SEISMIC BEHAVIOR OF INFILL FRAMES

Unreinforced masonry (URM) infill walls are extensively used throughout the world, including seismically active regions. They often serve as partitions in reinforced concrete (RC) buildings, in which they affect both the structural performance and the post-earthquake usability of these buildings.

Non-ductile RC frames with URM infill walls may be considered as one of the world's most common types of seismically vulnerable buildings. In such buildings, the seismic vulnerabilities present in the RC system (such as lack of confinement at the beam and column ends and the beam-column joints, strong beam-weak column proportions, and presence of shear-critical columns) are compounded by the complexity that results from the interaction of the infill walls and the surrounding frame, and the brittleness of the URM materials. Many buildings of this type have performed poorly and have even collapsed during recent earthquakes in Turkey, Taiwan, India, Algeria, Pakistan, China, Italy and Haiti.

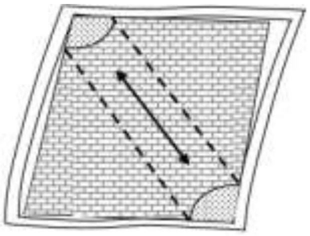
Adding infill walls to the RC frame modifies the behavior of the structure, especially under seismic loads. The type of failure that will occur in an infilled frame depends on several factors and is usually difficult to predict. For example, the relative stiffness of the frame and the infill panel, the strength of the structural components and the dimensions of the structure all influence the failure mode. In some cases, the overall failure is one of the failure modes shown below; at other times, it is a combination of these failure modes.

Modes of Failure of Masonry Infill Frames without Openings

Based on both experimental and analytical results during the last five decades (for example, by Thomas (1953), Wood (1958), Mainstone (1962), Liauw and Kwan (1983), Mehrabi and Shing (1997), Al-Chaar et al. (2002)), different failure modes of masonry infilled frames without openings have been proposed by these researchers. These failure modes can be classified into five distinct modes (Wood (1978), El-Dakhakhni (2002), Ghosh and Amde (2002), El-Dakhakhni et al., (2003)), as shown below (the following drawings have been adopted from Mosalam and Günay (2012)):

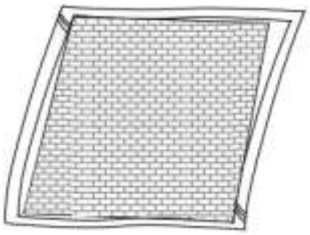
Compression failure of diagonal strut

The compression failure of diagonal strut (also referred to as the Corner Crushing (CC) mode of failure) usually occurs through crushing of the infill in at least one of its corners, as shown in the drawing at right. This type of failure takes place when the infill material has a low compressive strength. This mode of failure is frequently observed.



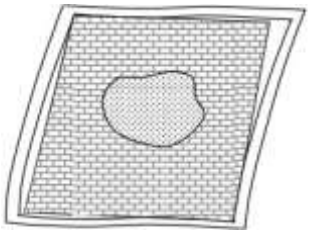
Damage in the frame members

When the compressive strength of the masonry infill is high, then the forces transferred from the infill wall to the surrounding frame result in the damage of the columns earlier than the damage in the infill, as shown in the drawing on the right. Some researchers describe this as the Frame Failure (FF) mode. If the building design does not consider the effect of the adjacent strong infill walls, then this failure mode might result in shear damage in the columns due to the additional horizontal forces transferred from the infill wall, even when the columns are designed with capacity design. In addition, plastic hinges may form in the columns, beams, or beam-column joints. In rare cases, tension failure of the columns may occur in the infilled frames with a high aspect ratio (wall height to length ratio) due to the additional vertical forces transferred from the infill walls. This mode of failure may result in the collapse of the structure, if the damage to the frame is severe enough.

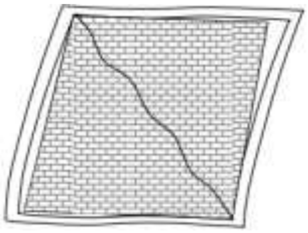


Out-of-plane failure

Out-of-plane effects cause failure in which the damage occurs in the central region of the infill panel due to the arching action of the infill wall, as shown in the drawing at right. This mode of failure may occur for two reasons: the inertial forces in the out of plane direction of the wall, or the out-of-plane buckling instability of the infill associated with a relatively slender infill (Mosalam and Günay (2012). In the first circumstance, the combined effect of out-of-plane and in-plane forces reduces the infill strength in both directions, which increases the probability of both an out-of-plane and an in-plane failure. Failure due to the second reason is rarely observed: it requires a high slenderness ratio of the infill, which results in an out-of-plane buckling of the infill under in-plane loading. This is uncommon when practical panel dimensions are used, and when the panel thickness is designed to satisfy acoustic isolation and fire protection requirements. It should be noted that out-of-plane (OOP) failure of the URM infill walls creates a life-safety hazard due to falling debris.

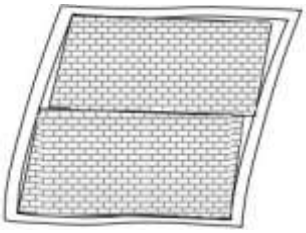


Diagonal cracking



In cases where the infill wall material has a high compressive strength, diagonal cracking may be observed connecting the two corners where contact between the infill and the frame takes place, as shown in the drawing at right. Even after cracking, the infill wall can still carry some loads. For that reason, this mode is not designated a failure mode by some researchers.

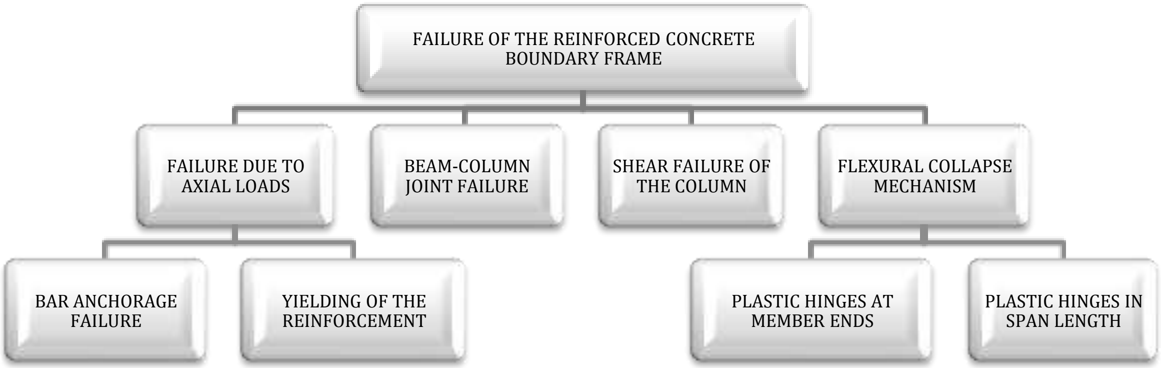
Sliding shear



Weak mortar joints may result in shear failure through the bed joints of a masonry infill wall, as shown in the drawing at right. When mortar joints are weak in comparison to the masonry units, or when shear stress predominates over normal stress (low to medium aspect ratio), cracking usually occurs via debonding along the mortar joints. The cracking may be horizontal or along the diagonal, with a stepped pattern. This mode of cracking is widely observed.

In summary, the failure of masonry panels can take place through debonding of the mortar joints, cracking or crushing of the masonry units, or a combination of any of these. The type of failure depends upon the material properties and stress state induced in the panel (Zhang (2006)).

As mentioned above, different failure mechanisms can develop in the surrounding frame due to the properties of structural components, frame and infill panels, and the interaction between them. Crisafulli (1997) presented the different frame failure mechanisms listed above in a graphical form.



Modes of Failure of Masonry Infill Frames with Openings

Experimental studies, such as those carried out by Asteris et al. (2011), indicate clearly that the behavior of infilled frames with openings differs considerably from that of solid infill frames. The size and, in particular, the location of the opening have a significant effect on the overall behavior of the structural system. The modes of failure of infill frames with openings are far more complex than those of solid infill panels. Plastic hinges may appear in columns; there may be a combination of compressive failure and crushing of the infill; there is a different behavior of the infill in the region between the opening (door/window) and the column in tension as compared to the region between the opening and the column in compression; and there may also be a shear sliding of the infill (Asteris et al. (2011)).

Interaction of the Infill Panels with the Frame

URM infill walls are often treated as architectural elements and thus, not considered during structural analysis and design. However, as structural elements, they may have either beneficial or detrimental effects. Infill walls contribute to the lateral force-resisting capacity and damping of the structure, up to a certain level of ground motion. They increase the initial stiffness, and decrease the initial period, of the structure. This might be beneficial, depending on the frequency content of the experienced ground motion; the 2009 earthquake in L'Aquila, Italy offers one example of this beneficial observed behavior. However, URM infill walls are prone to an early brittle failure, which may lead to the formation of a weak story. In addition, the infill walls may interact with the surrounding frame in such a way that a column shear failure occurs.

Also, non-uniform or unbalanced distributions of infill walls within the frame may lead to some global configuration problems and failure modes, such as weak or soft stories, and torsion. Weak or soft stories result when there are comparatively few (or no) infill panels in one story - particularly, the ground story. Commercial spaces (shops) or parking areas at the ground story are common reasons why the ground story may have fewer walls. During an earthquake, the deformation and damage tend to concentrate in the relatively open story and can lead to its collapse. Even in instances when solid infill walls extend the full height of the building, if they are of the same strength, then earthquake forces will generally be the largest in the bottom story. These forces will tend to cause infill walls to fail, leading to the formation of a weak and soft story.

Infill walls can also induce torsion in instances when some sides of a building have solid infill walls, while other sides (usually for architectural or usage purposes) have either infill walls with openings or no infill walls. Torsion failures occur when infill walls are concentrated on one side of a building. An example would be a building with two property line walls, where all bays are completely infilled and there are two relatively open sides with windows and shop fronts. The stiffness imbalance may cause the building to twist, thereby increasing the deformation demands on the frame members in the two more open sides.

Considering the behavioral features mentioned above, a proper understanding of the failure modes of URM infill walls and the surrounding RC frames is important for the seismic evaluation and selection of adequate retrofits of existing buildings, as well as for developing new building designs.

Selected References

Al-Chaar, G., Issa, M. and Sweeney, S. (2002). “Behavior of Masonry-Infilled Nonductile Reinforced Concrete Frames.” J. Struct. Engrg. ASCE, 128 (8), pp. 1055-1063.

Bin Zhang. (2006). “Parametric Study on the Influence of Infills on the Displacement Capacity of RC Frames”. Master’s Thesis, European School for Advanced Studies in Reduction of Seismic Risk.

Crisafulli, F.J. (1997). “Seismic Behaviour of Reinforced Concrete Structures with Masonry Infills,” PhD Thesis, University of Canterbury, New Zealand.

El-Dakhakhni, W. W. (2002). “Experimental and Analytical Seismic Evaluation of Concrete Masonry-Infilled Steel Frames Retrofitted using GFRP Laminates.” PhD Thesis, Drexel University.

El-Dakhakhni, W. W., Elgaaly, M., and Hamid, A. A. (2003). “Three-Strut Model for Concrete Masonry-Infilled Frames.” J. Struct. Eng., ASCE, 129(2), 177-185.

Ghosh, A. K., Amde, A.M. (2002). “Finite Element Analysis of Infilled Frames.” J. Struct. Engrg., ASCE, 128(7), 881-889.

Liauw, T. C., and Kwan, K. H. (1983). “Plastic Theory of Nonintegral Infilled Frames”, Proceedings of the Institution of Civil Engineers (London), Part 2, 75, 1983, pp. 379-396.

Mainstone, R. J. (1962). “Discussion on Steel Frames with Brickwork and Concrete Infilling.” Proc., Instn. Civ. Engrs., 23, 94-99.

Mehrabi, A. B., Shing, P. B. (1997). “Finite Element Modeling of Masonry-Infilled RC frames.” J. Struct. Engrg., ASCE, 123(5), 604-613.

Mosalam, K.M. and M.S. Günay, (2012)“Chapter 23: Seismic Analysis and Design of Masonry-Infilled Frames," in Structural and Geotechnical Engineering, S.K. Kunnath, Editor, Encyclopedia of Life support Systems (EOLSS) Publishers, Oxford, UK.

P.G. Asteris, D.J. Kakaletsis, C.Z. Chrysostomou, E.E. Smyrou. (2011).“Failure Modes of In-filled Frames.” Electronic Journal of Structural Engineering 11(1).

Thomas, F. G. (1953). “The Strength of Brickwork.” Struct. Engrg. 31(2), 44-46.

Wood, R. H. (1958). “The Stability of Tall Buildings.” Proc., Instn. Civ. Engrs., 11, 69-102

Wood, R. H. (1978). “Plasticity, Composite Action and Collapse Design of Unreinforced Shear Wall Panels in Frames.” Proceedings of the Institute of Civil Engineers 1978: 65(2): 381–441.