9TH CANADIAN MASONRY SYMPOSIUM

MASONRY RESEARCH AT THE MID-AMERICA EARTHQUAKE CENTER

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ABSTRACT

The Mid America Earthquake Center is a collaborative research center, established by seven participating core universities with funding from the National Science Foundation. The primary vision of the center is to reduce earthquake losses through research. Research at the Center is directed at improving seismic resistance through effective mitigation procedures. This results from the vulnerability of gravity-load designed buildings located in the eastern and central United States to an infrequent, but large future earthquake. A complementary program of research on earthquake resistant evaluation and rehabilitation for low-rise, unreinforced masonry buildings is underway at the MAE Center. This paper provides a summary of masonry-related research at the Mid-America Earthquake Center. It will include descriptions of experimental and computational research done to study seismic performance of unreinforced masonry building structures, and the effectiveness of various retrofit procedures. The summary will highlight:

(a) Behavior of unreinforced clay-unit masonry walls and piers behaving in shear or flexure and retrofitted with shotcrete, FRP and ferrocement coatings, and reinforced cores.
(b) Dynamic response of low-rise buildings with flexible floor diaphragms where dynamic stability of out-of-plane walls is a concern.
(c) Behavior of timber floor diaphragms retrofitted with various means.
(d) Three-dimensional behavior of a full-scale, two-story URM test structure subjected to simulated earthquake forces, and a corresponding half-scale replicate structure subjected to simulated earthquake motions.
(e) Response modification procedures for seismic retrofit of URM low-rise buildings.

Each description will include statements as to the relevance of the research for impacting structural engineering practice through the updating of seismic codes and guidelines for reducing losses resulting from future earthquakes in the central and eastern United States.

Key words: Masonry Testing, URM Building, earthquakes, Mid America

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INTRODUCTION

The mission statement for the Center is to develop new fundamental knowledge on seismicity and response of the built environment, and risk assessment technologies, that can be used as the bases for the development of consequence based engineering methodologies for various loss reduction systems. This is a vision to minimize the impact of future earthquakes on the Central and Eastern United States (CEUS).

The method used to depict this vision as an engineered system is illustrated as a flow chart that summarizes the ten fundamental questions of earthquake engineering, which is shown for an urban area in Fig. 1.

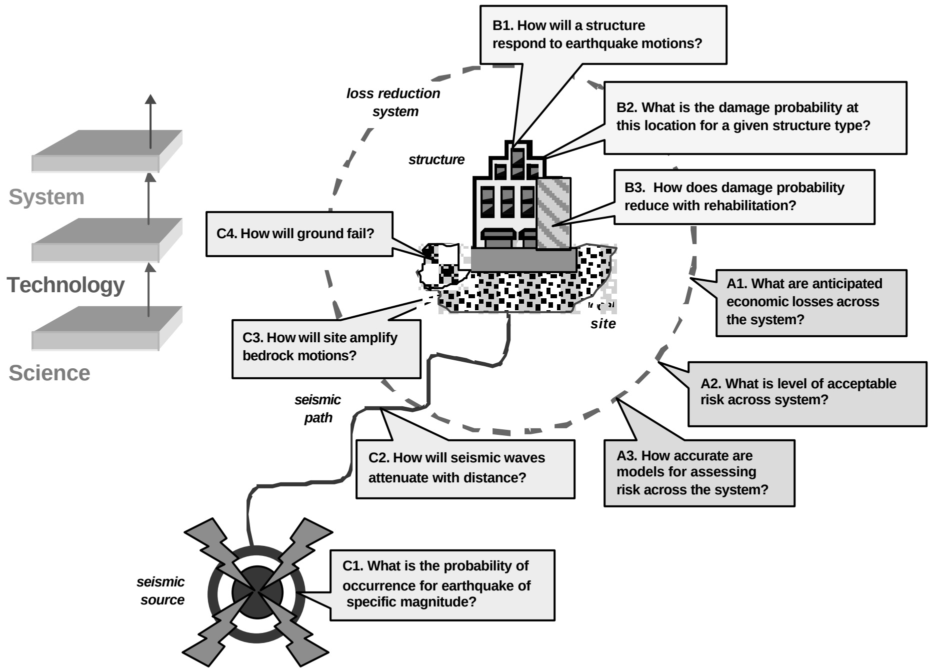

Figure 1. The ten fundamental earthquake questions

The objectives of interest in this current specific engineering research are:

- Question B1: How will a structure respond to earthquake motion?
- Question B2: What is the damage probability at this location for a given structure type?
- Question B3. How does the damage probability reduce with rehabilitation?

There are large urban areas of older masonry construction in the Central and Eastern United States. Four cities that are typical for the use of masonry in the urban environment are Memphis, TN, Charleston, SC, Boston, MA and St Louis, MO. Each of these cities is located adjacent to areas of previous seismic activity that is within a distance and at a level of intensity that is known to damage masonry. Charleston was extensively damaged in an 1886 earthquake. A picture that shows the typical type of damage to unreinforced masonry buildings in Charleston after the 1886 earthquake is shown in Fig. 2. These types of masonry buildings are suited to the implementation of rehabilitation techniques to improve their seismic resistance. The interesting research question is which of the methods provides benefits in terms of ductility and strength imparted to the walls? The forces of the market economy will then determine which of the appropriate techniques are economically suited to the task.

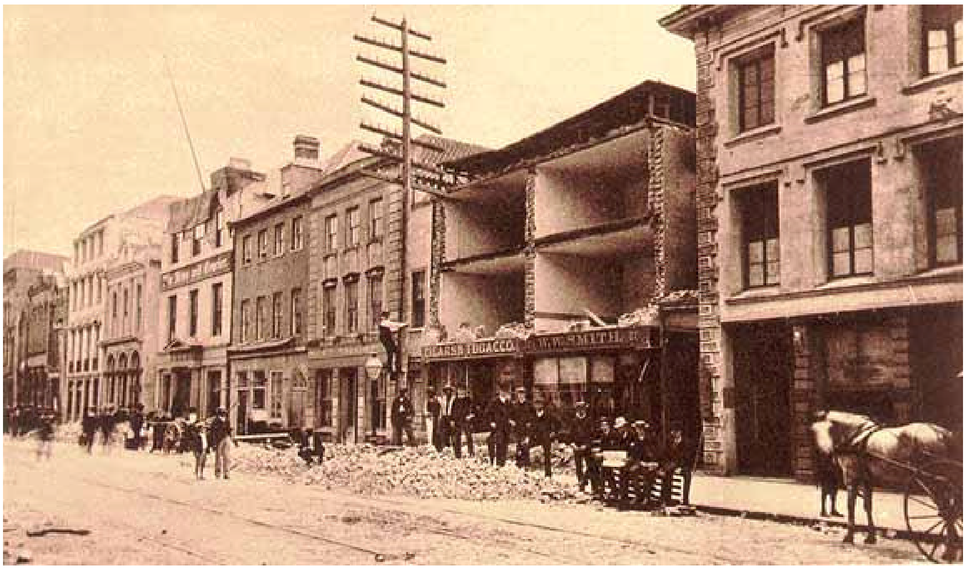

Figure 2. Masonry damage in Charleston, SC 1886

This paper provides a summary of the masonry-related research at the Mid-America Earthquake Center, which forms part of the overall study of the question of "how does the damage probability reduce with rehabilitation?" This summary of the various experimental and computational masonry programs will include descriptions of research done to study seismic performance of unreinforced masonry building structures, and the effectiveness of various retrofit procedures. This outline provides some of the answers to the question of strength and ductility.

BACKGROUND

In looking to the development of consequence based engineering the types of losses and their relative magnitude needs to be considered. The two types of loss of interest in any engineering study are the likely building costs and the economic losses. The building costs in this case are strictly the cost to repair or replace the losses in an earthquake event.

The masonry research at the UIUC, which is designed to meet the stated objective of reducing the probability of damage, is based on two important safety levels, life safety or can we hold the building together long enough to get everyone out alive. The second level is immediate occupancy or can we still use the building for its intended purpose. This is critical to business survival, there is enough damage caused in earthquakes and the goal must be to maintain the business function and keep the cash flows going. It is within this background that the masonry research at the MAE Center was developed as a systematic program that is part of the Center's basic strategy to achieve research outcomes that meets our vision and mission statements.

EXPERIMENTAL AND COMPUTATONAL RESEARCH

Unreinforced Clay-Unit Masonry Walls and Piers and their Rehabilitation

Research on unreinforced masonry piers and walls has the intended purpose of determining the improvements to the strength and ductility of the piers and walls from the various rehabilitation methods. The rehabilitation methods that were investigated were shotcrete, fiber reinforced polymers (FRP), ferrocement coatings, and reinforced cores. The brick selected for this testing is a salvaged common brick from Chicago. The results from testing in the late nineteenth and early twentieth centuries reported by Baker (1912) confirm that the common brick used in these current experiments is at the low end of the test range for Mid-American bricks of this earlier period. The estimated Young's modulus from the current panel tests at 4.4 ± 2 GPa is low for a commercial brick. The presence of internal voids in the bricks and the lack of a frog, and the variability in the Young's modulus suggest that the bricks were formed under low pressure.

Details of the pier test set up, used by Franklin and Abrams (2000), are shown in Fig. 3.

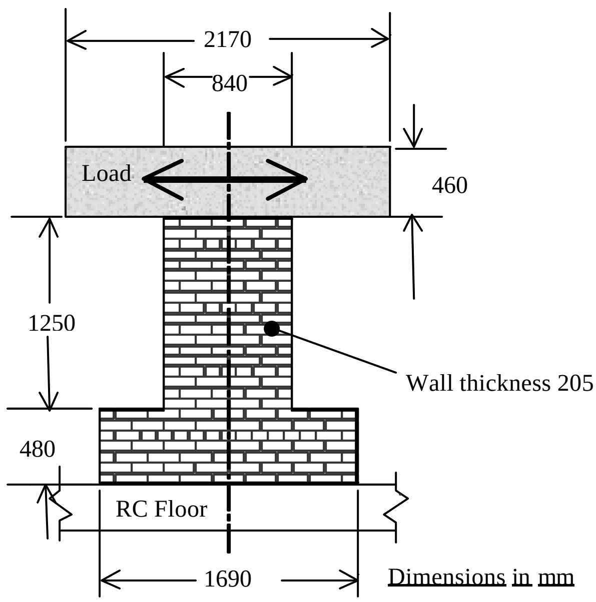

Figure 3. Pier Rig Test Setup

In addition to the pier specimens described in Figure 3, a series of three shear wall specimens were tested that were the same height as the test piers and 3.83 metres long (Erbay, and Abrams, 2001). A summary of the results is shown in Fig. 4 for an unreinforced pier and the center cored piers. The shotcrete, FRP and ferrocement coatings results are presented in Franklin and Abrams (2000). An unreinforced pier was first tested as part of this experimental work. The force against drift level is shown on Fig. 4, as test 1F for an unreinforced pier. This pier shows typical results for URM masonry that reaches the cracking point and then translates to a rocking mode. The pier geometry and the applied vertical load control the limit of the rocking mode. The two reinforced core results are shown in test 7F (10 mm bar) and 8F (15 mm bar) on Fig. 4. The results clearly demonstrate the improved strength and ductility for the masonry pier when it is reinforced with center cores. The difference in the results between 7F and 8F has been attributed to the embedment depth of the bars rather than the change in the bar diameter between the tests. The provision of reinforcement provides a measure of ductility to the masonry that is not normally present in the generally brittle material. This reinforcement increases the flexural capacity in the pier by a factor of approximately two and the rocking drift level to about 2.5 percent.

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Figure 4. Summary of Results for the Pier Tests

The shotcrete was a 100 mm layer with 10 mm (410MPa) bars placed in the center of the concrete. The shotcrete and masonry pier behaves as a composite unit that has the properties of a general ductile brittle material (Krajcinovic, 1996, Fig 4.4.2). The flexural capacity of the shotcrete reinforced pier increased by a factor of three and the peak drift level was about 1.5 per cent. The pier failed in a torsion mode probably induced by the offset location of the reinforcement. The ferro-cement coating showed a minor increase in flexural strength, but once the product cracked the pier resumed the rocking mode and capacity of an unreinforced masonry pier. The FRP provides a three-fold flexural strength increase and a rocking drift level of 1.8 percent. Erbay and Abrams (2001) present the results and provide a discussion for the large shear walls. The primary purpose of this shear wall and pier research is to quantify the increase in the flexural and shear strength from commonly used repair and retrofit techniques for masonry structures. The secondary purpose is to determine the drift levels that the retrofit techniques will allow before failure occurs in the specimen. These results then provide data to revise the FEMA 273 guidelines and its derivative documents that form the future codes of practice.

Dynamic Response of Low-Rise Buildings

Low-rise buildings are a core construction form in the provision of the essential service facilities such as fire stations. These types of structures are often constructed from unreinforced masonry with stiff diaphragms such as reinforced concrete or weak diaphragms such as timber flooring on bearers and joists. This project looked at the response of existing and rehabilitated structural systems commonly used in these building types. This testing looked at the loading of an out-of-plane wall using both stiff and flexible diaphragms that provided a shear transfer pinned mechanism at the top of the wall.

These types of walls can occur in many URM buildings. The experimental work was completed on the one DOF table at the UIUC. The arrangement of the test elements is shown in Fig. 5. A description of the test system and the mathematical model are provided in Simsir *et. al.*, (2001).

Figure 5. Arrangement of the shaking table tests

The specific objective of the research was to investigate effects of diaphragm flexibility on the stability of out-of-plane URM concrete block walls. Parameters reviewed in the experimental work were:

- Wall: height/thickness ratio, axial load and its eccentricity, P-D effect
- Diaphragm: flexible, stiff, elastic, yielding, energy dissipating retrofits

A typical set of results for the response of the out-of-plane loading of the wall is presented in Figure 6.

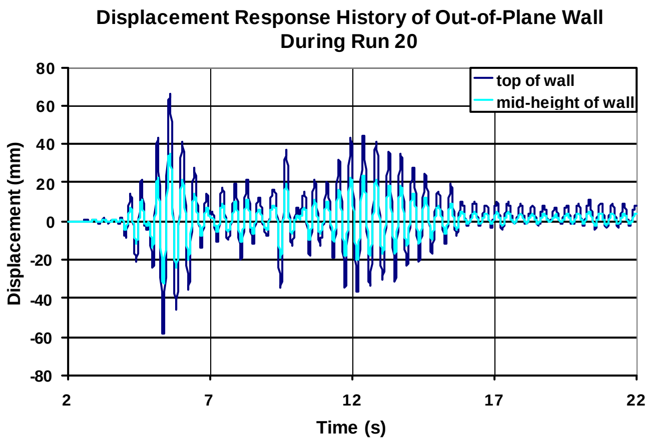

Figure 6. Response of the out of plane wall to a earthquake loading pattern

It is self evident from the results shown in Fig 6 that the wall is essentially rocking in the first mode of vibration. The numerical modeling component focused on a number of difficult three-dimensional analysis modeling issues that need to be addressed for reliable prediction of the test responses of the buildings. Many of these difficult testing issues require detailed beam, shell and/or three-dimensional solid finite element models of entire structural systems and subassemblies of these systems. The preliminary conclusion from these experimental tests and the numerical modeling is that post cracking behaviour for out-of-plane bearing walls provides the necessary tolerance for such walls to sustain large lateral drifts despite the gravity force or the height/thickness ratio of the wall. This finding is limited to out-of-plane walls that secured to the floor and roof diaphragms (Tena-Colunga and Abrams, 1996).

Behavior of Timber Floor Diaphragms

The research on the dynamic response of low-rise buildings has demonstrated the importance of being able to develop rocking modes in the out-of-plane walls. One of the common observations in masonry buildings after earthquakes is a detachment of the walls in an out-of-plane failure. A simple example of this failure mode is observable in the century-old flourmill, which is shown in Fig. 7. The repairs to the wall that occurred after the earthquake are clearly visible in the change in hue of the upper area of masonry. The damage to the building might have been less if the gable had been properly secured to the roof diaphragm and the roof diaphragm had adequate stiffness.

Figure 7. Flour Mill after repairs from the damage of the 1989 Newcastle Event.

The MAE Center has investigated the behaviour of diaphragms attached to masonry walls. This series of experiments investigated low rise building diaphragms ranging from

tongue and groove planking with a thickness of 6 mm to a 7.3 m x 3.658 m roof diaphragm with 50 mm by 250 mm joists with 25mm x 150 mm straight sheathing.
The test set up for a tongue and groove floor system is shown in Fig. 8.

Figure 8. Experimental set up for testing a timber floor diaphragm

The purpose of the tests was to examine the strength, stiffness, and deformation capabilities of existing floor diaphragms. The second component of the testing then led to the evaluation of retrofit strategies for improved seismic performance for these types of diaphragms in low-rise buildings. The retrofit methods used in the experimental program for the timber decking included the provision of shear connectors between the wall and diaphragms. A typical example is shown in Fig 9.

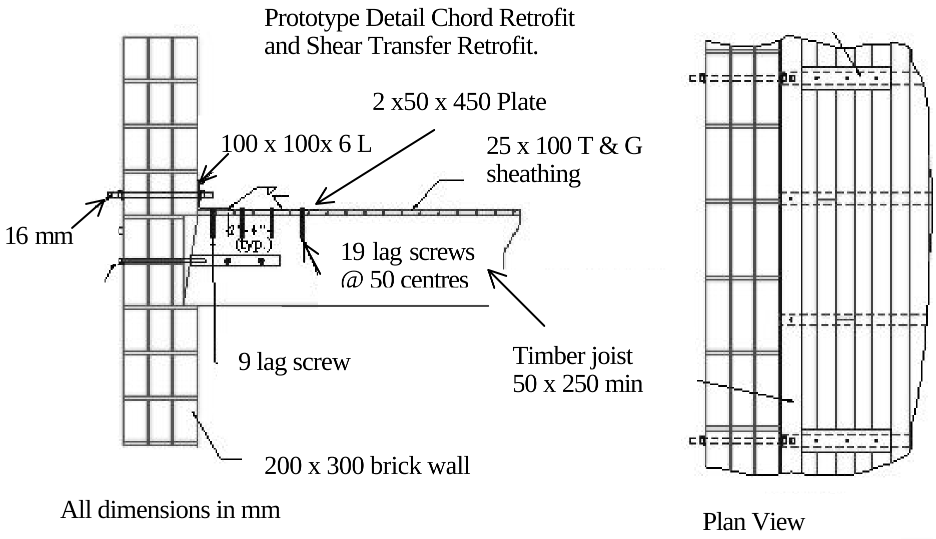

Figure 9. Floor Diaphragm Shear Connector Retrofit Technique

Four rehabilitation techniques were tested, which were steel strapping and enhanced shear connectors, steel truss, unblocked plywood overlay and blocked plywood overlays. Each method achieved an increase in the shear strength and stiffness for the diaphragm. The final results include a comparison to the FEMA 273 guidelines (Peralta, *et. al.,* 2000).

Two-Story URM Test Structure subjected to Simulated Earthquake Forces

An interesting issue that has an impact on masonry research is that of the validity of scale testing of masonry elements. It is fundamentally and significantly cheaper to test at half scale rather than full scale. The issue of relating the results from full-scale static testing to half scale dynamic testing is being investigated experimentally as part of the systematic masonry research at the MAE Center. This overall work is being completed in two distinct projects. Project ST-22 is a joint program of the Construction Engineering Research Laboratories (CERL) of the U.S. Army Corp of Engineers and the Mid-America Earthquake Center. This project investigates a half scale model of a masonry structure. This model will be tested on the six degree of freedom CERL shaking table. Orton, *et. al.*, (2001), outlines the work completed to date on the half scale modeling. Project ST-11 of the MAE Center is a full-scale test of a low-rise building system. A two-story masonry building is being constructed at full scale and will to be tested in a static reaction frame. The initial work will center on two types of structural systems that represent extremes of masonry testing requirements. The model is an unreinforced masonry structure. It will be fitted with wood diaphragms. The model represents critical older structures in Mid-America, but results in experimental problems, given the magnitude of the base shears required to test such a structure to destruction. In summary, this joint research work is demonstrating that the results and conclusions from smaller scale testing can be directly applied in the field of earthquake engineering. Project ST-11 will serve as proof-of-concept at a large scale for the evaluation and retrofit strategies developed by other MAE Center researchers. Tests of this type show building code officials and the engineering profession that research results based on reduced-scale models or component tests can be extended to entire structural systems.

Response Modification Procedures for Seismic Retrofit of URM Low-Rise Buildings

Project ST-4 Response Modification Applications for Essential Facilities is being undertaken at the Georgia Institute of Technology as part of the MAE Center program on reducing the impact and thus consequences of earthquakes on the urban areas of the CEUS. This project is investigating low to mid-rise essential buildings that have irregular structural configurations. This is a commonly identified problem in these types of facilities. This work is a direct extension of the previous research on such facilities in the western part of the U.S. (Tena-Colunga and Abrams, 1996). In this project, the proposed response modification protocols are based on passive and semi-active damping. Technologies are being investigated that are suitable for retrofit of structures. These technological elements must have an extremely high long-term reliability. The experimental work has examined the problem using numerical analysis models of buildings and seismic simulation studies. This work provided the background information that is needed to determine optimal retrofit solutions for relatively complex structures, which are typical of these facilities. Seismic strengthening of at-risk structures as well as applications for new construction are critical to the study if the consequences for earthquake damage are to be reduced for existing and new facilities. Generic buildings that are representative of the CEUS will form part of these demonstration studies, which has the purpose of assessing the practical usefulness of different passive and semi-active damping technologies. The anticipated research results will include: structural analysis and simulation methods that extend present 2-D capabilities to 3-D configurations, and identification of appropriate passive and semi-active response modification technologies. Cladding renovation or replacement appears to be a practical method to achieve the objective of reducing earthquake damage for many types of structures.

Project ST-9 has investigated the response of the nonstructural component categories (e.g., architectural, mechanical, electrical components, or furnishings and interior equipment) to seismic motions. This work has used simple linear and nonlinear analysis models, which have provided a better understanding of factors affecting their damageability. This has lead to specification of permissible levels of damage and improved rehabilitation guidelines. This work demonstrates the need to address all issues of the building's fabric, not just the structural elements.

CONCLUSIONS

Masonry is one of the common building materials in the major cities of the eastern part of the country. The Mid America Earthquake Center has a masonry research programme that is designed to investigate the issues associated with the development of new masonry and the retrofitting of the older masonry buildings in the Central and Eastern United States to reduce the damage to the buildings and associated consequences from earthquakes that affect an urban area.

URM buildings though commonly recognized as vulnerable buildings, can perform well during earthquakes if adequate measures are taken to provide load paths, suitable connections and adequate diaphragms. Research at the MAE Center has shown that:

a) URM piers behaving in a rocking mode can possess significant deformation capacity.
b) Retrofit techniques for URM piers and shear walls can be effective for increasing strength and deformation capacity
c) The shotcrete, FRP and center cores provided a significant increase in flexural strength to the piers. The flexural strength increased from a factor of two to three and the drift capacity increased by corresponding amounts. These three methods are appropriate measures to provide ductility and tensile capacity to unreinforced masonry walls and piers that may be subjected to future seismic loads.
d) Out-of-plane bearing walls can resist substantial diaphragm deflection provided that well anchored at the diaphragms.
e) Retrofit methods for timber diaphragms can be effective for altering the strength and stiffness of these elements within a building system.
f) Response modification procedures for URM buildings can be effective in decreasing seismic demand forces.
g) Non-structural damage can be minimized substantially by anchoring unbraced concrete masonry units at the top of the walls.

ACKNOWLEDGEMENTS

The Earthquake Engineering Research Centers Program of the National Science Foundation supported this work under Award Number EEC-9701785 to the Mid America Earthquake Center.

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