Fig. 14, torsion occurs at third mode of modal analysis for modified infilled frame like bare frame. The results in Table 12 show that the distance between CM and CR along two axes are less than 10% of building dimension and the ratios of the maximum relative story drift to the average relative story drift which are summarized in Table 13 are less than 1.2. So the irregularity of infilled frame in plan is modified by some architectural modifications and it is not expected that torsion occur during earthquakes.

6. CONCLUSIONS

Conclusion of this case study in two states of bare frame and infilled frame for analyzing design condition and construction condition has been presented in two sections as follows:

Torsion: The building in construction condition will suffer torsion in the earthquake because the infill walls which are not modelled in design process are attached to the structure in construction phase. Since this research has been done on a residential building in southern lot with the most symmetrical arrangement of infill walls, the results increase the importance of studying arrangements and connections of walls in other buildings such as ones located in northern or corner lots.

Soft Story: Contrary to the initial impression that there is a soft story in municipal buildings because of

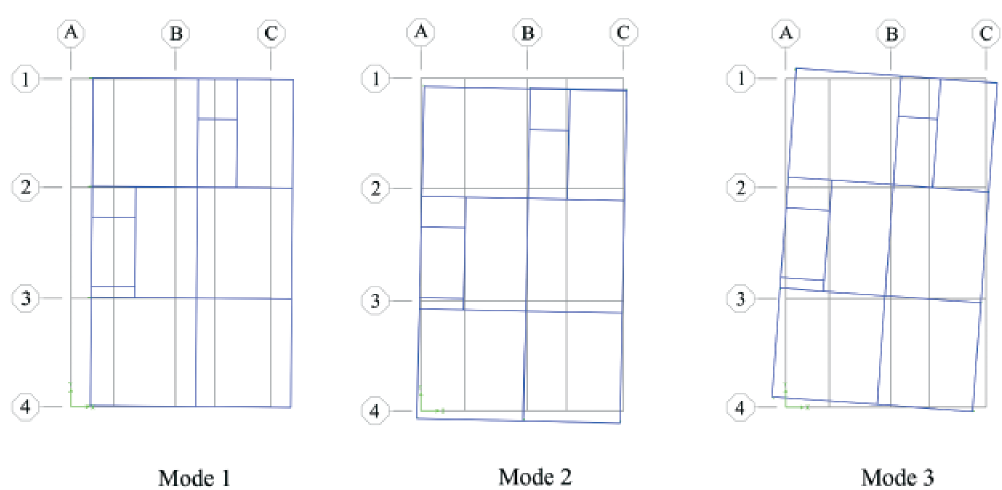

Figure 14.
The first three modes of modal analysis for modified infilled frame

Table 11.
The fundamental vibration periods of building in first three modes of modal analysis after architectural modification

Mode 1				Mode 2				Mode 3			
Period [s]	Dir.	UX	UY	Period [s]	Dir.	UX	UY	Period [s]	Dir.	UX	UY
0.884	X	76.16	0.00	0.618	Y	0.10	50.13	0.594	T	0.23	28.56

Table 12.
The distance between CM and CR to building dimension at two directions after architectural modification

STORY 1		STORY 2		STORY 3		STORY 4		STORY 5	
%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey
4.015	6.285	2.262	5.642	2.013	4.152	1.742	3.146	-0.097	-0.232

Table 13.
Ratio of the maximum relative story drift to the average relative story drift with accidental eccentricity of 5% after architectural modification

	EQX	EQXP	EQXN	EQY	EQYP	EQYN
STORY 1	1.0135	1.0685	1.0811	1.0135	1.0811	1.0270
STORY 2	1.0091	1.0818	1.0270	1.0091	1.0625	1.0208
STORY 3	1.0382	1.0992	1.0231	1.0382	1.0926	1.0370
STORY 4	1.0619	1.1150	0.9912	1.0619	1.0652	1.0000
STORY 5	1.0556	1.1111	0.9889	1.0556	1.1250	1.0323

parking and open spaces on ground floor, in buildings with architectural plan similar to the analyzed one, because of high stiffness ratio of structure in the bottom floors to the top floors and longitudinal walls along adjacent neighbors lots in all floors, soft story would not happen with a high safety factor.

This case study proves that it is possible to prevent irregularity effects of infills through modifying architectural drawings. For modifying architectural drawings an algorithm is proposed in this research. These modifications include slight changes in size of spaces and structural axes, reducing the opening length and separating some infill walls from structure without fundamental changes in concept, functional and aesthetic aspects. This is valuable because there is poor collaboration between architects and structural engineers in design and construction of conventional residential buildings and controlling seismic behavior of infill walls are usually neglected. Since architects determine arrangement and adjacency of spaces, size of opening, material and construction details, they can easily achieve continuous and symmetrical arrangement of infill walls by a few modifications.

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