EFFECT OF INFILLS ON TORSION AND SOFT STOREY IN A CONVENTIONAL RESIDENTIAL BUILDING IN TEHRAN-IRAN

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ABSTRACT

Masonry infill walls are usually consideredas non-structural elements, so analysis and design of structures are based on the bare frames.Butmany experiences of past earthquakes show that some designed and constructed buildings by engineers have been damaged during earthquakes because of disregarding the negative effects of walls.

The main goal of this paper is to evaluate the amount of overall detrimental effects of infill walls such as torsion and soft storeyin conventional buildings.A5-storey residential building in Tehran has been selected as a case study.For studying the effects of infill walls in seismic behaviour of structures, simulations have been performed with and without walls to compare construction condition with design condition based on linear static method. To model infill walls an equivalent compression diagonal strut has been used.

As a result of this case study it can be said that the building in construction condition will suffer torsion because of infill walls which are not modelled in design process but connected to the structure in implementation. Since this research has been done on a residential building in southern lot with the most symmetrical arrangement of infill walls, it increases the importance of studying arrangements and connections of walls in other buildings such as ones located in northern or corer lots. Contrary to the initial impression that there is a soft storey in urban buildings because of parking and open spaces on ground floor, in buildings with architectural design similar to the analysedone, due to the high stiffness ratio of the structure on ground floor to the upper floors, soft storey would not happen with a high safety factor.

INTRODUCTION

Nowadays structural engineers usually consider masonry infill walls as non-structural elements during analysis and design process of buildings (MondalandJain, 2008;Tsai and Huang, 2009; Rodrigues et al, 2010; Pradhan et al, 2012;Noorifardet al, 2014) and only calculate their weight. Consequently, analysis and design of the structures are based on the bare frames without the effects of infills(MostafaeiandKabeyasawa, 2004; Pradhan et al, 2012; Noorifardet al, 2014).Experiences of past earthquakes show that some designed and constructed buildings by engineers have been damaged during earthquakes because of disregarding the negative effects of walls(Tabeshpour, 2009; Rodrigues et al, 2010).Althoughseismicstandardssuch asstandard No. 2800implicitly takeinto accountinfill walls in calculation and determination of seismic forces butthey areoftenneglected.In fact, despite special attention to seismic resistant design of structures, disregarding to infill walls willcauseloss of lifeand property(Mahdi Tet al, 2010).

Structures with simple and regular geometry performwell 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 (Mahdi et al, 2010; Tabeshpour et al, 2012). Unfortunately these irregular buildings constitute a large portion of the modern urban buildings (DubeyandSangamnerkar, 2011) 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 (Dubey and Sangamnerkar, 2011). A significant part of torsional effects created by inappropriatedistribution of stiffness in buildings is the result of arrangement of walls(Tabeshpour, 2009;Moghaddam et al, 2010; Charleson, 2011; Aliaari and Memari, 2005; Key,1988; Vicente et al, 2012; Özmen and Ünay, 2007) (Fig.1).Sometimes,in spiteofdesigning regularstructuresinelevation, due to reducing or eliminating infill walls in adjacent floors, vertical irregularityoccurs (Mahdi et al, 2010; Özmen andÜnay, 2007; Asteris, 2003; Zhao, et al, 2009; Arnold, 2006; Mulgund and Kulkarni, 2011; Yatağan, 2011) andsoft story is formed in an earthquake (Fig. 2).

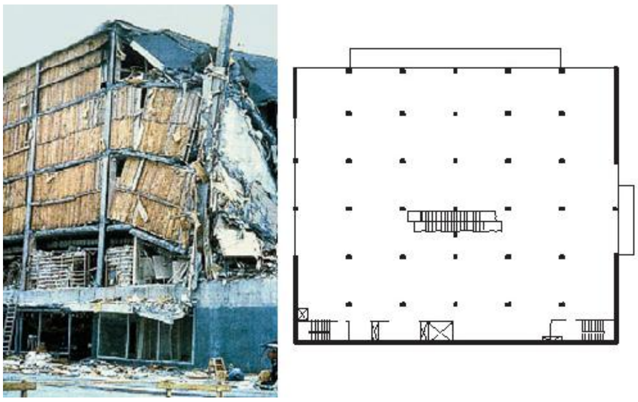

Figure1.J. C. Penneybuildingwas destroyed during the 1964 Alaska earthquake because of torsional effect formed by arrangement of walls (Arnold, 2006)

Figure 2.Soft storey in the 1999kocaeli (Turkey) earthquake due to elimination of masonry infill wall in ground floor(Yatağan, 2011)

The main goal of this paper is to evaluate the amount of detrimental effects of infill walls in conventional buildings.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, a 5-storey residential building in a south lot with a width of 10 m in Tehran has been selected as a case study. In selected building, parkingis locatedon the ground floorandfourupper floors areresidential. Eachfloorcontains asetresidentialunit with three bedrooms. Bedroomslocated on south side and stairandliving roomon north sideof the building. Due tothe separation ofpublic, semi-privateand privatezones, askylightfor lightingand ventilation ofthe kitchenis designedin middle ofwest side(Fig.3).

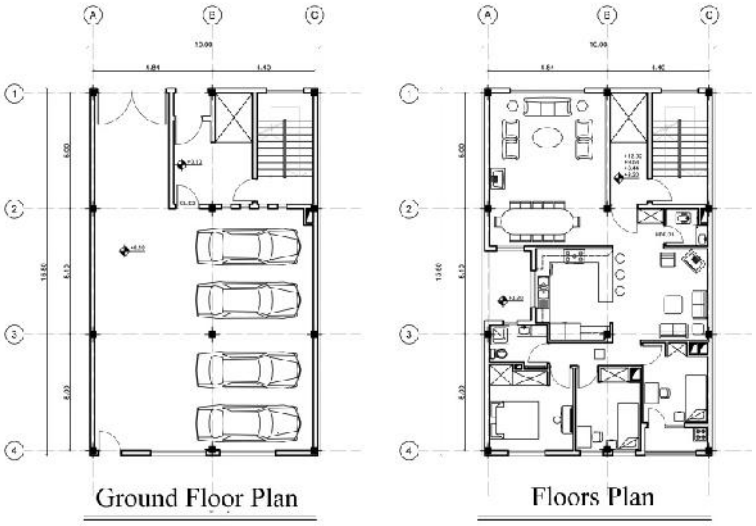

Figure 3.Architectural Plans

ANALYTICAL MODELLING

For studying the effects of infill walls in seismic behaviour of structures, simulations are performed by a structural analysis and design software for two cases; with and without walls to compare construction condition with design condition. In both cases, seismic force has been calculated based on period of infilledframewhich is 80% ofempirical period of bare frame according to standard No. 2800. In this paper designed IF has been used for first condition or designed infilled frame and constructed IF has been used for second condition or constructed infilledframe.Since linear static method is used in structural calculation of conventional buildings, this method is selected for analytical modelling.

MATERIAL PROPERTIES AND DESIGN GRAVITY FORCES

Since infill walls have the most influences on seismic behaviour of reinforced concrete moment frames, so the structural system of selected building is 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 by hollow clay block with a thickness of 20 cm and interior walls by hollow clay block with a thickness of 10 cm.Building cladding and inner layer of stair walls are granitetiles and inside ofwalls and ceilings are coatedby2-cm-thick gypsum and clay plaster and 1-cm- thick gypsum plaster. According to these introduced material, design forces have been determined based on requirements of the Iraniannational building code-part 6.

Table 1.Concrete and rebar properties

Density	Modulus of Elasticity	Poisson's Ratio	Coefficient of Thermal Expansion	f'c Concrete compressive Strength	fy Bending Reinforcement Yield Stress	fys Shear Reinforcement Yield Stress
kgf/m^3	kgf/cm^2	-	1/°c	kgf/cm^2	kgf/cm^2	kgf/cm^2
2500	2.5E5	0.15	1E-5	250	4000	4000

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 of7. 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.

MODELLING OF INFILL WALLS

As it is tried to study detrimental overall effects of walls such as torsion and soft storey, so simulation is based on macro model. In this method infill walls are modelled with an equivalent compression diagonal strut. Modulus of elasticityhas been assumed 800 times of compressive strength of wall, the effective width of equivalent strut, 0.2 times of wall diameter (Tabeshpour et al, 2012; Tabeshpour, 2013) and thicknessof strut, the same as wall.

Dimensions of 9holes 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. Since the assumptions presented in top paragraph are based on previous researches done on 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 hollowclayblock and cement mortar is 39 kg/cm^2 (Shahnazari, 1998).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 (NZSEE, 2006).

$$\lambda_{\text{Opening}} = 1 - \frac{1.5\, L_{\text{Opening}}}{L_{\text{inf}}} \tag{1}$$

EVALUATION CRITERIA

Since the main goal of this paper is to investigate the influence of infill walls on formation of torsion and soft story in buildings, therefore, the evaluation criteria of these two phenomena for assessingthe outputs of analyses are discussed in the following.

EVALUATION CRITERIA OF TORSION

For evaluating torsion, three criteria are considered as bellow:

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 stiffness:**According to the section 1-5-3 of standard No. 2800, 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, be less than 5% of the building dimension in that level in direction under consideration. In section 1-8-1-1-b of standard No.2800 as a condition of plan regularity, in each story, the distance between the center of mass and stiffness in each orthogonal directionshall not exceed 20% of building dimension in that direction (Standard No 2800-05, 2005).In this standard there is no mandatory for the maximum allowable amount of eccentricity, butin Nepal National Building code (NBC 201), the distance between center of mass and center of rigidity including the effects of infill wallshall be less than 10% of building dimension at the same direction(NBC 201, 1994).
3. **The ratio of the maximum relative storey drift to the average relative storey drift:**Intable 9.5.2.3.2 of ASCE 7-02standard and in section 1-8-1-1-e of standard No.2800 as a condition of plan regularity, in each storey the maximum drift, including accidental torsion, at one end of the structure shall not exceed 20% of the average of the storey drift of the two ends of the structure (ASCE 7-02, 2003; Standard No. 2800-05, 2005).

EVALUATION CRITERIA OF SOFT STOREY

In table 9.5.2.3.3 of ASCE 7-02 standard and in section 1-8-1-2-b of standard No.2800 as a condition of vertical regularity, the lateral stiffness of each story shall not be less than 70% of that in the storey above or 80% of the average stiffness of the three stories above (ASCE 7-02, 2003; Standard No. 2800-05, 2005).

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. Thesevalues are 1.5 times ofmoment 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 storey is also evaluated.

RESULTS OF TORSIONEVALUATION

First three modes of modal analysis are presented in table 2, and structure movements illustrated in Fig 4. According to these results of simulation, torsion occurs at second mode of modal analysis for constructed infilled frame, while this is not expected for designed infilledframe.It should be noted that torsional effects of short column like C1, B4 are neglected in simulation, it may increase torsional vulnerability. The results in table 3and Fig 5show that the distance between CM and CR along Y axis is greater than10% of building dimension, it also confirms torsion of the structure in construction conditions. Comparison of eccentricity in design condition with construction condition in table 3 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.

Ratios of the maximum relative storey drift to the average relative storey drift are summarized in table 4 and Fig 6.However, these are less than 1.2 but in the case of constructed infilled frame, ratios along X axis with considering negative accidental eccentricity are close to 1.2.

Table 2: The fundamental vibration periods of building in first three modes of modal analysis

	Mode 1				Mode 2				Mode 3			
	Period	Dir.	UX	UY	Period	Dir.	UX	UY	Period	Dir.	UX	UY
Designed IF	1.015	X	73.75	0.002	0.965	Y	0.008	73.43	0.823	T	0.188	1.044
Constructed IF	0.890	X	74.93	0.000	0.620	T	1.360	3.372	0.589	Y	0.049	77.04

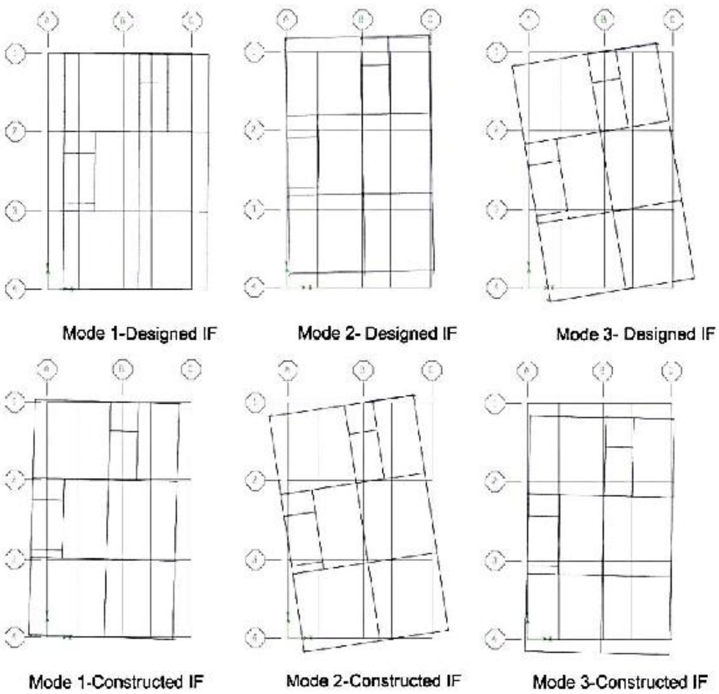

Figure 4: The first three modes of modal analysis

Table 3:Thedistancebetween CM and CRto building dimension at two directions

	STOREY 1		STOREY 2		STOREY 3		STOREY 4		STOREY 5	
	%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey
Designed IF	4.264	6.609	2.652	6.497	2.316	5.583	1.883	5.007	-1.461	2.285
Constructed IF	4.026	9.490	2.511	11.470	4.524	12.570	6.190	13.483	6.017	12.477

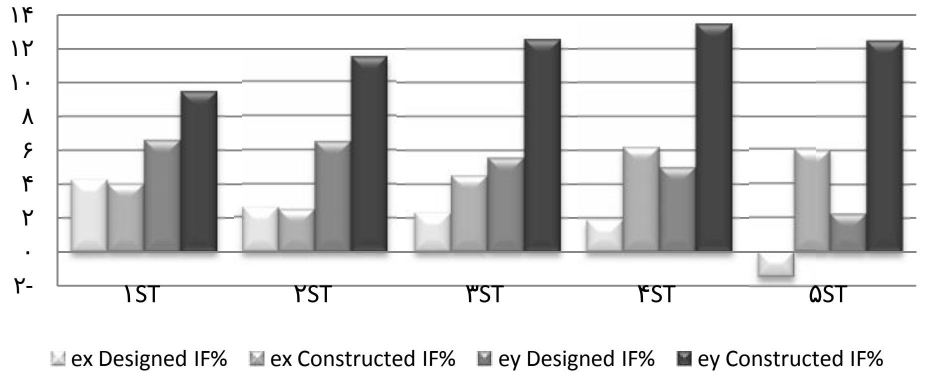

Figure 5:Thedistancebetween CM and CRto building dimension at two directions

Table 4: Ratio of the maximum relative storey drift to the average relative storey drift

	EQX	EQXP	EQXN	EQY	EQYP	EQYN
	Δ max/Δ ave	Δ max/Δ ave	Δ max/Δ ave	Δ max/Δ ave	Δ max/Δ ave	Δ max/Δ ave
STOREY 1						
Designed IF	1.0250	1.0680	1.1170	1.0120	1.0480	1.0240
Constructed IF	1.0920	1.0220	1.1600	1.0170	1.0700	1.0350
STOREY 2						
Designed IF	1.0080	1.0850	1.1000	1.0130	1.0490	1.0230
Constructed IF	1.0970	1.0300	1.1620	1.0110	1.0680	1.0440
STOREY 3						
Designed IF	1.0050	1.0980	1.0870	1.0160	1.0530	1.0200
Constructed IF	1.1060	1.0410	1.1700	1.0100	1.0500	1.0690
STOREY 4						
Designed IF	1.0140	1.1060	1.0780	1.0200	1.0560	1.0170
Constructed IF	1.1120	1.0490	1.1740	1.0240	1.0370	1.0850
STOREY 5						
Designed IF	1.0160	1.1090	1.0760	1.0300	1.0660	1.0070
Constructed IF	1.1200	1.0580	1.1800	1.0320	1.0310	1.0940

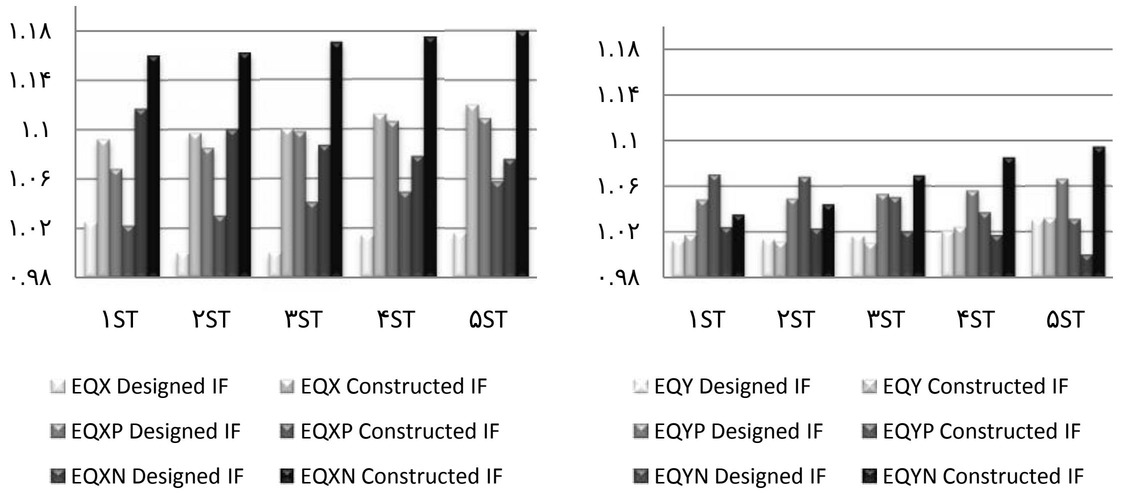

Figure 6:Ratio of the maximum relative storey drift to the average relative storey drift

RESULTS OF SOFT STOREYEVALUATION

To control the soft storey, a point in center of mass of upper floor has been defined and connected to the diaphragm. To calculate the stiffness of floors, the force of 5% of building weight, equal to 4500 kgfin each direction applied to the point and displacement has been calculated.The results presented in table 5 shows that there is no soft storey neither in constructed infilled frame nor in designed infilled frame.

Table 5: The ratio of storey stiffness at two directions for controlling soft storey

Unit: kgf, m	STOREY 1					
	K_x	K_{x1}/K_{x2}	$K_{x1}/((K_{x2}+K_{x3}+K_{x4})/3)$	K_y	K_{y1}/K_{y2}	$K_{y1}/((K_{y2}+K_{y3}+K_{y4})/3)$
Designed IF	122951	1.76	2.41	126404	1.76	2.34
Constructed IF	151515	1.62	2.07	312500	1.34	1.56
Unit: kgf, m	**STOREY 2**					
	K_x	K_{x2}/K_{x3}	$K_{x2}/((K_{x3}+K_{x4}+K_{x5})/3)$	K_y	K_{y2}/K_{y3}	$K_{y2}/((K_{y3}+K_{y4}+K_{y5})/3)$
Designed IF	69876	1.54	1.84	71885	1.47	1.72
Constructed IF	93555	1.40	1.58	233161	1.23	1.30

Unit: kgf, m	STOREY 3				STOREY 4				STOREY 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
Designed IF	45409	1.21	48966	1.18	37594	1.21	41436	1.18	31163	35019
Constructed IF	66667	1.13	189076	1.06	58901	1.12	178571	1.04	52570	171103

CONCLUSIONS

Conclusion of this case study has been presented in two sections as follows:

Torsion: Thebuilding in construction condition will suffer torsion in the earthquakebecause of infill walls which are not modelled in design process but connected to the structure in implementation. 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. It should be noted that torsional effects of short column are neglected insimulation; it may increase torsional vulnerability of building in construction condition. Another issue that mustbenoted is thatdue to popularityofhollow clay blocks in construction of residential buildings in Iran, walls in simulation are assumed like this, while recycled material from demolition of old building like solid clay brick are often used for walls of underground floor, groundfloororkitchens.Since the compressive strength of solid clay brick is higher than hollow clay block, risk of torsion will be much more severe.

Soft storey: Contrary to the initial impression that there is a soft storey in urban buildings because of parking and open spaces on ground floor, in buildings with architectural plan similar to the analyzedone, due to high stiffness ofstructure in the bottom floors to the top floors and longitudinal walls along adjacent neighbours lots in all floors, soft storey would not happen with a high safety factor.

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