BEHAVIOR AND MODELING OF REINFORCED CONCRETE FRAMES WITH UNREINFORCED MASONRY INFILL WALLS

Khalid M. Mosalam and **M. Selim Günay**
Department of Civil and Environmental Engineering, University of California, Berkeley, CA 94720-1710, USA

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Contents

Summary

Reinforced Concrete (RC) frames with Un-Reinforced Masonry (URM) infill walls are commonly used structural systems in seismic regions around the world. It is recognized that many buildings of this type have performed poorly during earthquakes. In the United States, their construction is no longer permitted. However, many such structures still exist. Besides, their construction is still continuing in many seismic regions around the world. Hence, it is essential to understand the behavior of this complex structural system. Accordingly, proper modeling is required for the seismic evaluation and for the selection of adequate retrofit methods, if needed. This chapter presents observations of damage from recent earthquakes related to RC frames with URM infill walls. Previous experimental and analytical research on infill walls is subsequently reviewed. Finally, a multi-phase study of RC frames with URM infill walls is presented.

1. Introduction

Un-Reinforced Masonry (URM) infill walls are widely used throughout the world, including seismically active regions, particularly as partitions in Reinforced Concrete (RC) buildings affecting both the structural and nonstructural performance of these buildings. When 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, presence of shear-critical columns, etc) are combined with the complexity due to the interaction of the infill walls and the surrounding frame and the brittleness of the URM materials, non-ductile RC frames with URM infill walls may be considered as one of the world's most common types of seismically vulnerable buildings. It is recognized that many buildings of this type have performed poorly and even collapsed during recent earthquakes in Turkey, Taiwan, India, Algeria, Pakistan, China, Italy and Haiti. In many countries with emerging economy, vulnerable infilled frame buildings continue to be built at a rapid rate in order to keep up with urban population growth, representing major contributors to the increasing levels of global earthquake risk. Many buildings of this type that predate modern codes are also present in cities of developed countries.

URM infill walls are generally treated as non-structural elements which are used mainly for architectural purposes. However, as structural elements, they have both beneficial and 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, which might be beneficial depending on the frequency content of the experienced ground motion, an example of which is the recent 2009 earthquake in L'Aquila, Italy. However, the URM infill walls are prone to early brittle failure and the infill wall failure may lead to the formation of a weak story. In addition, infill walls interact with the surrounding frame in such a way that column shear failure is made more likely. There is an interaction effect between the in-plane strength of the wall and its out-of-plane strength, with load in one direction reducing the strength in the other. Moreover, Out-Of-Plane (OOP) failure of the URM infill walls leads to life-safety hazard from falling debris. Related to configuration problems, non-uniform distribution of infill walls may lead to negative effects on the general behavior of a building. Many buildings have a soft story created by commercial space (shops) or parking at the ground floor. Infill walls can also induce torsion when some sides of the building have solid infill walls and the other sides have either infill walls with openings or no infill walls for architectural or usage purposes.

Considering the above mentioned behavioral features, proper modeling of URM infill walls within RC frames is important for seismic evaluation and consequently for the selection of adequate retrofits. This chapter presents observations and damage of RC frames with URM infill walls from recent earthquakes. Previous experimental and analytical research on infill walls is subsequently reviewed. Finally, a multi-phase study of RC frames with URM infill walls is presented.

2. Observations from Recent Earthquakes

A large number of RC frames with URM infill walls have performed poorly and even collapsed during recent earthquakes in the 1990s and 2000s. In this section, observations related to damage in RC buildings with URM infill walls from four recent earthquakes, namely 1999 Kocaeli earthquake in Turkey, 2008 Wenchuan earthquake in China, 2009 L'Aquila earthquake in Italy, and 2010 Haiti earthquake, are presented. Kocaeli earthquake was a 7.4 magnitude earthquake which took place on the 1500-km-long North Anatolian fault in northwestern Turkey on August 17, 2009. Wenchuan earthquake was an 8.0 magnitude earthquake occurred on the 480 km-long and 100 km-wide Longmenshan fault on the northwestern margin of the Sichuan basin, China, on May 12, 2008. L'Aquila earthquake was a 6.3 magnitude earthquake which struck the central region of Italy near the city of L'Aquila, the capital of the Abruzzo region on

April 6, 2009. Haiti earthquake was a 7.0 magnitude earthquake centered approximately 25 km west of Port-au-Prince, the capital of Haiti, on January 12, 2010.

Two buildings, for which the damage after Wenchuan earthquake is concentrated at the first story, are shown in Figure 1. The first building, shown in Figure 1(a), is a six story building where the first story was used as a parking space and had less infill walls while the upper stories were residential and had many infill walls. The building leaned to the west after the Wenchuan earthquake with about 200 mm drift concentrated in first story columns. Figure 1(b) shows the second building which is a five-story RC frame building with the first story used as a commercial space and the upper stories were residential. The building was constructed with hollow shale tiles infill walls in the frames perpendicular and parallel to the sidewalk in the stories above the first story. In the first story, URM infill walls were only present in the back of the building with open front and sides. The first story columns in this building were severely damaged and likely close to loss of gravity load capacity because of the combined effect of soft first story and the torsional irregularity created by the non-uniform distribution of infill walls around the building perimeter.

(a) Six story building (b) Five story building

Figure1. First story damaged buildings – Wenchuan earthquake (photos by K. Mosalam)

Figure 2 compares the damage of the building shown in Figure 1(a), the frontal one in Figure 2(a), with a building having more infill walls in the first story, the back one in Figure 2(a). As mentioned before, the former building experienced about 200 mm drift in the first story, whereas the latter building exhibited shear cracks in the first story infill walls and minor damage in the columns (Figures 2(b) and (c)), where the presence of infill walls in the first story likely played an important role in this better performance.

(a) Major damage (b) Moderate damage (c) Infill and column damages

Figure 2. Effect of the lack of first story infill walls on damage – Wenchuan earthquake (photos by B. Li)

Figures 3(a) to (f) show a group of photographs of infill walls in several three-story moment resisting frame buildings that were under construction during the time of the Wenchuan earthquake. All of these infill walls were constructed with hollow shale tiles, some of them had facing material or decorative surfacing. Some of the weakest hollow shale tiles suffered compression damage, and then parts of the infill wall collapsed at the time of the earthquake. However, the beams and the columns suffered minor damage in the cases shown in Figures 3(a), (b) and (c). The lower strength and greater stiffness of the hollow shale tiles infill walls compared with the RC frames caused damage to concentrate in the former, which dissipated part of the earthquake energy and protected the RC frame. The beams and columns suffered moderate to major damage in the cases shown in Figures 3(e) and (f). In all cases, infill walls suffered a combination of compression and shear damages.

Figure 3. Damage of URM infilled RC frames – Wenchuan earthquake (photos by B. Li)

The interaction between the URM infill wall and the surrounding frame depends on the relative strength and stiffness of the infill wall with respect to the bounding frame as well as the interface between the frame and the infill wall. As shown in Figure 3, when the infill wall is stiff but has low strength (hollow shale tiles), it can be damaged before it transfers sufficient force to the frame to cause damage of the frame. In the case of the infill being stiff and possessing higher strength (solid clay bricks), it can damage the surrounding frame as shown in Figure 4(a). However, in the case of no connection between the frame and the infill wall, the infill wall is damaged because of its brittle behavior. In this case, the frame may undergo minor damage because significant force is not transferred from the infill wall even though it has high stiffness and strength (Figures 4(b) and (c)).

(a) Moderate damage to RC frame and URM infill wall

(b) URM infill wall damage and negligible RC frame damage

(c) URM infill wall damage and minor RC frame damage

Figure 4. Frame-infill wall interaction – Wenchuan earthquake (photos by B. Li)

Figure 5 shows a five-story building, the third story of which collapsed during the 2009 L'Aquila earthquake. It can be observed that the column sizes are small and therefore the infill walls had significant contributions to the story stiffness. For low to medium rise URM infilled RC buildings without vertical stiffness or strength discontinuities, first story infill walls are expected to be damaged first since they are subjected to the highest shear forces due to earthquake shaking. However, under bidirectional loading, infill walls of the upper stories may fail under the combination of OOP and In-Plane (IP) effects. Infill walls of the third story of the building in Figure 5 likely failed under the OOP/IP interaction. It can also be observed that some of the fourth story infill walls also failed, while infill walls of the other (first, second, and fifth) stories remained intact. After the failure of the infill walls, a soft and weak third story formed. It is speculated that the presence of stronger beams relative to the columns led to the formation of hinges at both of the column ends, which led to the collapse of the third story as a result of increasing deformations.

Figure 5. Story collapse due to infill failure – L'Aquila earthquake (photos by K. Mosalam)

A corner joint damage from L'Aquila earthquake is shown in Figure 6. It can be observed that the upper portions of the infill walls on both sides of the joint failed. These infill failures clearly affected the level and nature of the corner joint damage. If these infill walls did not fail, they would have transferred additional shear forces to the column from both building sides by compression strut actions. Moreover, these additional forces on the column would have reduced the shear forces on the corner joint. Although it can be observed that the joint is poorly detailed due to the lack of sufficient transverse reinforcement, it may have been possible to reduce the joint damage caused by the earthquake by spreading the damage to the column if the infill walls did not fail.

Figure 6. Joint failure due to infill damage – L'Aquila earthquake (photos by K. Mosalam)

As it is stated previously, for low to medium rise URM infilled RC buildings without vertical stiffness or strength discontinuities, first story infill walls are expected to be damage first leading to the formation of weak and soft stories during ground shaking. Two buildings, the first story of which failed in Kocaeli and Haiti earthquakes are shown in Figure 7 and Figure 8, respectively. The first two stories of the building in Figure 7 failed completely, but damage in the upper four stories with even unbroken glass windows was limited. The first story of the building in Figure 8 failed, but there was no visible damage in the upper stories. Significant stiffness of the infill walls with respect to the framing system might have played a role in these failures. The brittle fracture of the first and second story infill walls in Figure 7 or only first story infill walls in Figure 8 prior to columns flexural yielding would have overloaded the non-ductile first and second story (Figure 7) or only first story (Figure 8) columns in shear, likely resulting in the observed gravity load failure.

Figure 7. First two stories collapsed building – Kocaeli earthquake (photos by K. Mosalam)

Figure 8. First story collapsed building – Haiti earthquake (photos by E. Fierro)

3. Previous Research on Infill Walls

Effect of infill walls on the behavior of frames under earthquake excitation has been the subject of numerous analytical and experimental investigations in the last three decades. Previous research on infill walls and the effect of infill walls on the behavior of frames under earthquake excitation are presented in this section.

3.1. Analytical Studies

Analytical models of infill walls can be categorized as micro-models and macro-models from the point of view of the utilized simulation technique. Micro-models are more detailed Finite Element (FE) models, which are better suited for analyzing the behavior of frames with masonry infills, whereas macro-models are more global elements (generally equivalent diagonal struts) which are suitable for design and practical assessment purposes.

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Bibliography

Federal Emergency Management Agency (2000), *Pre-standard and Commentary for the Seismic Rehabilitation of Buildings*, (FEMA 356); Reston, Virginia. [This report is a pre-standard for seismic rehabilitation of buildings which is widely used throughout the world.]

American Society of Civil Engineers (2008). *Seismic Rehabilitation of Existing Buildings* ASCE/SEI Standard 41-06, ASCE, Reston, VA. [This report is the recent standard in USA for seismic rehabilitation of buildings which is widely used throughout the world.]

Elkhoraibi, T. and Mosalam, K.M. (2007), "Generalized Hybrid Simulation Framework for Structural Systems Subjected to Seismic Loading," *Pacific Earthquake Engineering Research Center*, PEER

2007/101. [This report presents the development of the hybrid simulation framework utilized for the multi-phase study of RC frames with URM infill walls.]

Fardis M. N., Bousias S. N., Franchioni G. and Panagiotakos T. B. (1999). "Seismic Response and Design of RC Structures with Plan-Eccentric Masonry Infills," *Earthquake Engineering and Structural Dynamics*, **28**(2), 173-191. [This paper presents shaking table tests performed on single-bay, two-story RC frames with eccentric masonry infills subjected to bidirectional ground acceleration.]

Flanagan R.D. and Bennett R.M. (1999). "Bidirectional Behavior of Structural Clay Tile Infilled Frames," *Journal of Structural Engineering*, ASCE, **125**(3), 236-244. [This paper presents a set of experiments which consists of a series of in-plane, out-of-plane, and combined in-plane and out-of plane experiments for a single story, single-bay clay tile infilled RC frame.]

Günay, S., Korolyk, M., Mar D., Mosalam, K.M., and Rodgers, J. (2009). "Infill walls as a Spine to Enhance the Seismic Performance of Non-Ductile Reinforced Concrete Frames," *ATC&SEI Conference on Improving the Seismic Performance of Existing Buildings and Other Structures*, December 9-11, San Francisco, California. [This paper presents a cost-effective retrofit solution that is intended to be used in cities of emerging countries to prevent building collapses and save lives for non-ductile reinforced concrete frames with un-reinforced masonry walls.]

Hashemi, S.A. and Mosalam, K.M. (2007), "Seismic Evaluation of Reinforced Concrete Buildings Including Effects of Infill Masonry Walls," *Pacific Earthquake Engineering Research Center*, PEER 2007/100 [This report presents the shaking table experiments, finite element modeling, and reliability analyses for the multi-phase study of RC frames with URM infill walls.]

Kadysiewski, S. and Mosalam, K.M. (2009), "Modeling of Unreinforced Masonry Infill Walls Considering In-Plane and Out-of-Plane Interaction," *Pacific Earthquake Engineering Research Center*, PEER 2008/102. [This report presents one of the infill wall macro-models that takes into account in-plane and out-of-plane interaction within the scope of multi-phase study of RC frames with URM infill walls.]

Li, B., Wang, Z., Mosalam, K.M., and Xie, H. (2008), "Wenchuan Earthquake Filed Reconnaissance on Reinforced Concrete Framed Buildings with and without Masonry Infill Walls," *Proceedings of 14th World Conference on Earthquake Engineering*, Beijing, China, October 12-17, Paper S31-035. [This paper presents observations from Wenchuan, China earthquake related to reinforced concrete framed buildings with and without masonry infill walls.]

Liauw T.C. and Kwan K.H. (1985), "Static and Cyclic Behaviors of Multistory Infilled Frames with Different Interface Conditions," *Journal of Sound and Vibration*, **99**(2), 275-283. [This paper presents cyclic tests of small-scale models of four story infilled frames conducted with the aim of investigating the effect of connection between the infill wall and surrounding frame on the behavior of infilled frames.]

Mazzoni, S., McKenna, F., Scott, M.H., and Fenves, G. (2009), "Opensees User's Manual," Available from www.opensees.berkeley.edu. [This website contains the source code, manuals and examples for OpenSees, a software framework for developing applications to simulate the performance of structural and geotechnical systems subjected to earthquakes.]

Mehrabi, A.B., Shing P.B., Schuller M.P., and Noland J.L. (1994), "Performance of Masonry-Infilled R/C Frames under In-Plane Lateral Loads," *Structural Engineering and Structural Mechanics Research Series*, CU/SR-94/6, University of Colorado, Boulder, CO. [This report presents cyclic tests of 14 half-scale RC frames infilled with concrete block masonry with the objective of evaluating the influence of the relative strength and stiffness of an infill wall with respect to those of the bounding frame, the panel aspect ratio, the lateral load history, adjacent infill bays, and the magnitude and distribution of vertical loads on the performance of infilled frames.]

Mosalam, K.M., White, R.N., and Gergely, P. (1997), "Static Response of Infilled Frames Using Quasi-Static Experimentation," *Journal of Structural Engineering*, ASCE, **123**(11), 1462-1469. [This paper presents cyclic tests conducted on multiple-bay infilled frames with hollow concrete blocks with the aim of determining the effects of the number of bays, the relative strength between the concrete blocks and mortar joints, and the configuration of openings on the behavior.]

Mosalam, K.M., White, R.N., and Ayala, G. (1998), "Response of Infilled Frames Using Pseudo-Dynamic Experimentation," *Earthquake Engineering and Structural Dynamics*, **27**(6), 589-608. [This paper presents pseudo-dynamic tests conducted on multiple-bay, multiple-story infilled frames with hollow concrete blocks.]

Mosalam K.M. (2009), "Seismic Evaluation of Reinforced Concrete Frames with Masonry Infill Walls: Experiments, Observations, and Simulations," *11th Canadian Masonry Symposium*, Toronto, Ontario, keynote paper, May 31-June 3. [This paper presents an overview of experiments, simulations, and observations from earthquakes related to seismic evaluation of reinforced concrete frames with masonry infill walls.]

Reflak, J. and Fajfar, P. (1991), "Elastic Analysis of Infilled Frames Using Substructures," *Proceedings of 6th Canadian Conference on Earthquake Engineering*, Toronto, 285–292. [This paper represents an interesting approach in which each infill is treated as a substructure and the degrees of freedom are reduced to the boundary degrees of freedom by static condensation.]

Rivero C.E. and Walker W.H. (1982), "A model to Study the Interaction of Frames and Infill Walls," *Proceedings of the 3rd North American Masonry Conference*, 76:1-76:14. [This paper presents a nonlinear finite element model for dynamic analysis of infilled frames accounting for frame/wall discontinuities and interaction, wall cracking, wall bracing effect on the frame, and the frame inelastic behavior.]

Smith, B.S. (1966), "Behavior of Square Infilled Frames," *Journal of Structural Division*, ASCE, ST1, 381-403. [This paper presents one of the earliest uses of equivalent strut approach for modeling infill walls and it relates the width of the equivalent diagonal strut to the infill/frame contact lengths using an analytical equation.]

Talaat, M. M. and Mosalam, K.M. (2008), "Computational Modeling of Progressive Collapse in Reinforced Concrete Frame Structures," *Pacific Earthquake Engineering Research Center*, PEER 2007/10. [This report presents the development of the progressive collapse analysis for the multi-phase study of RC frames with URM infill walls.]

Zarnic R., Gosti S., Crewe A.J., and Taylor C.A. (2001), "Shaking Table Tests of 1:4 Reduced-Scale Models of Masonry Infilled Reinforced Concrete Frame Buildings," *Earthquake Engineering and Structural Dynamics*, **30**(6), 819-834. [This paper presents two shaking table tests performed on ¼-scale, one and two-story RC frames with strong block, weak mortar masonry infill walls subjected to unidirectional sinusoidal motion at the base of the structure.]

Biographical Sketch

Khalid M. Mosalam obtained his BS and MS from Cairo University and his PhD from Cornell University. He joined the SEMM group of UC-Berkeley in 1997 where he is currently a Professor and CEE Vice-Chair. He teaches structural analysis, finite element methods, and behavior and design of reinforced and pre-stressed concrete structures. He conducts research related to the performance and health monitoring of reinforced concrete, masonry, earth, wood and composite structural systems subjected to severe loading due to earthquakes or blasts. He also conducts research on essential facilities such as bridges and electrical substations. His research approach covers large-scale simulations, both deterministic and probabilistic, and large experimentation. He was a Visiting Prof. of Kyoto Univ. and Middle East Technical Univ. He is the recipient of the 2006 ASCE Walter L. Huber Civil Engineering Research Prize with the citation "For advanced computational research integrated with large experiments to solve practical structural engineering problems."

M. Selim Günay completed his Bachelor of Science in Middle East Technical University in Turkey in 2000. Then, he earned his M.S. and PhD degrees from the same university focusing on earthquake engineering in 2008. Since then, he has been a postdoctoral researcher at the University of California, Berkeley.