PREVENTING UNDESIRABLE SEISMIC BEHAVIOUR OF INFILL WALLS IN DESIGN PROCESS

Azadeh NOORIFARD
Ph.D. Candidate, Architect, Department of Architecture and Environmental Design, Iran University of Science and Technology, Tehran, Iran,
e-mail: anoorifard@iust.ac.ir

Fatemeh Mehdizadeh SARADJ
Associate Professor, PhD, Department of Architecture and Environmental Design, Iran University of Science and Technology, Tehran, Iran,
e-mail: mehdizadeh@iust.ac.ir

Mohammad Reza TABESHPOUR
Assistant Professor, PhD, Department of Mechanical Engineering, Sharif University of Technology, Tehran, Iran,
e-mail: tabeshpour@sharif.edu

Abstract. Dividing walls are usually considered as non-structural elements, but experiences of past earthquakes show that some buildings designed and constructed by engineers have been damaged during earthquakes because of disregarding the negative effects of walls. Apart from the poor quality of construction and materials, inattention in design process is the main reason for undesirable seismic behaviour of walls.The main aim of this paper is to investigate the measures taken in different stages of architectural and structural design for improving the seismic behaviour of infilled concrete structures. As a general principle, with the further progress of project from basic architectural design to detailed structural design, there is a need to reduce designer authority and increase obligation, furthermore the cost of project increases too. The conclusion of this study implies that, in order to achieve the desirable seismic behaviour of walls, close collaboration between architects and structural engineers is required from the early stages of design. The results of this study are presented in a check list for designing reinforced concrete (RC) moment resisting frame and RC shear wall.

Key words: Walls, Seismic Behaviour, Architectural Design, Structural Design, Concrete Structures

1. Introduction

Experiences of past earthquakes show most of non-structural elements such as architectural elements are damaged even in mild or moderate earthquakes (Lee *et al.*, 2007; Tasligedik *et al.*, 2011; Vicente *et al.*, 2012). Walls are one of the most important architectural elements that have been damaged in past earthquakes and can lead to the collapse of buildings. Evaluation of walls' behaviour shows that apart from the poor quality of construction and materials, inattention to the design process is the main cause of damage to walls and their adverse effects on the seismic performance of structures.

In the current design process, structural engineers usually consider masonry infill walls as non-structural elements and only calculate their weight during structural analysis and design (Mostafaei and Kabeyasawa, 2004; Kaushik *et al.*, 2006; Mondal and Jain, 2008; Tsai and Huang, 2009; Rodrigues *et al.*, 2010; Pradhan *et al.*, 2012; Noorifard *et al.*, 2014; Noorifard *et al.*, 2015; Bârnaure *et al.*, 2016). They assume that architects are responsible for designing walls and they themselves do not need to do anything. On the other hand, architects determine the specifications of walls and their arrangement in plan and elevation without considering their seismic behaviour (Noorifard *et al.*, 2016). They assume that structural engineers are responsible for designing buildings against seismic forces. While designing in a seismic area is a shared architectural and engineering responsibility (Saradj, 2008). In this way, one of the most important non-structural elements with the potential to destroy the whole building has been neglected in the engineering community (Noorifard *et al.*, 2016). However, the experiences of past earthquakes show that, despite the special attention to the seismic resistant design of structures, disregarding the design of infill walls can cause irreparable damage to lives and property. Even beyond this, many scholars and practicing architects think that it is sufficient that structural engineers calculate the structure after architectural design is completed (Bachmann, 2003; Erman, 2005). Even the cleverest calculations and detailed design cannot compensate for errors and defects in the conceptual seismic design of the structure or in the selection of non-structural elements, in particular partition walls and facade elements (Bachmann, 2003). In fact 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 (Erman, 2005). For reducing vulnerability and costs, close collaboration between the architect and the engineer from the earliest planning stage to construction stage is essential (Bachmann, 2003; Saradj, 2008).

Basically, the range of seismic behaviour of walls is wide. In the past earthquakes, numerous buildings designed by engineers were severely damaged or even collapsed as a result of anomalies in the basic structural system induced by non-structural masonry partitions. Although there were other buildings without any lateral force resistance elements constructed by non-specialist people remained stable as a result of the contribution of masonry infill walls. In this paper, only effective measures to protect undesirable seismic behaviour of walls are investigated, in other words, using the potential of walls for the lateral resistance of buildings which is a higher level of seismic performance will not be considered.

Accordingly, the main research questions are formed as follows:

1. How are walls damaged during earthquakes?
2. How can walls cause damage to structure during earthquakes?
3. Are the effects of walls on seismic performance of different types of common structural systems the same?
4. Which measures can prevent undesirable seismic behaviour of walls at different stages of architectural and structural design?
5. Who is responsible for the poor seismic performance of walls in conventional medium rise buildings (structural engineers or architects)?

To answer these questions, four main stages are defined for this study. First, the conventional process of architectural and structural design and measures taken by architects and structural engineers in different stages of basic and detail design are investigated. Then, the undesirable seismic behaviour of walls (either their own damage or causing damage to the main structure) is discussed on three general levels based on the experiences of past earthquakes. On each level, the main causes of damage are presented according to the documents of past earthquakes. Moreover for each case, an attempt will be made to present the provision of seismic codes briefly and conceptually.

Infill walls have the most influences on the seismic behaviour of reinforced concrete moment frames and more than half of current buildings in developing countries are constructed by reinforced concrete.

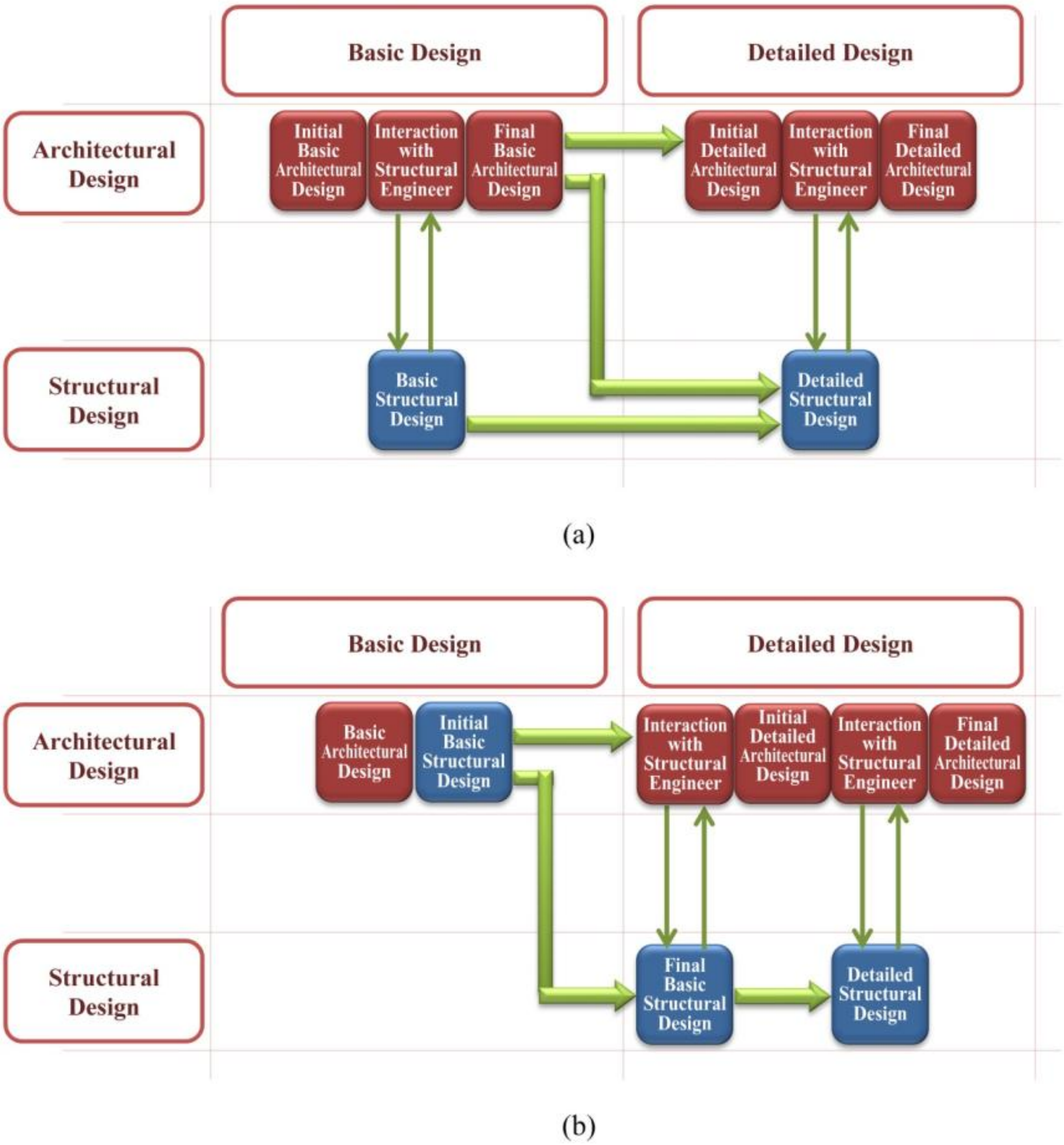

Fig. 1. Diagram of two main types of design process of conventional building (a) The basic structural design is carried out separately (b) The basic structural design is not carried out separately

This study selected these two types of structures consisting of 1- Reinforced concrete moment resisting frame and 2- Reinforced concrete frame with shear walls. So, in the next section, the stiffness of these systems is compared with infill walls and the importance of each of the above damages and the effect of walls on the seismic performance of each system is determined. Finally the results of studies in the above three sections are presented in a check lists for designers. This check list will be arranged in the form of a matrix. The rows of the matrix are related to the undesirable seismic behaviour of walls and the columns are related to the different stages of basic and detailed architectural and structural design. In each element of matrix, effective measures are presented to prevent undesirable seismic behaviour of walls.

2. Design process in conventional building

In this section, a brief review of decisions which are made in the different stages of architectural and structural design and have influence on seismic performance of wall are presented. Fig. 1 focuses on two main types of design process in conventional buildings.

2.1. Basic architectural design

The main decisions which have been made by architects at this stage include considering the context and the site of project, climate and how to use natural light and ventilation, determining the quality of spaces, spatial relationships, functional relationships, form, volumetric composition, size of spaces, circulation and access routes. In fact, at the end of this stage, the size and location of spaces and openings are almost final. According to Fig. 1 if the basic structural design is carried out separately, at final stages of basic architectural design, an interaction between the architect and the structural engineer is needed to finalize geometry, system and material of the structure. If the basic structural design is not carried out separately, architects make initial decisions in this regard at the final stages of basic architectural design and it is finalized by structural engineer in primary stages of detailed structural design.

2.2. Basic structural design

In this stage, decisions such as selecting structural system (moment resisting frame, shear wall, braced frame and dual system), material of structure (reinforced concrete, steel), determining geometry of structure (location of columns, shear walls and braced frames) are made. As mentioned in basic architectural design, these decisions may be made separately by structural engineers, in basic structural design, or a part of them are made by architects in basic architectural design and the others by structural engineers in early stages of detailed structural design. In any case, in this stage interaction between the architect and the structural engineer is necessary to make decisions about geometry, system and material of structure.

2.3. Detailed architectural design

At this stage, if interaction between the architect and the structural engineer has been performed in the final stage of basic architectural design and necessary modifications have been applied, all effective cases on geometry of spaces is finalized and the only factor that does not have a high degree of certainty is detail and section of structural elements, the amount of stiffness and displacement of structure. As mentioned in the previous paragraph, required interaction between the architect and the structural engineer may be performed in the early stage of detailed design instead of the final stage of basic design. In any case, during the main part of this stage, fundamental measures on the geometry and dimensions of spaces are not expected and most of the activities are focused on materials specifications, construction details, connections between architectural elements, connection between architectural and structural elements, meeting environmental needs (including thermal, sound and water insulation and protecting against fire). It is necessary to perform many interactions between the architect and the structural engineer for finalizing detailed architectural design. At the first step, structural engineer uses material specifications which are determined in architectural drawings to calculate applied forces to the structure. The issue that often remains neglected is the transmission of information about the connections between non-structural elements, especially the infill walls and structural elements. In the next step, after finalizing detailed structural design, it is necessary to transmit information from structural design to architectural design. The purpose of this step is to control approximate dimensions of the structural elements, the separation joints, the joints between structural and architectural element and similar items in architectural drawings.

2.4. Detailed structural design

As mentioned before, if initial decisions about the geometry, system and material of structure have been made in basic design, this stage is started after developing detailed architectural design, otherwise, first it is necessary to finalize the geometry, materials and structural systems in collaboration with the architect and then after developing detailed architectural design, applied forces to the structure based on material and details in architectural drawings is calculated. At this stage, the structural engineer designs the sections of structural elements for allowable stress and displacement. At the final stage, outputs of structural calculations such as the size of structural elements, the amount of structural stiffness and displacement and other required factors for modifying architectural details or improving structural performance should be given to the architect to check and revise architectural drawings.

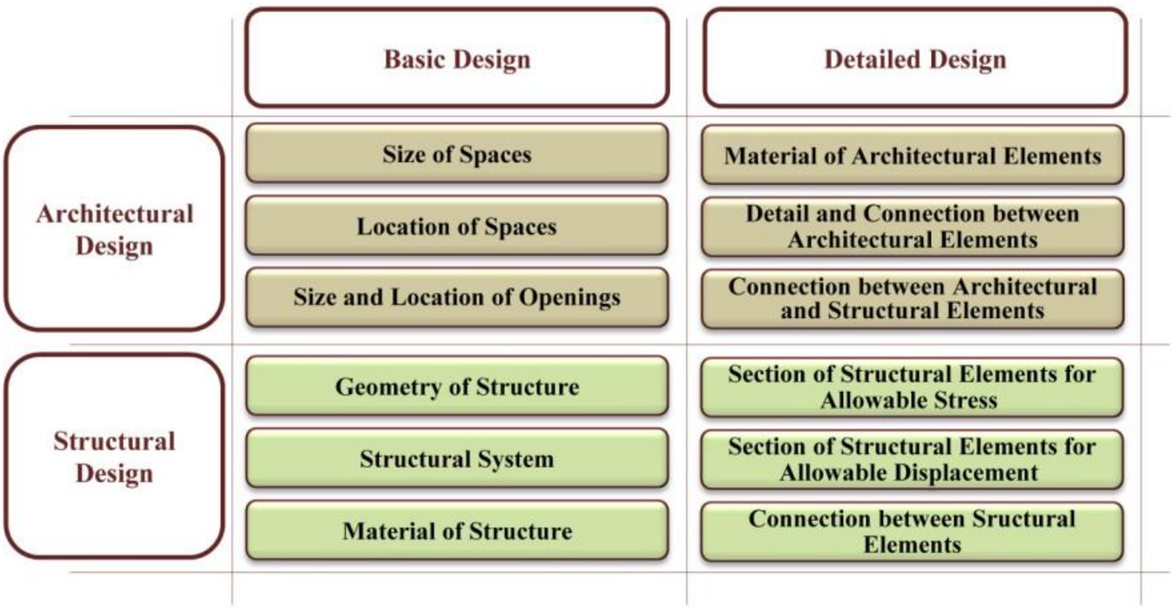

Fig. 2. The output of each stage of conventional buildings design

According to the description presented in this section, the main issues which are used in the next section against the undesirable seismic behaviour of walls are presented in Fig. 2.

3. Undesirable seismic behaviour of walls

According to the experiences of past earthquakes, undesirable seismic behaviour of walls, either causing damage to their own structure or to the main structure, can be classified into three general levels. At the first level only the wall is damaged. This is known as in-plane failure. At the second level, the wall is damaged and there is the possibility of other non-structural elements damage and human injury too. This kind of failure is known as out-of-plane failure. At the third level, material, form, connection and arrangement of walls in plan and elevation cause the structure to damage. Failures such as short column, torsion and soft storey are in this group. Certainly in the case of structural damage, damage to non-structural elements and human casualties are expected too (Fig. 3). In the following, these levels and the main causes of damage will be discussed according to the documentation of previous earthquakes and an attempt will be made to present the provision of seismic codes briefly and conceptually. In each case, based on the classification presented in the first part of the paper, effective measures to prevent damage in the various stages of design will be discussed.

3.1. First level: in-plane failure

In-plane failure occurs when the applied forces are parallel to the wall. In infill walls, this failure occurs when the strength of wall is less than the frame. This failure in mild or moderate earthquakes is known as undesirable seismic behaviour of walls, but in severe earthquakes it is considered desirable. In other words, in this case, the wall plays the role of a fuse and dissipates the earthquake's energy through the in-plane failure. If there is no wall or the walls are separated from the frame, this force will be completely applied to the structure.

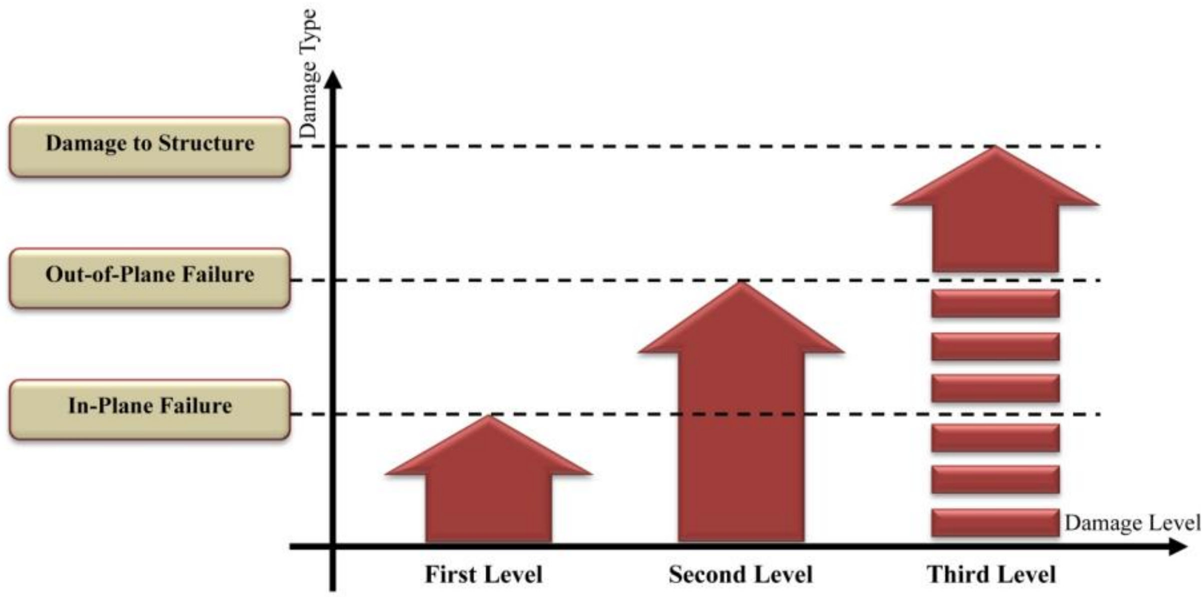

Fig. 3. Diagram of undesirable seismic behaviour levels of walls

Weak components and joints, and location and size of openings can be noted as two categories of factors of this level of failure.

3.1.1. In-plane failure induced by weak components and joints

The main reasons for in-plane cracking of walls in past earthquakes were the inherent weakness of used bricks, blocks and mortars as well as the lack of integrity of wall components (Fig. 4). Basically, the level of in-plane damage of walls is proportional to the level of inter storey drift of structure (Vicente *et al.*, 2012), strength and deformation capacity of walls. Hence in New Zealand assessment code and FEMA 306, based on experimental evidence an inter-storey drift limit states is proposed for various masonry infill panels (Table 1) (NZSEE study group on earthquake risk buildings, 2006; Federal emergency management agency, 1998).

Table 1. Maximum proposed drift for different masonry infill panels (NZSEE study group on earthquake risk buildings, 2006; Federal emergency management agency, 1998)

Type of Infill Panel	Maximum Drift
Brick masonry	1.5%
Grouted concrete block masonry	2.0%
Ungrouted concrete block masonry	2.5%

- **Effective Measures**: An important part of effective measures to prevent this level of failure is in the detailed architectural design when the specifications of bricks and mortars are determined. However, in many cases this type of failure is due to poor quality of construction. In the next stage, structural system can be changed to braced frame or shear wall in basic structural design and finally in detailed structural design, cross section of structural elements can be increased and the displacement of structure can be reduced.

Fig. 4. Diagonal cracking and in-plane failure of wall, 2009 Wenchuan earthquake, China (Zhao *et al.*, 2009)

3.1.2. In-Plane Failure Induced by the Location and Size of Openings

Experiences of past earthquakes show that numerous and large openings in external walls and openings which are located at the edge of walls or in the corner of buildings cause damage during earthquakes. This is due to stress concentration at the corner of openings and sudden changes in wall section (Fig. 5). To avoid the negative effects of openings in walls, a number of seismic codes or masonry buildings codes have provisions for openings. Section 9.5.3 of Eurocode 8 states that vertical confining elements should be placed at both sides of any wall opening with an area of more than 1.5 m^2 (European committee for standardization, 2003). The followings limitations are presented in section 7-3 of Iranian standard No. 2800. If these are not met, both sides of the opening shall be reinforced with vertical tie beams that are connected to the horizontal top and bottom tie beams of the storey (Building and housing research center, 2015):

1. The total area of opening shall not exceed $\frac{1}{3}$ of total area of the wall.

2. The total length of the openings shall not exceed $\frac{1}{2}$ of the length of the wall.
3. The distance of the first opening from the external edge of the building shall be less than $\frac{2}{3}$ of the height of the opening or 75 cm, whichever is less.
4. The horizontal distance between two adjacent openings shall not be less than $\frac{2}{3}$ of the height of the shorter of the two openings and also less than $\frac{1}{6}$ of the sum of the lengths of the two openings.
5. Neither of the dimensions of the opening shall exceed 2.5 meters.

In Nepal's building code, only infill wall panels with openings having a total area less than 10% of the gross panel area shall be considered as resisting seismic loads. Such openings shall be located outside the middle two-thirds of the panel and the restricted zone (Fig. 6) (Ministry of physical planning and works, 1994).

Fig. 5. Diagonal cracking in piers, the 2009 L'Aquila earthquake (Ceci *et al.*, 2010)

- **Effective Measures:** To avoid this level of failure, in the basic architectural design, when the area of openings based on natural lighting and ventilation, landscape view are determined, opening to wall area ratio, opening to wall length ratio, distance between openings and distance from the edge of wall to openings should be checked based on seismic codes provisions. If this cannot be applied, then around the openings should be provided reinforced ties in detailed architectural design.

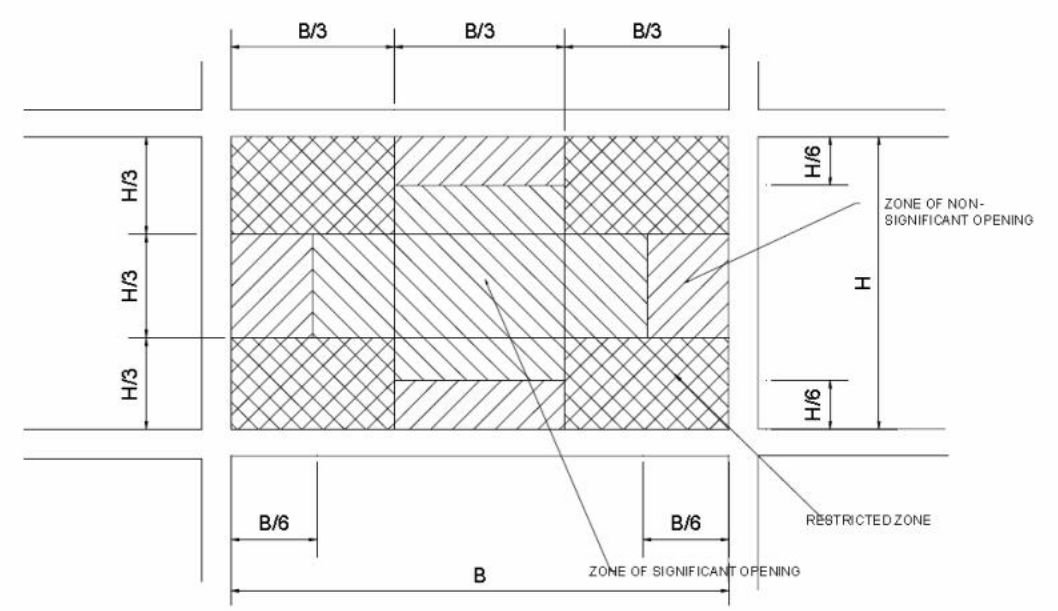

Fig. 6. Possible location of openings in load-bearing infill wall (Ministry of physical planning and works, 1994)

3.2. Second level: Out-of-plane failure

Out-of-plane failure occurs when the applied forces are perpendicular to the wall (Fig. 7). With in-plane failure, the only damage is to the wall and sometimes it has advantage for the structure. However in out-of-plane failure, there is the possibility of damage to other non-structural elements and human injury too. In addition, in out-of-plane failure, if the wall is integrated with the frame, a sudden change of applied force to the frame can cause a shock to the structure. Weak components and joints, undesirable aspect ratio and undesirable connection to the structure can be noted as three important factors of this level of failure.

Fig. 7. Out-of–plane failure, of wall, the 2009 L'Aquila earthquake (Ceci *et al.*, 2010)

3.2.1. Out-of-plane failure induced by weak components and joints

Similar to in-plane failure the inherent weakness of bricks and blocks, lack of connection of wall components to each other generally due to weak mortar between bricks and the weak connection of double-leaf walls are the main reasons of out-of-plane failure of walls. In recent years, new codes and standards have been established to improve the quality and precise energy efficiency requirements for new buildings. For achieving the requirements of the new thermal codes and modifying thermal bridges, construction detail of exterior walls have been changed. Slenderness of the masonry leafs, non-confinement of the external leaf, lack of ties or anchoring systems to the inner leaf and insufficient width support of the outer leaf over the slab or beam have created new risks (Fig. 8) (Vicente *et al.*, 2012). Eurocode 6 recommends that wall ties connecting the two leaves of a cavity wall or a veneer wall to its backing wall should not be less than 2 per square meter (European committee for standardization, 2005).

- **Effective Measures:** Effective measures to prevent this level of failure are in detailed architectural design. However, like in-plane failure in many cases this type of failure is due to poor quality of construction.

3.2.2. Out-of-plane failure induced by undesirable aspect ratio

In the out-of-plane failure, the ratio of height to thickness and the ratio of length to thickness are very important. There are requirements in various standards for load-bearing walls, shear walls and non-structural walls.

Fig. 8. Out-of-plane failure of the outer leaf due to the lack of anchoring systems to the inner leaf and insufficient width support over the beam, the 2009 L'Aquila earthquake (Vicente *et al.*, 2012)

According to the subject of this paper, only the necessities for non-structural walls are investigated. Based on the section 7.5.3 of Iranian standard No. 2800, the maximum permissible length of non-structural walls and partitions between two supports shall not be more than 40 times the thickness of the wall or 6.0 meters. The minimum ratio of thickness to the height of non-structural walls shall not be less than $\frac{1}{300}$ and the maximum permissible height of non-structural walls and partitions is 3.5 meters (Building and housing research center, 2015). The section 4.3.6.4 of Eurocode 8 states that particular attention should be paid to masonry panels with a slenderness ratio (ratio of the smaller of length or height to thickness) of greater than 15 (European committee for standardization, 2003). Section 7.5.3 of FEMA 356 mentions that unreinforced infill panels with $\frac{h}{t}$ ratios less than those given in Table 2 and meeting arching action requirements do not need to be analyzed for out-of-plane seismic forces (Federal Emergency Management agency, 2000).

- **Effective Measures:** By checking these aspect ratios and designing ties in appropriate distances in detailed architectural design this level of failure can be prevented.

3.2.3. Out-of-plane failure induced by undesirable connection to structure

Other factors contributing to out-of-plane failure are the lack of the wall's connection to surrounding columns and beams, the lack of interconnection of orthogonal partitions and the lack of ties in corners (Fig. 9). In relation to the integrated wall with the frame, the out-of-plane strength of the infill depends on the arching action. In other words if the wall is confined well by the top boundary, an arching action would develop between the compressive zones and provide lateral resistance. An arching mechanism may develop even through a partially filled gap. When cracks appear on the sides where tension occurs at the top and base of the wall, a diagonal thrust forms between the opposite compressive sides (Fig. 10) (Tu *et al.*, 2010). The stiffer the surrounding frame is and the more adhesion between the frame and the infill wall is the more arching action is available. For this purpose the wall should be connected to the frame by an appropriate connection. One method is to use inclined bricks at the top course and hitting bricks with rubber hammer to create the post tension in walls (Tabeshpour, 2009). Another method is to use connecting bars and angels between the wall and the structure, the latter is useful for out-of-plane strength of both walls either integrated with or separated from frames.

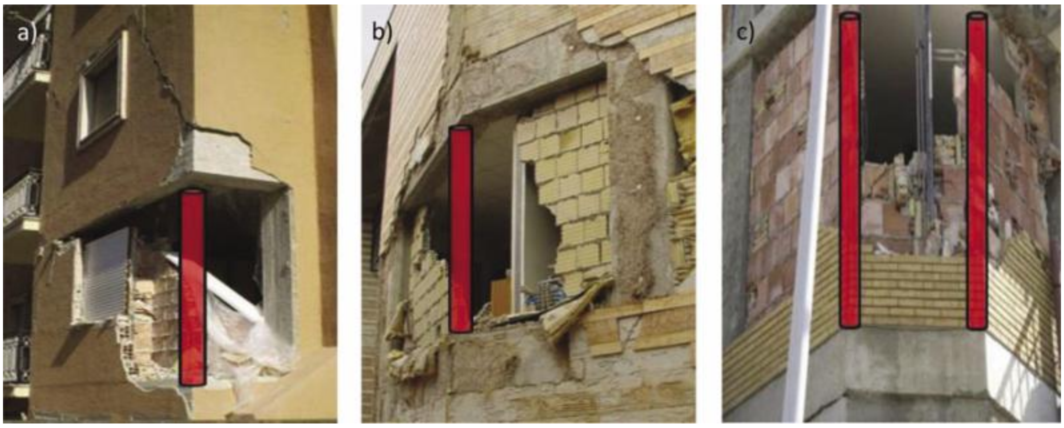

Fig. 9. Out-of-plane failure due to the lack of tie at corners, the 2009 L'Aquila earthquake (Vicente *et al.*, 2012)

Table 2. Maximum $\frac{h}{t}$ ratios (Federal emergency management agency, 2000)

	Low Seismic Zone	Moderate Seismic Zone	High Seismic Zone
IO (Immediate Occupancy)	14	13	8
LS (Life Safety)	15	14	9
CP (Collapse Prevention)	16	15	10

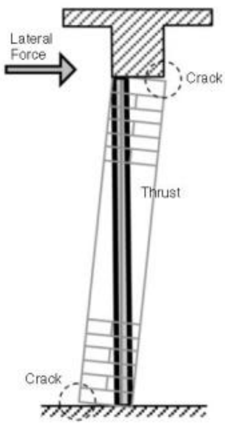

Fig. 10. Arching action against out-of-plane force (Tu *et al.*, 2010)

Eurocode 8 recommends some measures such as light wire meshes well anchored on one face of the wall, wall ties fixed to the columns and cast into the bedding planes of the masonry, and concrete posts and belts across the panels and through the full thickness of the wall to improve both in-plane and out-of-plane integrity and behaviour (European committee for standardization, 2003). In Australian standard of masonry structures there are different details for anchoring walls against out-of-plane forces based on ductility and performance of structure, support conditions and thickness of masonry (Council of standards Australia, 2001).

- **Effective Measures:** Effective measures to prevent this level of failure are in detailed architectural design, while providing arching action of wall is dependent on the skill of mason.

3.3. Third level: Damage to structure

In this level, the wall failure especially in-plane failures may occur first and then be followed by structural failure. In other cases, wall could remain stable but due to its form, material, connection and arrangement of walls in plan and elevation might cause damage to the structure. These types of damage include torsion, soft storey, short column, shear failure due to interaction, non-ductile stiff storey and strong beam- weak column.

3.3.1. Torsion

From the stand point of structural analysis, seismic forces apply to the center of mass and the resistance force formed in the center of rigidity of the lateral resistance system, if the center of rigidity does not coincide with the center of mass, torsional moment around the center of rigidity will be created in addition to the lateral seismic force. Several studies about structural damage during the previous earthquakes reveal that torsion is the most critical factor leading to a major damage or the complete collapse of buildings (Dubey and Sangamnerkar, 2011; Charleson, 2011). A significant part of torsion phenomenon caused by asymmetric distribution of stiffness, is created by disregarding arrangement of infill masonry panels during the design process (Aliaari and Memari, 2005; Özmen and Ünay, 2007; Charleson, 2011; Vicente *et al.*, 2012; Tabeshpour *et al.*, 2012; Noorifard *et al.*, 2016) (Fig. 11). Unfortunately Irregular buildings constitute a large portion of the modern urban infrastructure (Dubey and Sangamnerkar, 2011) and the experiences from previous earthquakes show that these buildings are vulnerable. Due to urban regulation and natural light, most buildings have adjacency from three sides and at corners of streets from two sides. In three-sided buildings, there are not sufficient walls on the street side, therefore the stiffness of building on the opposite side is greater than on the street side and torsion will occur in earthquakes. In two-sided buildings which there are not sufficient walls along two perpendicular sides, this problem is more severe.

In the table 12.3.1 of ASCE 7-10, table 4 of IS 1893 (Indian Standard), section 1-7-1-b of standard No.2800 and table 2.1 of Turkey's seismic code 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. It should be indicated that in these codes, accidental eccentricity is 5% (American society of civil engineers, 2010; Bureau of Indian standard, 2002; Building and housing research center, 2015; Ministry of public works and settlement, 2007). In the 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% (Council of standards New Zealand, 2004).

In Australian standard 1170.4-1993, torsional irregularity shall be considered when distance between center of mass and center of rigidity is more than 10% of structure dimension in each direction but it is omitted in new version of 2007 (Council of standards Australia, 1993; Council of standards Australia, 2007). According to Iranian standard No. 2800 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 (Building and housing research center, 2015). In Nepal National Building Code about mandatory rules of reinforced concrete buildings with masonry infill walls (NBC 201), 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 (Ministry of physical planning and works, 1994).

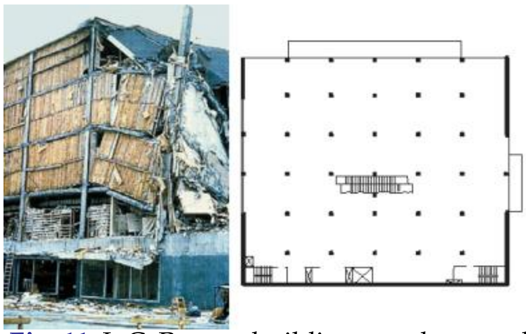

Fig. 11. J. C. Penney building was destroyed during the 1964 Alaska earthquake because of torsional effect formed by the arrangement of walls (Arnold, 2006)

- **Effective Measures:** It is possible to take measures in all stages of design to prevent this type of failure. Some times in basic architectural design by changing the arrangement, the adjacency and the size of spaces, to the extent that functional and aesthetic aspects and the sense of space do not lost, all or part of torsion created by infills can be prevented. In the basic structural design, changing arrangements of structural elements and designing more structural elements like columns, shear walls or braced frame in the part of building with the low density of walls is effective. In the detailed architectural design, separating walls from frame in the part of building with the high density of walls is useful (Fig. 12).

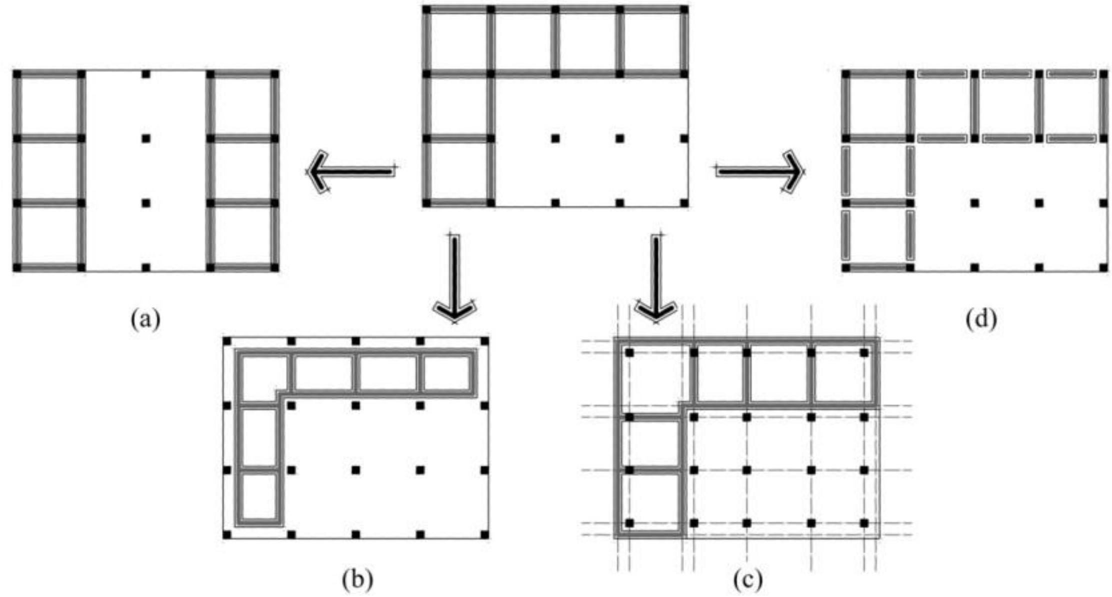

Fig. 12. Effective measures to prevent torsion: (a) Changing the arrangement of spaces, (b) Changing the size of spaces, (c) Changing the arrangement of structural elements, (d) separating asymmetric walls from frame

Finally, if nothing was done in previous stages, designing the structure for more forces and increasing the stiffness and strength of structural elements in the part of the building with the lack of stiffness is mandatory.

3.3.2. Soft Storey

Soft storey occurs due to the discontinuity of stiffness in height. If the stiffness of a storey (usually ground storey) is significantly lower than the upper storeys, a significant portion of the lateral displacement concentrates on ground storey (Asteris, 2003; Arnold, 2006; Arslan and Korkmaz, 2007; Mulgund and Kulkarni, 2011; Tabeshpour *et al.*, 2012; Harmankaya and Soyluk, 2012; Caterino *et al.*, 2013) and plastic hinges form at the bottom and top of columns (Tabeshpour, 2009). This is usually happened because of architectural design for creating large open spaces, car parking, lobbies, etc. In many cases, despite regular design in height, by reducing or eliminating infill walls in adjacent storeys, vertical irregularity occurs (Asteris, 2003; Arnold, 2006; Özmen and Ünay, 2007; Zhao *et al.*, 2009; Yatağan, 2011; Bârnaure *et al.*, 2016) (Fig. 13). Sometimes mass distribution intensifies soft storey in building with stiffness irregularity so it is necessary to study stiffness distribution and mass distribution of adjacent storeys simultaneously to control soft storey (Tabeshpour and Noorifard, 2016).

Fig. 13. Soft storey due to the elimination of masonry infill wall in ground floor, the 1999 kocaeli (Turkey) earthquake (Yatağan, 2011)

In the table 12.3.2 of ASCE 7-10, the section 4.5.1.2 of NZS 1170.5, the table 5 of IS 1893 and section 1-7-2-e of standard No.2800 as a condition of vertical regularity, the lateral stiffness of each storey shall not be less than 70% of that in the storey above or 80% of the average stiffness of the three storeys above (American society of civil engineers 7-10, 2010; Council of standards New Zealand, 2004; Bureau of Indian standard, 2002; Building and housing research center, 2015). There is the same provision in Australian standard 1170.4-1993, but it is omitted in new version of 2007 (Council of standards Australia, 1993; Council of standards Australia, 2007).

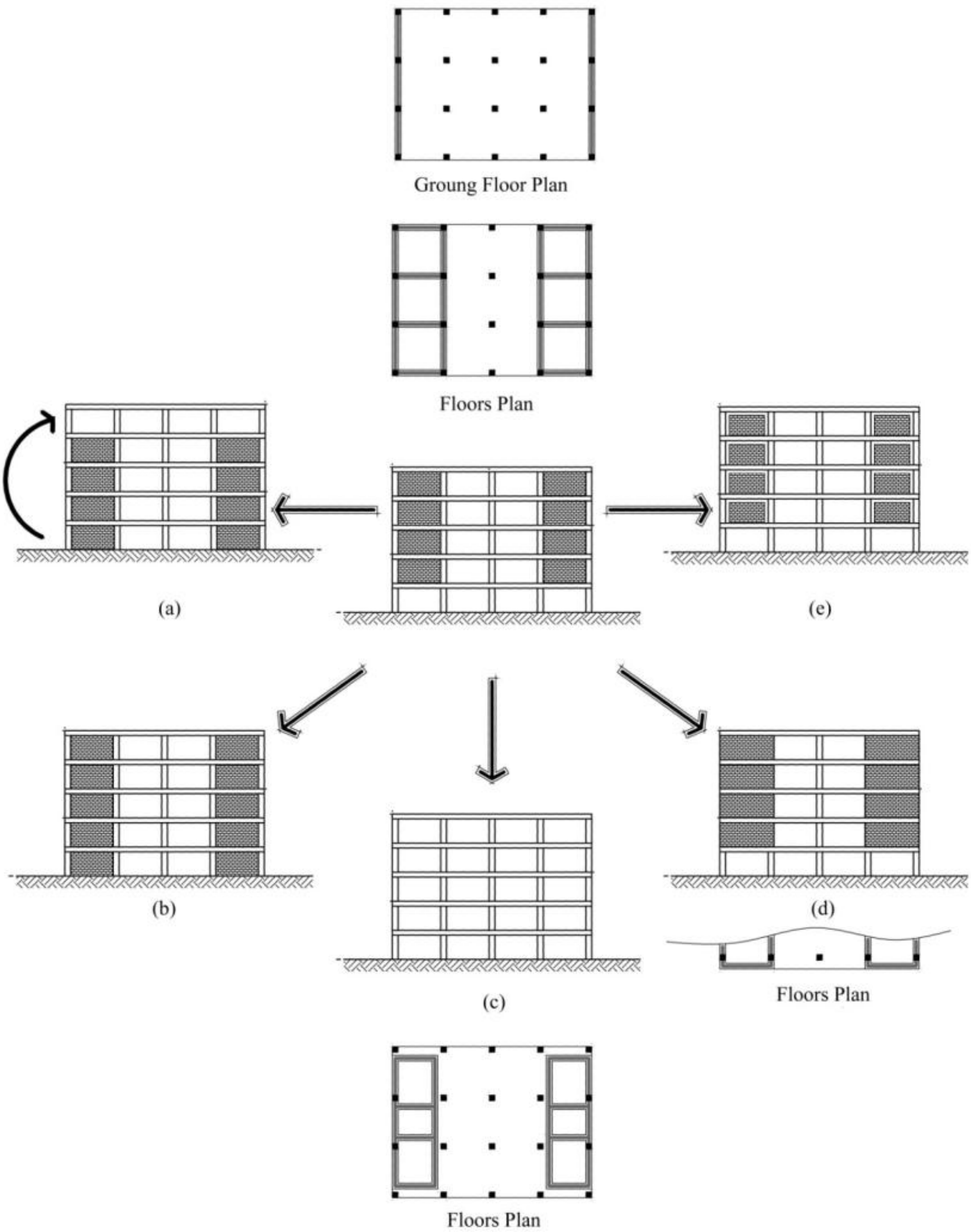

Fig. 14. Effective measures to prevent soft storey: (a) Changing the location of spaces,(b) Continuing the walls in soft storey , (c) Changing the size of spaces, (d) Changing the arrangements of structural elements, (e) separating discontinuous walls from frame

In Table 2.1 of seismic code of Turkey as a condition of inter storey stiffness irregularity (soft storey) has been indicated that Stiffness Irregularity Factor which is defined as the ratio of the average relative storey drift at any storey to the average relative storey drift at the storey immediately above or below, is greater than 2 in each of the two orthogonal directions, ±%5 additional eccentricities shall be considered in calculation (Ministry of public works and settlement, 2007).

- **Effective Measures:** It is possible to take measures in all stages of design to prevent this type of failure like torsion. Some times in the basic architectural design by changing the location and size of spaces, to the extent that functional and aesthetic aspects and sense of space do not lost, all or part of soft storey created by infills can be prevented. In the basic structural design, changing arrangements of structural elements and designing more structural elements like columns, shear walls or braced frame in the storey where the infill walls are less than others is effective. In detailed architectural design, separating walls which are not continuous in elevation from frame is useful (Fig. 14). Finally, if nothing is done in previous stages, designing the structural elements in soft storey for more forces and increasing stiffness and strength of structural elements in this storey, is mandatory.

3.3.3. Short column

Short columns are usually created by low partition walls, which are not isolated from the structure (Aliaari and Memari, 2005; Vicente *et al.*, 2012; Urich and Beauperthuy, 2012). The stiffness of the column is proportional to the inverse cube of its height, when the height of a column decreases, the lateral stiffness of the element increases and the more rigid a column is, the more lateral force it attracts on itself (Arslan and Korkmaz, 2007; Özmen and Ünay, 2007) so when the lateral force is distributed to all columns in the same floor, shorter columns will be called upon to resist a larger portion of the storey shear than normal height columns (Guevara and Garcia, 2005) and shear failure of column occurs (Fig. 15, 16). It is necessary to note that interaction between the wall and the steel structure is different from interaction between the wall and concrete structure and short column failure does not usually occur in steel ones (Tabeshpour, 2009).

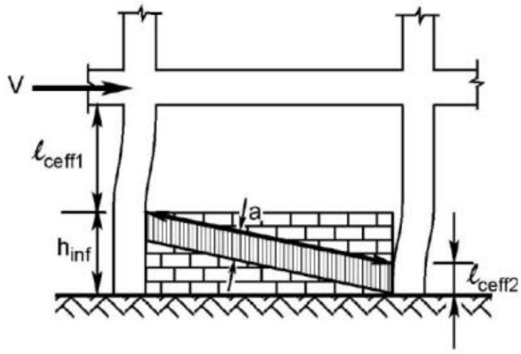

Fig. 15. Short column due to columns restrained by partial masonry infill walls (NZSEE study group on earthquake risk buildings, 2006)

Fig. 16. Short column due to the partial infill wall, the 1987 Miyagi-Ken Oki (Japan) earthquake (Guevara and Garcia, 2005)

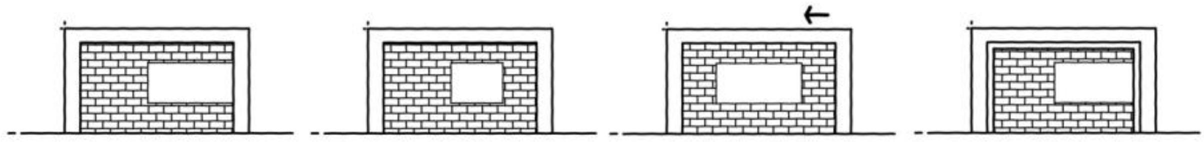

Fig. 17. Effective measures to prevent short column: (a) Changing the size of opening,(b) Changing the location of opening, (c) separating walls from column

In other words, local effects of short columns are only in concrete structures, but global effects like torsion and soft floor which caused by short column, occur in both concrete and steel structures.

- **Effective Measures**: It is possible to take measures in all stages of design to prevent short column failure. In the basic architectural design by modifying the size and location of openings and providing sufficient pier between opening and columns, without compromising the natural lighting and ventilation and view to the landscape, both local and global effects of short column can be prevented. In the basic structural design, the change of structural system to the shear wall or the braced frame for preventing local effects and designing more structural elements in the side with less stiffness in plan or within the softer storeys in elevation for preventing global effects are useful. In the detailed architectural design, separating short walls from columns is effective. Sometimes depending on the height of walls and the shear strength of concrete column, it is the only solution (Fig. 17). Finally, if nothing is done in previous stages or the measures are not sufficient, in detailed structural design, increasing the shear strength of short columns and increasing section of other columns for preventing local effects and increasing the stiffness and strength of structural elements in the side with less stiffness in plan or softer storeys in elevation for preventing global effects are effective.

3.3.4. Shear Failure due to Interaction

Basically, the infill walls cause the structural behaviour change from bending action to axial compressive action. This distribution of forces in the interaction between wall and frame, depending on the geometric characteristics and strength of wall and frame can create concentrated shear forces in the top and bottom part of column, the start and end of beam or the joint between beams and columns and if the shear strength of these areas are not designed for this interaction, shear failure of the structural elements will occur. The most dangerous of these failures are the shear failure of columns. These failure patterns indicate that captive column conditions can develop dynamically in columns restrained by full-bay masonry infill walls (Irfanoglu, 2009). In the New Zealand's assessment code, it has also emphasized that the presence of infills magnifies the shear demands on the frame members and the area which shear demand is maximum called "Short Column" (Fig. 18) (NZSEE study group on earthquake risk buildings, 2006). In fact, this type of failures is a kind of in-plane failure described in section 2 with the exception that in this case the strength of wall is higher than frame. Therefore, unlike the case in which, the wall lead to the dissipation of energy during earthquakes, in this case, the wall create concentrated shear forces in structural elements and if the shear strength of the structure is low, the shear failure will occur (Fig. 19). Generally this type of failure occurs in reinforced concrete structures, especially in the moment resisting frame.

- **Effective Measures**: Effective measures to prevent this level of failure are in the detailed structural design, unless in the detailed architectural design, walls have been separated from the frame.

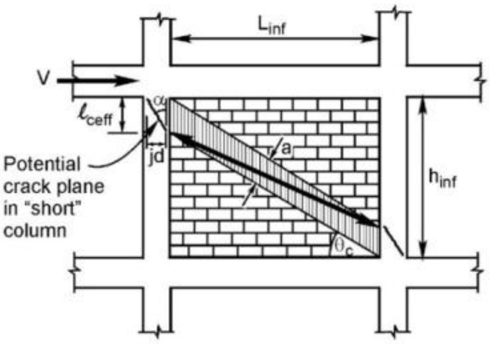

Fig. 18. Short column due to columns restrained by full-bay masonry infill walls (NZSEE study group on earthquake risk buildings, 2006)

Fig. 19. Failure of wall corner and shear failure of column; the 2008 Wenchuan earthquake (Zhao *et al.*, 2009)

3.3.5. Non-Ductile Stiff Storey

The failure of stiff floor is similar to the failure of soft storey in appearance. Like soft storey, non-uniform distribution of stiffness causes this phenomenon. With the exception that in soft storey, the most portion of the lateral displacement concentrates on the storey with less stiffness compared to the others, but in stiff storey, the most portion of lateral force concentrates on the storey with more stiffness than others. The difference in stiffness can be caused by short columns. When the height of infill walls on one storey of the building is half of the height of columns, the stiffness of these columns are more than other storeys with full infill walls and this leads to a force concentration and the formation of non-ductile stiff storey (Fig. 20).

- **Effective Measures:** This failure can be prevented in the basic architectural design by modifying the size and location of openings and providing sufficient piers between openings and columns, to the extent that natural lighting and ventilation and the view to the landscape are not lost. In detailed architectural design, separating short walls from columns is effective (Fig. 21).

3.3.6. Strong Beam-Weak Column

Moment resisting frames should be designed in such a way that first, the plastic hinges are created in beams and columns remain elastic. Because ductile deformation of columns before beams will probably cause the destruction of entire building, on the contrary if columns are more rigid than beams, the ductile deformations of beams can absorb a lot of energy without an important loss in the load carrying capacity (Özmen and Ünay, 2007; Charleson, 2011; Harmankaya and Soyluk, 2012). When the parapet become integrated with structural beam in construction phase, despite avoiding the principle of strong beam-weak column in design phase, building behaviour would be like this in earthquakes (Charleson, 2011) (Fig. 22).

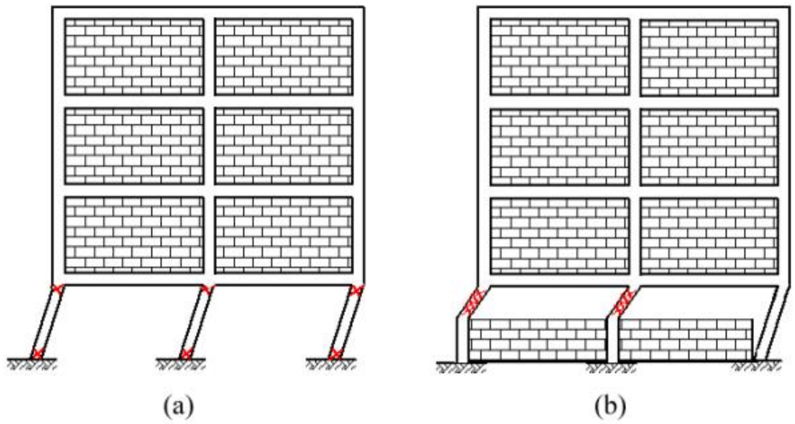

Fig. 20. Failure due to the non-uniform distribution of stiffness; (a) Soft Storey, (b) non-ductile stiff storey

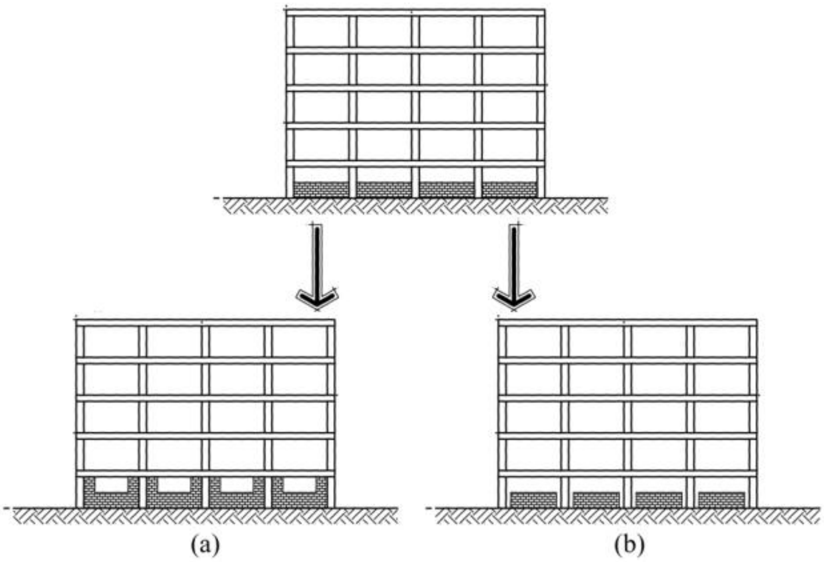

Fig. 21. Effective measures to prevent stiff storey: (a) Changing the size of openings,(b) separating walls from columns

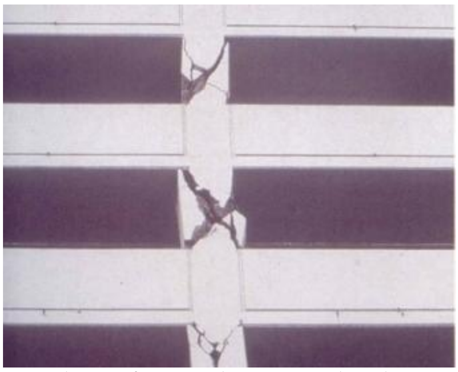

Fig. 22. Failure of strong beam-weak column due to the integrity of parapets with beams; the 1994 Northridge earthquake, California (Bachmann, 2003)

- **Effective Measures:** In the basic architectural design, by decreasing the size of continuous openings and in the detailed architectural design, by separating infill walls from structure, the prevention of this failure is possible (Fig. 23).

4. Concrete structures

More than half of current buildings in developing countries are constructed by reinforced concrete, this type of structures consist of two common systems; 1- Reinforced concrete moment resisting frame and 2- Reinforced concrete frame with shear walls. The stiffness of shear walls comparing to the moment resisting frames is very high, so the effect of infill walls on this type of structures is very low. The stiffness of an infill wall with hollow clay block, one RC moment resisting frame and one RC shear wall with width of 5 meters and height of 3 meters are calculated with following assumptions. The stiffness of infill wall has been calculated by an equivalent compression diagonal strut.

- Infill Wall with Hollow Clay Block

$$t = 200mm$$
$$a = 0.2d$$
$$L = d = \sqrt{5000^2 + 3000^2} = 5830mm$$
$$E = 2000\,{}^{N}\!/\!_{mm^2}$$
$$\cos\theta = \frac{5}{\sqrt{5^2+3^2}} = 0.85$$
$$K_1 = \frac{AE\cos^2\theta}{L} = \frac{200\times 0.2\times 5830\times 2000\times 0.85^2}{5830}$$
$$= 57800\,{}^{N}\!/\!_{mm}$$

- RC Moment Resisting Frame

$$400mm \times 400mm$$
$$E = 2.5\times 10^4\,{}^{N}\!/\!_{mm^2}$$
$$K_2 = \frac{24EI}{h^3} = \frac{24\times 2.5\times 10^4 \times {}^{400^4}\!/\!_{12}}{3000^3} = 47407\,{}^{N}\!/\!_{mm}$$
$$K_2 = 0.8K_1$$

- RC Shear Wall

$$t = 200mm$$
$$E = 2.5\times 10^4\,{}^{N}\!/\!_{mm^2}$$
$$K_3 = \frac{3EI}{\left[1+0.75\left(\frac{L}{H}\right)^2\right]\times H^3} = \frac{3\times 2.5\times 10^4 \times \frac{200\times 5000^3}{12}}{\left[1+0.75\left(\frac{5000}{3000}\right)^2\right]\times 3000^3}$$
$$= 1878908\,{}^{N}\!/\!_{mm}$$
$$K_3 = 32K_1$$

Comparing the results shows that the stiffness of bare frame is 0.8 times the infill wall and the stiffness of shear wall is 32 times of it. This means that if the design of structure is regular in plan and elevation, the arrangement of infills in moment resisting frames can create torsion, soft storey and short columns, but nothing will happen in shear walls. In addition due to the high stiffness of shear walls and therefore, the low displacement of structure, the in-plane failure of walls are not expected, in other words, the possible failure of infill walls in these types of the structures, is out-of-plane failure (Fig. 24).

5. Conclusion

The experiences of past earthquakes show that apart from the poor quality of construction and materials, inattention to the design process is the main reason for the damage to walls and their adverse effects on the seismic performance of structures. The results of this study indicates that it is possible to take measures in all stages of design to prevent some types of wall failure and for others only in one stage of design, effective measures can be taken. For the former, designer can select the measures according to the condition of the project, but as a general principle, with the further progress of project from the basic architectural design to the detailed structural design, there is a need to reduce designer authority and increase obligation, in other words, if the protection of one type of failure is done in the basic architectural design, this leads the effective measures at the next stages, for example, the detailed architectural or detailed structural design are not needed or the amount of required action are reduced. But if no measures have been taken in the basic architectural design due to the negligence of designer or the impossibility of taking the necessary measures for reasons such as the functional relationships, the municipal laws and the quality of spaces required actions in detailed architectural design and afterwards detailed structural design will be mandatory.

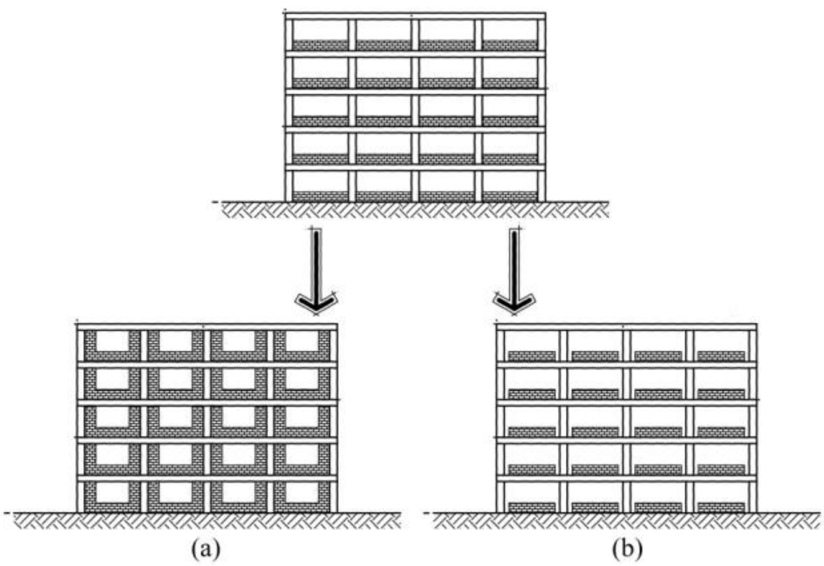

Fig. 23. Effective measures to prevent strong beam-weak column: (a) Decreasing the size of continuous openings, (b) separating walls from structure

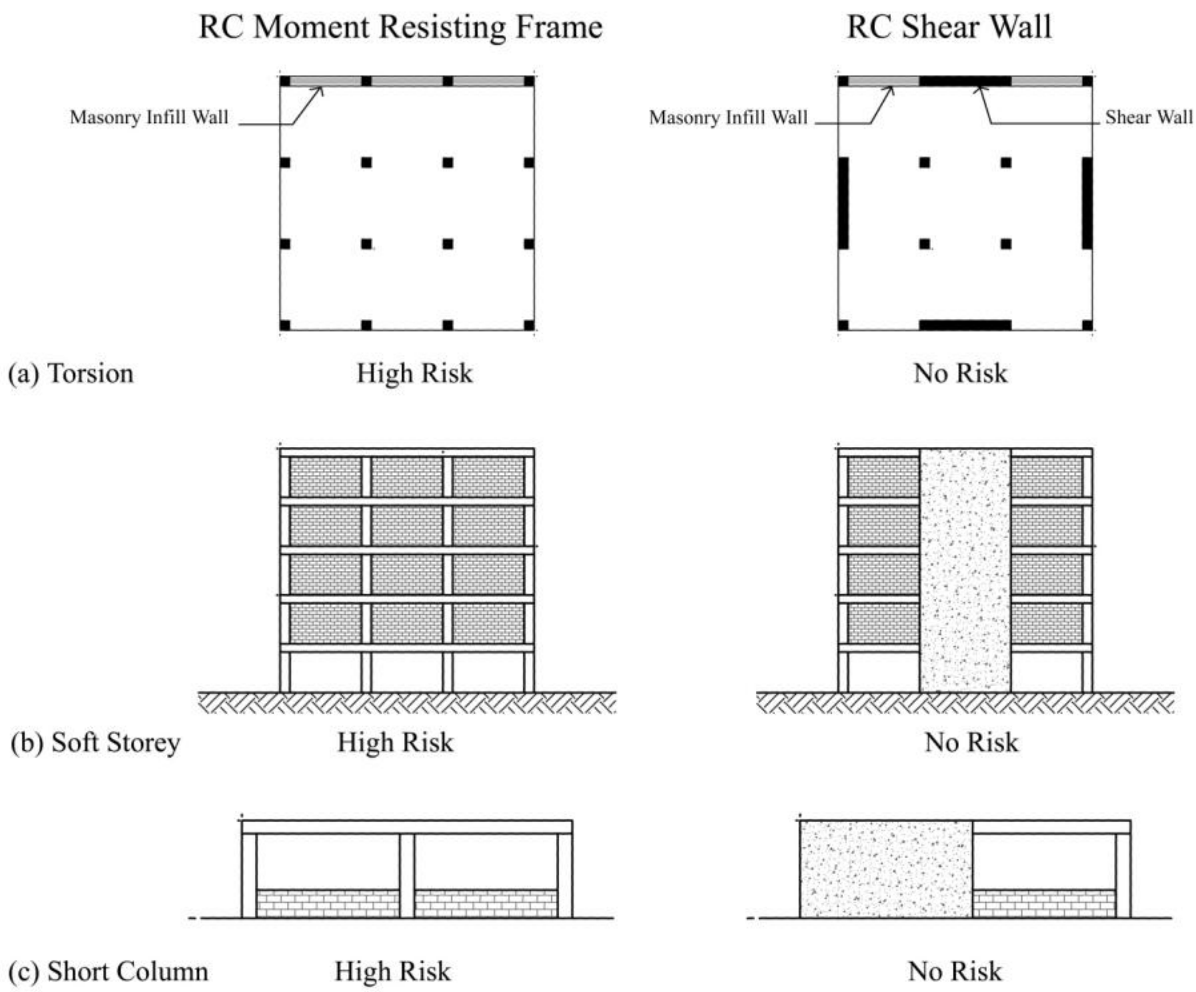

Fig. 24. Comparing the risk of structural failures due to infill walls for RC moment resisting frame and RC shear wall: (a) Torsion, (b) Soft Storey, (c) Short Column

Table 3. Check list for preventing the undesirable seismic behaviour of walls in RC moment resisting frame and RC shear wall. For RC shear wall only highlighted items are applicable.

			Authority ←			→ Obligation
			Basic Architectural Design	**Detailed Architectural Design**	**Basic Structural Design**	**Detailed Structural Design**
First Level In-plane Failure	Weak Components and Joints		-	-Specification of bricks and blocks -Specification of mortars	Increasing structural elements or changing structural systems to shear walls	Decreasing the displacements of structure by increasing the section of structural elements
	Location and Size of Openings		- Opening to wall area ratio - Opening to wall length ratio -The distance between openings -Distance from edge of wall to	Ties around openings	-	-
Second Level Out-of-plane Failure	Weak Components and Joints		-	-Specification of bricks and blocks -Specification of mortars	-	-
	Undesirable Aspect Ratio		-	-Ratio of height to thickness -Ratio of length to thickness -Tying	-	-
	Undesirable Connection to Structure		-	-Proper connection to structure -Tying corners	-	-
Third Level Damage to Structure	Torsion		Changing the location and dimension of spaces	Separating some of walls from structure in the high density part of building	-Changing the arrangements of structural elements Increasing structural elements in the low density part of building	-Increasing design forces -Increasing the stiffness and strength of structural elements in the low density part of building
	Soft Storey		Changing location and dimension of spaces	Separating walls from structure in other storeys	Increasing structural elements in soft storey	Increasing the stiffness and strength of structural elements in soft storey
	Short Column	Local	-Distance from opening to column -Size of openings	Separating walls from structure	Changing structural system to shear wall or braced frame	Increasing shear strength of short columns and section of other columns
		Global	-Distance from opening to column -Size of openings	Separating walls from structure	Increasing structural elements in the side with less stiffness in plan or softer storeys in elevation	Increasing the stiffness and strength of structural elements in the side with less stiffness in plan or softer storeys in elevation
	Shear Failure due to Interaction		-	Separating walls from structure	-	Increasing the shear strength of structural elements
	Non-Ductile Stiff Storey		- Opening to wall area ratio - Opening to wall length ratio -Distance from edge of wall to opening	Separating walls from structure	-	-
	Strong Beam-Weak Column		-	Separating walls from structure	-	-

It is obvious that from the basic architectural design to the detailed structural design, the cost of project increases too. For example, if modifying the location and size of spaces is possible to protect building against torsion caused by the arrangement of infill walls, extra costs will not be imposed to the structure, however if this is resolved in the detailed structural design, increasing the stiffness and strength of structural elements in the parts of building with the lack of stiffness, will be mandatory. So compared to the first case, the cost of the structure will be increased. It should be mentioned that in some cases, the effective measures in the detailed architectural design are preferred to the basic structural design and in some cases, it is reversed. Obviously, the failure for which there is only a preventive measure, this is mandatory. Despite the fact that at first glance walls are non-structural elements, this study implies that to prevent undesirable seismic behaviour of walls, special measures are needed both in architectural and structural design. In other words, to achieve the desirable seismic behaviour of walls and to prevent any interference in the seismic performance of structures, close collaboration between architects and structural engineers is required from the early stages of basic design to the final stages of detail design. The results of this study are presented in a check list for designers to prevent undesirable seismic behaviour of walls in RC moment resisting frame and RC shear wall. This check list is arranged in the form of a matrix of 12×4. The rows of this matrix are related to the undesirable seismic behaviour of walls and the columns are related to the different stages of basic and detailed architectural and structural design. In each element of matrix, effective measures which can be taken to prevent undesirable seismic behaviour of walls are presented. It should be noted that for shear wall only highlighted items are applicable (Table 3).

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