Seismic Behavior of Masonry Infilled Frame Structures

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Infilled frames are usually modelled in the context of global building analysis using simplified procedures without considering the aspects resulting from the interaction between the panel and the frame. Other aspects, such as adequate design of the floor beams and the beam-columns' joints, and control of potential sliding shear failure of the columns, that significantly affect the structural response, are also typically not accounted for.

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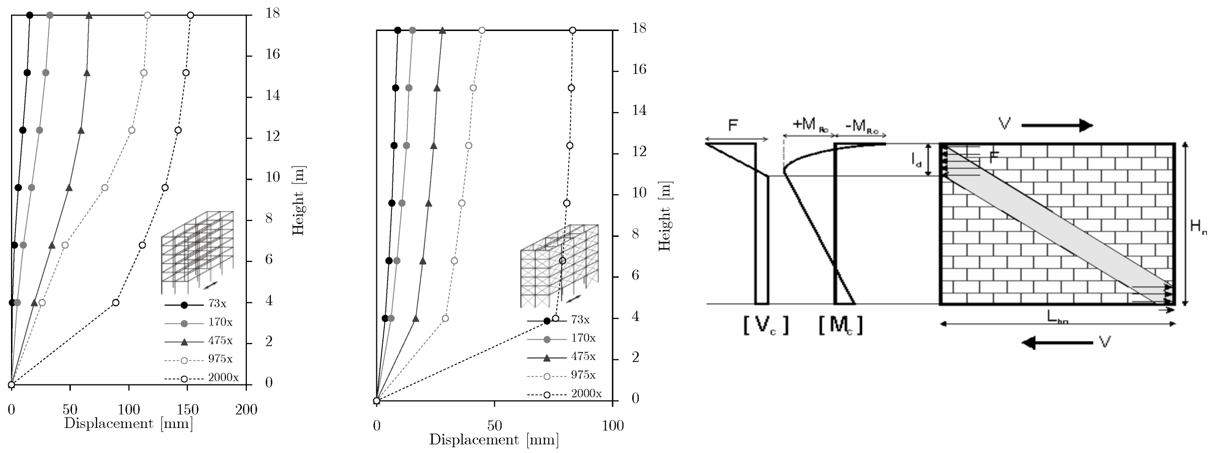
1. Behaviour of Masonry Infill Walls

Masonry walls, when integrated within a reinforced concrete frame, have a different mechanical behavior compared to unconfined masonry walls. The lateral loading on the confined system creates mainly biaxial stresses with compression on the diagonal connecting opposite corners and tension on the perpendicular direction. The walls can also be subjected to high shear demands, failing along the mortar layers. However, the greater changes on the stress demands occur to the frame. The interaction between the two elements changes the behaviour of the assemblage completely. **Figure 1**a,b supports these remarks by showing the differences both on global and local levels. Analysing the displacements between a building with and without infill masonry walls, it is possible to assess that the bare-frame structure has higher deformations that are more distributed in height than the infilled frame. It shows that, for higher seismic demands, there is a tendency for concentration of deformations at specific levels, especially for the infilled frame. This occurrence leads to the formation of a soft-storey mechanism, a possible consequence intensified by the implementation of brittle masonry walls. **Figure 1**c shows the influence of the wall at the local level; the typical stress diagram of a bare frame is normally completely different from the presented here, demonstrating that ignoring masonry walls during the design of a structure can lead to errors on the expected stress resultants.



(a) (b) (c)

Figure 1. Global displacements for different seismic demands for RC (**a**) Bare-frame and (**b**) Infilled frame (adapted from Ref. [1]), and (**c**) Local demands' influence on infill wall on the RC columns.

Infill walls are considered non-structural elements in RC structures because they are not intended to carry loads in static conditions. However, in case of higher deformations, lateral or vertical, these elements become active, change the response of the frame structure, and claim a structural influence, typically causing a reduction of the bending moments and an increase on the axial loads on the columns and beams. These aspects become even more important since the requirements for non-linear response evaluation of structures, according to new codes, are also higher. The walls increase the lateral strength of the frames locally, however globally they may reduce the base-shear strength of a structure due to failure on a certain level. At a global level, the infill walls can contribute to an increase of stiffness with the direct consequence of reducing the lateral displacements and can improve the dynamic behavior due to higher energy dissipation through friction on the structural interfaces between infill and frame.

The uncertainties related with the behavior of infilled frames are numerous. For medium-strong lateral loads, the frame tendency to deform creates a detachment between infill and frame. In this process, the contact length is mainly controlled by the relative stiffness between the involved elements. The bond strength between infill and frame on the mortar boundary layers is less significant for the global behavior of the system. Openings affect the behaviour of the infilled frame because the stiffness is not homogeneous which can result, for example, in short-column mechanisms, locally, or in undesirable loss of stiffness in a smaller region of the structure, globally. Hereupon it is noteworthy that infill walls with more than 50% of openings are usually ignored because the behaviour of the system is close to the bare frame. Moreover, as seen in **Figure 1**, infill walls completely change the load redistribution of the structure, creating, for example, local stresses concentrated near the corner region, which in turn can affect structural stability, causing another source of uncertainties.

Fardis (2009) assesses that the effect of masonry infills is generally beneficial for an infilled building without irregularities [2]. **Table 1** summarises the advantages and disadvantages on the integration of infill masonry walls on RC buildings.

Table 1. Pros and cons of infill masonry walls on frames.

Advantages	Disadvantages
Structure protection for low and medium earthquakes	Degradation of stiffness, strength, and energy dissipation capacity
Higher stiffness	Stiffness irregularity in height (soft-storey) and in plan (torsion)
Higher strength	Strength irregularity in height (weak-storey)
Reduction of lateral resisting contribution from the columns	Concentration of shear in columns beams and joints
Reduction of deformations on the structure	Increase of axial loads on columns
Higher energy dissipation capacity	Higher stress demand due to higher frequencies, especially on the foundations

By neglecting the existence of the infill walls, a wrong lateral stiffness is indirectly assumed [3][4] for the structure in analysis, introducing potentially dangerous consequences such as unrealistic seismic design actions, prevention from accounting for torsional effects, formation of mechanisms, or local failures. It is worth noticing that although many issues were discussed about the behavior of infilled frames, the capacity of these infilled systems are stronger when compared to unreinforced masonry walls.

1.1. Failure Modes

Different failure modes may occur depending on the properties of the materials and the stress rate [5]. Several researchers have classified those modes in a slightly different way. The following list is a collection of some definitions; however, it is important to keep in mind that failure is usually attained through a combination of different modes and not due to a single reason. Some failure modes are identified as dominant nevertheless.

1.1.1. On Masonry Infill Wall

Many studies in the literature assess the various masonry infill failure modes. In some research papers [6][7][8][9], the failure modes are categorised into the following groups:

- Purely Flexural. It is identified as the case in which frame and infill wall cooperate as a unique element during a low loading phase. Since it does not reach a failure state from this behaviour, the mode is not considered as a primary failure mechanism.

- Sliding Shear. This failure occurs from the shear failure on the bed joint layer of the masonry infill wall. It is one of the most important failure modes, which decreases the stiffness of the panel and may create local deficiencies on the frame, but not an ultimate failure because the panel maintain some lateral strength capacity for the infilled frame. The mode occurs in masonry walls with a weak mortar joint and a strong frame.

Multiple Sliding Shear. This mode is a special case of the previous one. While the single sliding shear is usually observed for an individual layer located near the middle of the panel, for the case of multiple sliding, the formations are distributed along the height of the panel, creating fewer local problems in the RC frame.

- Diagonal Compression. Occurs from the crushing of the infill. It may be located on the central region, and it is associated with slender infill walls and out-of-plane buckling.

- Corner Crushing. Crushing by compression located on one or more corners of the masonry panel, with probability of occurrence for weak infills within frames with strong members and weak joints.

- Diagonal Cracking. It is the formation of cracks along the infill compression strut, or also in the horizontal layer along the panel’s half height. It is common to occur together with sliding shear, corner crushing, or frame failure modes.

- Out-of-Plane. It is characterised by a more destructive and spectacular failure compared to in-plane failures. Seismic action does not occur perfectly aligned to the building directions. Therefore, the failure often occurs with a combination of in-plane and out-of-plane forces, with initial cracking caused by in-plane forces that weaken the wall substantially. Masonry walls, as infills for frame structures, due to the interaction with the bounding frame can develop out-of-plane resistance through the arching mechanism, which is mainly dependent on the slenderness of the wall, on the compressive strength of the masonry and on the support conditions. The risk for this type of failure can be greatly reduced by decreasing distances between supports, use of proper floor-to-ceiling supports, and attachment between walls and frames, however the available knowledge in this regard is still limited, especially for non-pure out-of-plane failure considering prior in-plane damage.

- Frame Failure. An obvious possibility for the failure is the formation of plastic hinges in the columns, or shear failure in the beam-column joints or columns. It can be caused by either a weak frame or weak joints with a strong infill. The failure induced by the infill walls may arise from a number of factors. The increase of stiffness and the forces introduced by the infills can elevate the axial stresses on columns (both in tension and compression). The diagonal truss of the infill creates a concentration region where the wall transfers some of the stress near the joints, resulting in increased shear stresses on both columns and the beams. In such a scenario the joints may fail, causing the failure of the system. The flexural and shear demands may increase even more if a short column is formed by an infill shear failure or by the existence of openings.

From this list, considering only in-plane demands, the most dominant types of failure are sliding shear on mortar layers, corner crushing, and cracking by diagonal tension. **Table 2** correlates the in-plane failure modes with the infilled frame conditions. The blank spaces are too unpredictable to assume a tendency for the failure.

Table 2. Prediction of failure relating the strength of the frame and infill panel.

Weak Infill	Strong Infill

Weak Frame		Shear Sliding Diagonal Cracking Frame Failure
Strong Members Weak Joints	Corner crushing	Shear Sliding Diagonal Cracking Frame Failure
Strong frame	Corner crushing	

1.1.2. Structural Implications

The interaction of the non-structural elements with the structural elements, specifically infill masonry walls with columns, beams and their joints, has great structural implications. The combination of both responses during an earthquake increases the complexity of the system and may prove crucial for the structural safety.

The infill walls, when distributed irregularly in plan, may introduce dangerous torsion effects on the buildings, which may lead to global collapse. On the other hand, when infills are distributed irregularly in elevation, soft-storey mechanisms (collapse/failure of a building’s level) can occur. Similar consequences can be inflicted if the stiffness of the infill walls is not properly balanced both in elevation and in plan, as a result of concentration of openings, thicker walls, etc., in a smaller region of the building. Weak infill walls, in-plane damage, and out-of-plane damage can induce the same vulnerable mechanisms of soft-storey and torsion. As a direct consequence on a local level, various adverse conditions may occur, such as column and joint shear failure due to strong infill or formation of short-column mechanism. At a global level, infill walls increase the stiffness of frames, which creates higher base-shear demands and also changes completely the redistributions of stresses on the structure.

2. Seismic Performance

The presented earthquakes were examined for the seismic behaviour of RC buildings.

Mosalam and Gunay (2012) and Estêvão (2012) are in-depth references on this topic [10][11].

Hamburger and Meyer (2006) studied the San Francisco, USA earthquake, in 1906, based on old damage-analysis reports [12]. The referred beliefs that infilled steel-frame structures had a good performance, with increased strength, stiffness and ductility, were questioned because they were dependent on the limited knowledge level of that period, since the infill wall’s influence started to be studied years later.

Tiedemann (1980), for the Guatemala City, Guatemala earthquake, concluded that 80% of the total costs associated with damage in buildings were due to the non-structural elements (namely, infill walls, supply systems, and other equipment) [13].

On the earthquake of Northridge, USA in 1994 [14], 16 of the 58 fatalities were due to collapses of buildings with a soft lower storey, characterised by the absence of strength degradation of infill masonry walls.

For Kobe, Japan in 1995 [15], the buildings built after the new Japanese seismic code of 1981 performed well, excluding buildings with a soft ground storey. The main issues on those RC buildings were soft-storey mechanisms leading to severe damage or collapse, torsion effects, insufficient detailing at the shear reinforcement, short-column mechanism, damages on infill walls, and damages on the separation joints between non-structural and structural elements.

In Dinar, Turkey 1995 [16], 40% of RC buildings collapsed or had severe damages. The main vulnerabilities were column slenderness, bad detailing on transversal reinforcement, soft-storey, bad quality of materials, and high levels of damage on infill walls.

The studies for the earthquake of Jabalpur, India in 1997 showed that the majority of buildings without infill walls at the base-storey suffered the most from the earthquake, and that—in general—buildings with infill walls had a satisfactory performance [17]. Moreover, the impact of infill walls placement was observed.

The major damages verified after the earthquake of Adana-Ceyhan, Turkey, 1998 [18], occurred on non-structural elements, both by in-plane and out-of-plane failure. The buildings designed with the new seismic philosophies still did not perform satisfactorily, showing vulnerabilities of weak-column-strong-beam mechanism, irregularities in plan, inadequate shear reinforcement, and other construction deficiencies.

The observed issues on Kocaeli, Turkey’s earthquake of 1999 [19][20], were soil liquefaction, weak storeys, short columns, inadequate column confinement, bad detailing, and damages on infill walls at the lower storeys. Some collapses were initiated with the failure of infills on a specific level. Different behaviours were observed in this earthquake, since some buildings showed a large level of damages while others nearby did not. Since those incidents involved buildings with similar design philosophies, the damages could be correlated to the influence of infill walls’ placement, quality of the concrete, bad detailing, or construction quality.

In Greece, until 1999, buildings were not designed with ductility requirements. When the Athens, Greece earthquake occurred on 7 September 1999, issues related to bad quality of materials, inadequate reinforcement, bad connection quality in joints, existence of short columns and weak storeys were observed [21].

On Chi-Chi’s earthquake, Taiwan in 1999 [22][23][24], the main issues observed were weak storeys, short columns, the weak-column-strong-beam mechanism, and low ductility on columns due to detailing.

For the earthquake of Gujarat, India in 2001 [25][26][27], the main damages were due to weak storeys, insufficient ductility because of bad detailing and quality of materials applied on the structural elements. Irregularities in plan and in elevation increased the observed damages. The infill walls were identified as inducing issues of soft storeys, the short-column mechanism, and torsion effects. Favourable aspects were also mentioned related with avoidance of collapse on some buildings with bad quality.

In Bingöl, Turkey 2003 [28][29][30], the main issues were related with discontinuities on vertical elements, weak storey, short columns, long cantilevers, irregularities in plan and elevation, and bad quality of detailing and execution.

For Sumatra, Indonesia, 2004 [31][32][33][34], the main issues were related with soft storeys, short columns, detailing on column-beam joints, and interaction between infill walls and structure.

On the earthquake of Sichuan, China 2008 [35][36], the main issues were the collapse of columns because of shear failure and excessive deformations, and also soft-storey mechanisms. The infill walls were considered to have a strong influence on the observed damages.

Haiti's earthquake of 2010 exposed bad construction quality and inadequate detailing. It was also verified that masonry walls, built with concrete units, performed badly [37][38]. The earthquake of Maule, Chile of 2010 had a long duration, between 2 and 5 min, and also high vertical accelerations. However, the design of RC buildings in Chile is very advanced and—in general—buildings had a good response. Some issues were identified regarding soft-storey mechanisms and horizontal cracks on the RC walls, instead of the usual diagonal [39]. The behaviour of the buildings for the earthquake of Christchurch, New Zealand in 2011 was—in general—satisfactory. The main issues were related with a pounding phenomenon between adjacent buildings [40][41]. For Tohoku, Japan's earthquake in 2011 the identified damages were highly related with the tsunami and liquefaction of the soils [42].

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