IMPROVING SEISMIC PERFORMANCE OF PARTIALLY-GROUTED REINFORCED MASONRY BUILDINGS

P. Benson Shing[1], Ahmad Hamid[2], Franklin Moon[3], Arturo Schultz[4] and Andreas Koutras[5]
[1]Professor, Department of Structural Engineering, University of California at San Diego, La Jolla, CA, USA, pshing@ucsd.edu
[2]Professor, Department of Civil, Architectural and Environmental Engineering, Drexel University, Philadelphia, PA, USA, ahmadhamid99@gmail.com
[3]Associate Professor, Department of Civil, Architectural and Environmental Engineering, Drexel University, Philadelphia, PA, USA, FLM72@drexel.edu
[4]Professor, Department of Civil Engineering, University of Minnesota, Minneapolis, MN, USA, schul088@umn.edu
[5]Graduate Student Researcher, Department of Structural Engineering, University of California at San Diego, La Jolla, CA, USA, akoutras@eng.ucsd.edu

ABSTRACT

This paper provides a summary of past research findings on partially-grouted reinforced masonry wall structures and an overview of a research project that has been recently initiated to examine the seismic performance of these structures at the system as well as component level, and to develop and validate economically competitive, improved, design details and retrofit methods to make new and existing partially-grouted reinforced masonry structures better meet current seismic performance standards. The project is being carried out as a joint effort of Drexel University, the University of California at San Diego, and the University of Minnesota. The experimental program to validate the new design methods and details will consist of seventeen partially-grouted reinforced masonry wall components and subassemblies to be tested with quasi-static cyclic loading, and two full-scale, one-story, buildings to be tested with earthquake ground motions on a shake table. Parallel analytical studies will be carried out to improve the shear strength formulas in current codes for partially-grouted walls and develop computational models that can predict the system level performance of these structures.

KEYWORDS: partially grouted, reinforced masonry, seismic performance, seismic design, seismic retrofit

INTRODUCTION

Reinforced masonry constitutes 10% of all low-rise construction in the US. Many of them are commercial, industrial, and school buildings. It is also used for multi-story hotels, college dormitories, and apartments. Walls are the main load-bearing elements in a masonry structure. According to ASCE/SEI 7-10 [1] and TMS 402-11/ACI 530-11/ASCE 5-11 [2], reinforced masonry load-bearing walls are classified into three types, namely, special, immediate, and ordinary wall systems, based on the reinforcing details and expected flexural ductility. These walls can be either fully or partially grouted. In a partially-grouted wall, only the cells containing reinforcing bars are filled with grout. For structures belonging to Seismic Design Category (SDC) D, only special wall systems are permitted. The maximum spacing of vertical reinforcing bars allowed for a special or intermediate wall is 1.2 m (4 ft.), while that for an ordinary wall is 3.0 m (10 ft.). For special walls, the economic benefit of partial grouting is not significant because any saving in the grouting material could be largely offset by the added labor. Hence, most of the reinforced masonry construction in the West Coast has fully-grouted walls, while those outside the West Coast are predominantly partially grouted even in regions of moderate to high seismic hazard levels.

The seismic performance of partially-grouted reinforced masonry wall systems has not been well studied. A few recent studies [3-10] have found some potential issues with this type of construction. First, their performance may not be as consistent as that of full-grouted masonry [8]. Furthermore, the strength design provisions in the masonry building code [2] are mainly based on experimental data obtained from fully-grouted walls. In particular, it has been observed that the shear strength formula in the code can be unconservative for partially-grouted walls [6]. To address these problems, a collaborative research effort has been undertaken by Drexel University, the University of California at San Diego, and the University of Minnesota. The main aim of this effort is to: (i) develop and validate practical and economically competitive design details to improve the seismic performance of partially-grouted reinforced masonry structures; (ii) develop and validate effective retrofit methods for existing partially-grouted reinforced masonry structures that may not meet current performance standards; (iii) assess and understand the seismic performance of partially-grouted reinforced masonry walls at the system level; (iv) improve the shear-strength formula in the current code for partially-grouted walls; and (v) develop reliable and efficient analytical models that can be used to assess the seismic performance and facilitate the design of these systems. This paper gives a summary of the past research that has motivated this effort and an overview of the research plan.

PAST RESEARCH FINDINGS

In the last twenty years, investigations on partially-grouted masonry include the work of Ghanem et al. [11,12], Schultz et al. [13,14], Ingham et al. [15], Voon and Ingham [16], Minaie [4], Minaie et al. [3,5,6], and Hamid et al. [7]. Ghanem et al. [11,12] investigated the effect of the distribution of vertical and horizontal reinforcement, and the axial compressive force on the in-plane response of partially-grouted masonry shear walls. They subjected six 1/3-scale wall specimens to monotonically increasing in-plane displacements under a constant vertical compressive load. They observed that the behavior and failure modes of partially-grouted masonry were strongly dependent on the distribution of the reinforcement and the level of the axial compressive load. Schultz [13] tested twelve partially-grouted concrete masonry shear walls under in-plane loads, six of which contained deformed bars as horizontal reinforcement in grouted bond beams, and six of which contained bed-joint wire reinforcement. The specimens were subjected to quasi-static cyclic lateral displacements with fixed-fixed end conditions and a nearly constant vertical compressive load. Schultz observed that the lateral load resisting mechanism developed in a partially-grouted wall could be vastly different from that in a fully-grouted wall. Cracks that formed between grouted and ungrouted cells tended to grow and disturb the anchorage region of the horizontal reinforcement where these bars intersected the vertical cells. Thus, increasing the amount of the horizontal reinforcement would only slightly increase the ultimate shear strength but had a negligible effect on the stiffness. Furthermore, upon evaluating different shear strength formulas, he concluded that a formula developed by Matsumura [17] best represented the trends observed in the tests.

Ingham et al. [15] tested thirteen partially-grouted concrete masonry walls with different aspect ratios, reinforcement quantities, and opening configurations. Nine of these walls had no openings, height/length ratios ranging from 0.6 to 3, and different reinforcement distributions. These walls were nominally reinforced and had shear reinforcement only in the top two courses of a wall. All of them showed diagonal shear failure because of the lack of shear reinforcement. Voon and Ingham [16] further tested eight partially-grouted walls that had openings. They observed that the strength of a wall decreased with the height of an opening and that extending the horizontal reinforcement right below a window opening to the ends of a wall can significantly enhance the lateral strength. Baenziger and Porter [18] studied the effectiveness of joint reinforcement in partially-grouted walls. They found that joint reinforcement was beneficial.

Minaie [4] tested four partially-grouted and four fully-grouted full-scale special reinforced masonry shear walls to compare their behaviors and to assess the appropriateness of current seismic design provisions for partially-grouted walls. The test variables included mortar formulation, level of axial stress, and boundary conditions. Results of this study have indicated that the behavior of partially-grouted masonry shear walls was similar to that of infilled RC frames, with a typical crack pattern as shown in Figure 1, and that there was little coupling between the vertical reinforcing bars in partially-grouted walls because the wall section did not remain plane during bending. Using these results along with those from past research, he has found that the shear strength formula provided in the masonry building code [2] was unconservative for partially-grouted walls. It could over-estimate their shear strengths by a factor of two. Results of this study can also be found in [3,5,6].

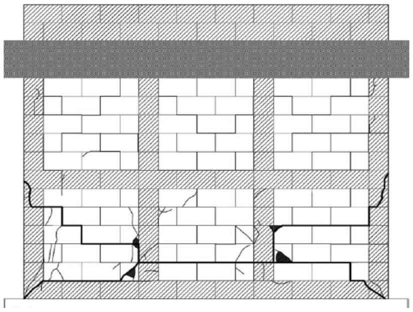
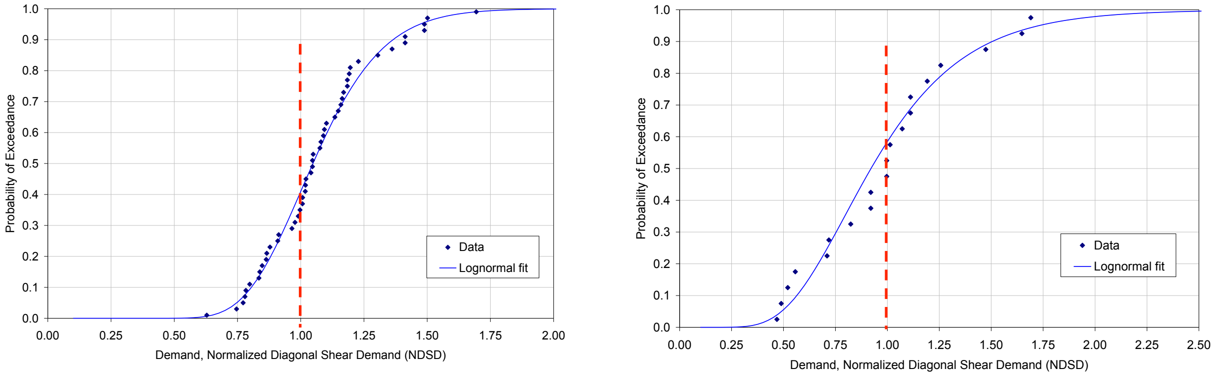


Figure 1: Partially-Grouted Wall Tested by Minaie [4]

Based on data obtained in a number of experimental studies, Murcia-Delso and Shing [8,9] have developed fragility functions for different flexural and shear damage states of partially- and full-grouted reinforced masonry walls. For the shear damage states, they have proposed a demand parameter that is defined as the maximum shear force induced in a wall component normalized by the nominal shear strength calculated with the code formula [2]. They have defined the state at which the peak shear strength of a wall has been reached as the severe damage state. Fragility curves depicting the probability of exceedance of this damage state as a function of the demand parameter are shown in Figure 2. One is for fully-grouted walls and the other for partially-grouted walls. The graphs illustrate two points. First, there are a lot more data available for fully-grouted walls than for partially-grouted walls. Second, the fragility function for partially grouted walls has a much higher dispersion than that for fully-grouted walls. This means that the probability of reaching the severe damage state at low demand values is a lot higher for partially-grouted walls. With the given definition of the demand parameter, one can conclude that the probability of having the actual shear strength of a partially-grouted wall lower than the nominal strength predicted with the code formula is a lot higher. For example, Figure 2b shows that there is a 30% chance that the shear strength of a partially-grouted wall is less than or equal to 75% of the nominal shear strength, while that probability is only 5% for fully-grouted walls. This study did not include the data of Minaie et al. [3,5,6], which would have further increased the dispersion.



(a) Fully-Grouted Walls

(b) Partially-Grouted Walls

Figure 2: Fragility Curves for Severe Shear Damage (Murcia-Delso and Shing [9])

ASCE/SEI 7 specifies that ordinary load-bearing reinforced masonry wall systems have a structural response modification coefficient, *R*, of 2 and an over-strength factor of 2.5. This implies that such wall systems are not permitted to develop significant inelastic deformation under a design earthquake. While this objective could be met with current code provisions, the safety of these structures under an extreme seismic load condition, such as the maximum considered earthquake (MCE), may not be warranted. A rational and systematic methodology has been recently developed under the FEMA P695 effort [19] to determine appropriate values for *R* and other structural performance factors with an aim to assure a consistent level of safety across different seismic load resisting systems. In this methodology, it is required that the probability of structural collapse under an MCE-level ground motion should not be greater than 10%. In a trial application of this methodology to reinforced masonry structures, Koutromanos and Shing [10] have found that partially-grouted ordinary reinforced masonry walls designed according to current code provisions might not meet this collapse prevention criterion. However, the analytical models used in this study were calibrated with limited experimental data available for partially-grouted walls. More data are needed to further examine this issue.

In spite of the aforementioned findings, one cannot conclude with certainty that partially-grouted reinforced masonry structures are in general unsafe because these studies considered only the behavior of individual wall components without considering the system behavior of a building. The seismic performance of a building could be influenced by the coupling forces from the spandrel beams as well as floor and roof diaphragms, and also enhanced by the inherent redundancy and over-strength introduced by architectural and functionality requirements rather than the load-bearing need. In particular, masonry walls are used not only for load-bearing purpose but also as partition walls and building envelopes.

RESEARCH PLAN

To address the aforementioned issues and to develop design details and retrofit methods that can improve the seismic performance of new and existing partially-grouted masonry construction, a research project is being carried out as a joint effort of Drexel University, the University of California at San Diego (UCSD), and the University of Minnesota. The project consists of the following main tasks.

Development of New Design Details and Retrofit Methods

The behavior of partially-grouted masonry walls is very similar to that of masonry-infilled non-ductile RC frames and confined masonry (see Figure 1). However, confined masonry normally has solid brick units; and furthermore, both infilled frames and confined masonry have more reinforcement in the concrete elements than grouted masonry elements. Past studies by Schultz [13] and Minaie et al. [3-6] have shown that vertically grouted cells in partially-grouted walls are vulnerable to shear failure as horizontal shear cracks propagate along bed joints from the ungrouted masonry into the grouted cells. Regions near the intersection of vertically grouted cells and bond beams are particularly vulnerable to damage due to the interaction between the grouted masonry elements and ungrouted panels, which is similar to the strut mechanism developed by masonry infill in an RC frame. One method to avoid or delay this kind of damage and improve the ductility of a wall is to use double side-by-side reinforced cells instead of single reinforced cells, which is currently used in practice. Vertical reinforcing bars in the side-by-side cells can be tied together with hooked tie bars, and this will make the grouted elements behave more like reinforced concrete elements. Since ordinary walls are normally sparsely reinforced and grouted, doubling grouted cells will only have a small impact on the construction cost and effort. However, while this design can be easily adopted used for new construction, it may not be feasible for the retrofit of existing structures.

One promising method to improve the performance of existing partially-grouted reinforced masonry structures is to use external vertical prestressing. Vertical prestressing will increase both the flexural and shear strengths. However, the additional axial precompression introduced by prestressing may jeopardize the flexural ductility. Studies on prestressed masonry are very limited, and they largely focused on post-tensioned construction with unbounded tendons, which is normally used in practice. For seismic resistance, the use of unbonded tendons, as in the case of external prestressing, has the advantage of providing more flexural ductility than bonded tendons. Studies by Laursen and Ingham [20] and Wight et al. [21] have demonstrated that post-tensioned masonry walls can exhibit favorable seismic performance with self-centering rocking behavior. However, these studies focused only on new construction with fully-grouted walls that had flexure-dominated behavior. The benefit of vertical prestressing for shear-dominated behavior has not been explored in any study. Increasing vertical compression in shear-critical walls can increase the shear strength of bed joints in ungrouted masonry, and may, thereby, deter the propagation of horizontal bed-joint cracks into grouted cells. Horizontal prestressing is not as convenient from the practical standpoint. Therefore, if the benefit of vertical prestressing is not sufficient, it may have to be supplemented with other strengthening strategies. One such option is to add fiber-reinforced polymeric strips as additional shear reinforcement.

The aforementioned design and retrofit schemes will be explored in this research and evaluated analytically and experimentally. They will be first evaluated with nonlinear finite element models to be developed in this project as described below, and improved if necessary before the laboratory evaluation will begin.

Development of Detailed Finite Element Models

Detailed nonlinear finite element models will be developed and calibrated to simulate the behavior of partially-grouted walls. Such models can be used to enhance our understanding of the behavior and intricate mechanisms developed in these walls, and can also be used for parametric studies to develop an improved shear strength formula for partially-grouted masonry walls.

The modeling approach to be used here is to combine smeared and discrete crack models [22]. It has been successfully used to simulate the inelastic behavior of a fully-grouted reinforced masonry wall, as shown in Figure 3, and masonry-infilled non-ductile RC frames under cyclic quasi-static loads and earthquake loads [23,24]. Details of the constitutive models can be found in Koutromanos [23] and Koutromanos et al. [24,25]. For infilled frames, cohesive crack interface elements have been used to model flexural and shear cracks in reinforced concrete columns and mixed-mode fracture of mortar joints in the masonry infill, while smeared crack elements have been used to capture the compressive failure of concrete and masonry.

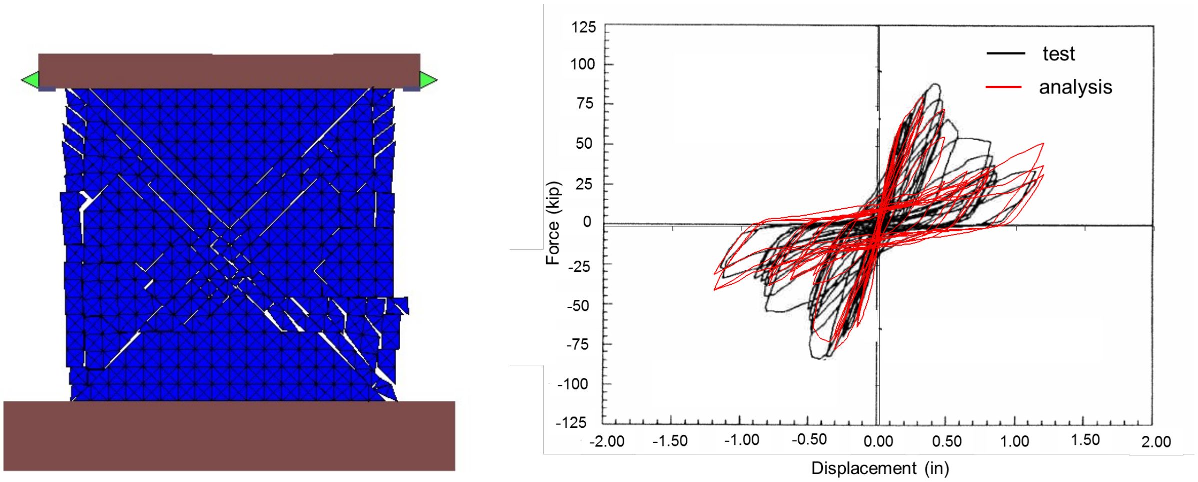


Figure 3: Modeling of a Fully-Grouted Shear-Dominated Wall by Koutromanos [23] (1 kip = 4.45 kN and 1 in. = 25.4 mm)

Since the behavior of partially-grouted walls is similar to that of infilled frames, as similar modeling approach as mentioned above can be adopted. The finite element models developed for partially-grouted walls will be validated with experimental data obtained in previous research and this project.

Design of Prototype Structure and Shake-Table Tests

To develop a model for shake-table tests, a prototype structure has been designed to comply with the Seismic Design Category (SDC) C following the provisions in ASCE/SEI 7 [1] and the masonry building code [2]. For SDC C, ordinary reinforced masonry walls are permitted. Since most reinforced masonry buildings constructed nowadays are one- to two-story tall, the prototype structure will be a one-story building with a tentative configuration shown in Figure 4. It will have a story height of 4.27 m (14 ft.), which is common for one-story commercial and industrial buildings. The building will have a large tributary roof area with a gravity frame in addition to the wall system to carry the roof load. This is to have sufficiently large seismic mass so that the walls will be a “low-end” design that barely meets the strength requirements of the codes. The wall configuration chosen here, as shown in Figure 4, is also representative of that found in office and school buildings.

The specimen configuration chosen for the shake-table tests is shown in Figure 5, which represents one of the four repetitive wall systems in the prototype building. A total of two specimens will be tested. One will comply with current design requirements, with reinforcing details shown in Figure 5, and the second will have improved design details using double reinforced cells. The design of the second specimen will be finalized based on findings from the quasi-static tests that will be carried out as described in the next section. The roof system will consist of precast hollow-core planks with a 2-inch cast-in-place topping. The building specimens will be tested on the outdoor shake table at the UCSD NEES (Network for Earthquake Engineering Simulation) site. The table has plan dimensions of 12 m x 7.6 m (40 ft. x 25 ft.) and is uni-directional with motion along the long direction.

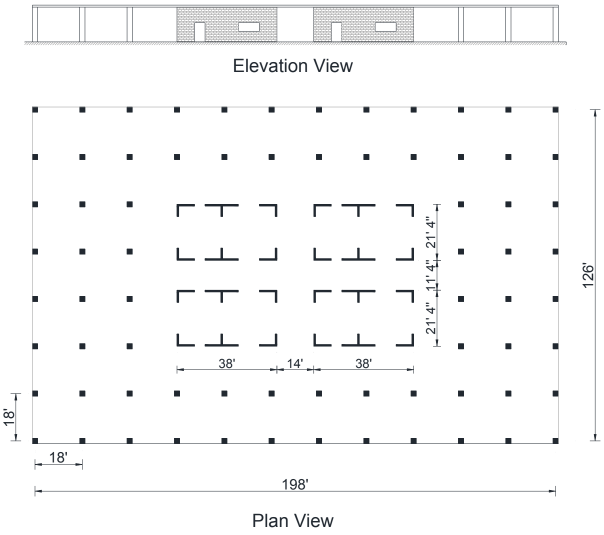


Figure 4: Prototype Building Configuration (1 ft. = 305 mm and 1 in. = 25.4 mm)

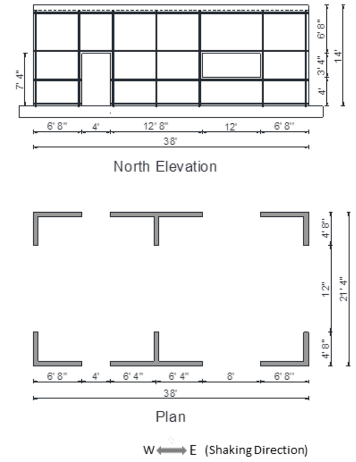


Figure 5: Shake-Table Test Specimen (1 ft. = 305 mm and 1 in. = 25.4 mm)

Quasi-Static Tests of Walls

Testing of Planar Walls

Thirteen planar wall specimens will be tested quasi-statically at Drexel University to evaluate the effectiveness of the new design details and retrofits method to be developed in this study. The specimens will resemble the middle wall of the wall system (shown in Figure 5) to be tested on a shake table, but it will not be identical to have test results easier to interpret and the tests done more efficiently. The dimensions and reinforcing details of the specimens are shown in Figure 6. The design parameters to be varied in the test series are the aspect ratio of the walls, extent of grouting, level of axial compression, type and amount of reinforcement, and the level of prestressing. The aspect ratio of walls will be changed by altering the boundary condition at the top of the walls (cantilever vs. fixed-fixed). Fully-grouted walls will be included for comparison. An improved level of reinforcement (double vertical and horizontal grouted cells as shown in Figure 6b) with and without joint reinforcement will be compared with the traditional practice (single grouted cells as shown in Figure 6a). Additionally, two walls will be tested with vertical prestressing with and without FRP laminates as shear reinforcement. A schematic of the test setup is shown in Figure 7.

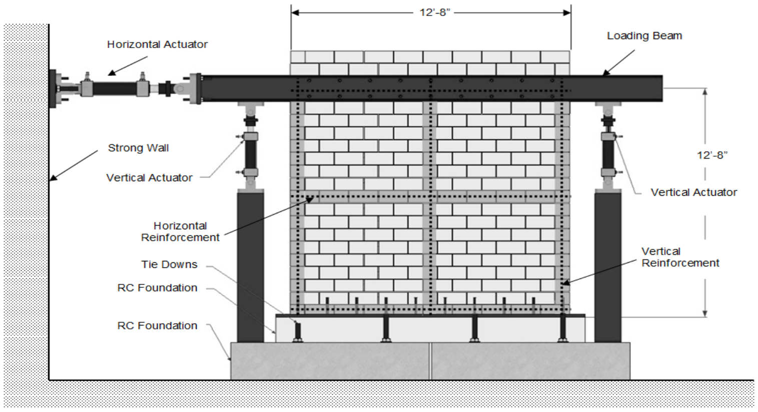
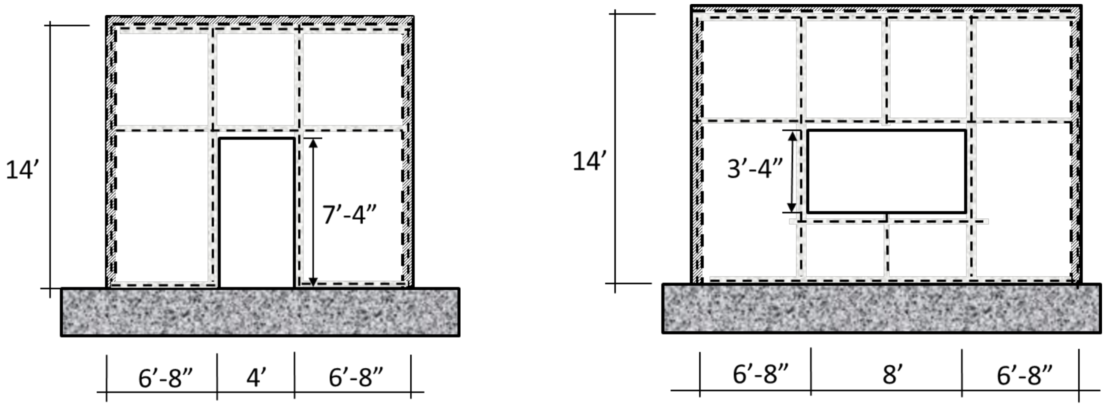


Figure 7: Test Setup at Drexel
(1 ft. = 305 mm and 1 in. = 25.4 mm)

For these tests, researchers at Drexel University are exploring the use of the Digital Image Correlation (DIC) technique to measure the displacement and strain fields in the test walls [26].

Testing of Flanged Walls

The second set of quasi-static tests will examine the influence of an opening on the behavior of a partially-grouted wall and in particular the coupling effect introduced by the spandrel beam and the roof diaphragm. Furthermore, the influence of wall flanges will also be investigated. Two specimen configurations, as shown in Figure 8, will be considered. They resemble a portion of the wall in the shake-table test structure (shown in Figure 5). The specimens will have roof diaphragms similar to that to be used in the shake-table tests.



Configuration 1

Configuration 2

Figure 8: Flanged Walls with Opening
(1 ft. = 305 mm and 1 in. = 25.4 mm)

Development of Improved Shear Strength Formula

The shear strength formula in the masonry building code [2] is largely based on experimental data obtained from fully-grouted reinforced masonry walls. A review and comparison of different shear strength formulas reported in the literature has been provided by Voon and Ingham [27,28] for fully-grouted walls. To develop an adequate shear strength formula for partially-grouted walls, the data obtained by Minaie et al. [3-6], Ingham et al. [15], and Voon and Ingham [16], and the quasi-static test results obtained in this project will be used. Furthermore, this effort will be assisted by a numerical parametric study with detailed finite element models considering different spacing of reinforced and grouted cells, axial compressive loads, and wall aspect ratios.

Analytical Modeling of Building Systems

The capability of refined finite element models and simplified strut-and-tie models to simulate the response of building systems will be evaluated. These models will be first validated with quasi-static test results. Once calibrated, analytical models of the shake-table test specimens will be developed for pre-test analysis. The models will be subsequently refined and recalibrated with shake-table test data. After refinement, the simplified model will be used in incremental dynamic analysis of the two shake-table test specimens following the FEMA695 methodology [19] to assess and compare the collapse margin ratios of the two systems.

ACKNOWLEDGEMENTS

This research is supported by the National Science Foundation under the Network for Earthquake Engineering Simulation program with Award No. CMMI-1208208. Partial support from the National Concrete Masonry Association for the experimental work is also gratefully acknowledged. However, opinions expressed in this paper are those of the authors and do not necessarily reflect the opinions of the sponsors.

REFERENCES

1. ASCE/SEI (2010), ASCE/SEI 7-10: Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers.
2. MSJC (2011), TMS 402-11/ACI-530-11/ASCE 5-11: Building Code Requirements for Masonry Structures, The masonry Society, American Concrete Institute, and ASCE/Structural Engineering Institute.
3. Minaie, E., Salama, M., d'Hermillon, B., Dulka, J., Moon, F.L. and Hamid, A.A. (2008) "Shear Strength of Partially Grouted Reinforced Masonry Shear Walls subjected to In-plane Loading" 6th Annual Meeting of NEES, Portland, Oregon.
4. Minaie, E. (2009) “Behavior and Vulnerability of Reinforced Masonry Shear Walls” Ph.D. Dissertation, Department of Civil, Architectural, and Environmental Engineering, Drexel University, Philadelphia, PA.
5. Minaie, E., Moon, F.L. and Hamid, A.A. (2009) “In-Plane Shear Resistance of Partially Grouted Reinforced Concrete Masonry Shear Walls” 11th Canadian Masonry Symposium, Toronto, Canada.
6. Minaie, E., Mota, M., Moon, F.L. and Hamid, A.A. (2010) “In-Plane Behavior of Partially Grouted Reinforced Concrete Masonry Shear Walls” Journal of Structural Engineering, 136(9), 1089-1097.
7. Hamid, A.A., Moon, F. L. and Minaie, E. (2009) “Seismic Performance of Partially Grouted Reinforced Concrete Masonry Buildings” 11th Canadian Masonry Symposium, Toronto, Canada, May 2009.
8. Murcia-Delso, J. and Shing, P.B. (2009) “Damage States and Fragility Curves for Reinforced Masonry Shear Walls” Report No. SSRP–09/14, Department of Structural Engineering, University of California at San Diego, La Jolla, CA.
9. Murcia-Delso, J. and Shing, P.B. (2012) “Fragility Analysis of Reinforced Masonry Shear Walls” Earthquake Spectra, 28(4), 1523–1547.
10. Koutromanos, I. and Shing, P.B. (2010) “Trial Applications: Reinforced Masonry Shear Wall Structures” Chapter 3 in Evaluation of the FEMA P-695 Methodology for Quantification of Building Seismic Performance Factors by NEHRP Consultants Joint Venture, Report No. NIST GCR 10-917-8, NIST, Gaithersburg, MD.
11. Ghanem, G.M., Essawy, A.S. and Hamid, A.A. (1992) “Effect of Steel Distribution on the Behavior of Partially-grouted Reinforced Masonry Shear Walls” 6th Canadian Masonry Symposium, University of Saskatchewan, Saskatoon, Canada.
12. Ghanem, G.M., Salama, A.E., Elmagd, S.A. and Hamid, A.A. (1993) “Effect of Axial Compression on the Behavior of Partially-grouted Reinforced Masonry Shear Walls” 6th North American Masonry Conference, Philadelphia, PA.

13. Schultz, A.E. (1996) “Seismic Resistance of Partially-Grouted Masonry Shear Walls” in Worldwide Advances in Structural Concrete and Masonry, CCMS Symposium held in conjunction with ASCE Structures Congress XIV, Chicago, IL, 211-222.
14. Schultz, A.E. and Hutchinson, R.S. (2001) “Seismic Behavior of Partially-Grouted Masonry Shear Walls, Phase 2: Effectiveness of Bed-Joint Reinforcement” Report No. NIST GCR 01-808, NIST, Gaithersburg, MD.
15. Ingham, J.M., Davidson, B.J., Brammer, D.R. and Voon, K.C. (2001) “Testing and Codification of Partially Grout-Filled Nominally-Reinforced Concrete Masonry Subjected to In-plane Cyclic Loads” The Masonry Society Journal, September, 83-95.
16. Voon, K.C. and Ingham, J.M. (2008) “Experimental In-Plane Shear Strength Investigation of Reinforced Concrete Masonry Walls with Openings” Journal of Structural Engineering, 134(5), 758-768.
17. Matsumura, A. (1988) “Effectiveness of Shear Reinforcement in Fully Grouted Hollow Clay Masonry Walls” 4th Meeting of the Joint Technical Coordinating Committee on Masonry Research, US-Japan Coordinated Earthquake Research Program, San Diego, CA.
18. Baenziger, G. and Porter M.L. (2011) “Joint Reinforcement as Primary Shear Reinforcement for Masonry Shear Walls” 11th North American Masonry Conference, University of Minnesota, MN.
19. ATC (2009), ATC-63: Quantification of Building Seismic Performance Factors, Applied Technology Council, Redwood City, CA.
20. Laursen, P.T. and Ingham, J.M. (2004) “Structural Testing of Large-Scale Posttensioned Concrete Masonry Walls” Journal of Structural Engineering, 130(10), 1497-1505.
21. Wight, G.D., Kowalsky, M.J. and Ingham, J.M. (2007) “Shake Table Testing of Posttensioned Concrete Masonry Walls with Openings” Journal of Structural Engineering, 133(11), 1551-1559.
22. Stavridis, A. and Shing, P.B. (2010) “Finite-Element Modeling of Nonlinear Behavior of Masonry-Infilled RC Frames” Journal of Structural Engineering, 136(3), 285–296.
23. Koutromanos, I. (2011) “Numerical Analysis of Masonry-Infilled Reinforced Concrete Frames Subjected to Seismic Loads and Experimental Evaluation of Retrofit Techniques” Ph.D. Dissertation, University of California at San Diego, La Jolla, CA.
24. Koutromanos, I., Stavridis, A., Shing, P.B. and Willam, K. (2011) “Numerical Modeling of Masonry-Infilled RC Frames Subjected to Seismic Loads” Computers and Structures, 89, 1026–1037.
25. Koutromanos, I. and Shing, P.B. (2012) “A Cohesive Crack Model to Simulate Cyclic Response of Concrete and Masonry Structures” ACI Structural Journal, 109(3), 349 - 358.
26. Vanniamparambil, P.A., Khan, F., Schwartz, E., Kontsos, A., Bartoli, I., Bollhassani, M., and Hamid, A. (2013) “Using DIC to Measure Deformation Fields of Concrete Masonry Test Specimens” 12th Canadian Masonry Symposium, Vancouver, British Columbia, Canada.
27. Voon, K.C. and Ingham, J.M. (2006) “Experimental In-Plane Shear Strength Investigation of Reinforced Concrete Masonry Walls” Journal of Structural Engineering, 132(3), 400-408.
28. Voon, K.C. and Ingham, J.M. (2007) “Design Expression for the In-Plane Shear Strength of Reinforced Concrete Masonry” Journal of Structural Engineering, 133(5), 706-713.