SEISMIC PERFORMANCE OF REHABILITATED UNREINFORCED MASONRY BUILDING SYSTEMS

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ABSTRACT

The progress of a research program focused on the seismic performance of rehabilitated masonry buildings is presented in this paper. This research will serve to obtain a better understanding of the earthquake behavior of unreinforced masonry buildings and how to effectively rehabilitate them. The research works in parallel with a static full-scale test being performed at the Georgia Institute of Technology. The testing involves the tri-axial shake table test of a half-scale masonry building. The test structure was developed to meet the objectives of the research. Analytical predictions of the pier strengths based on preliminary analysis and finite element modeling are presented. Various retrofit schemes and benefits anticipated from them are explained. The testing procedure is outlined.

Key words: Unreinforced masonry, Dynamic testing, Retrofit techniques

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INTRODUCTION

Many buildings in the Central and Eastern United States were constructed before the development of modern seismic codes. Some may be susceptible to damage caused by earthquakes and could benefit from rehabilitation of the structural elements. Many of these buildings have heritage value and therefore it is unfeasible to significantly alter the valuable fabric of the building. However, appropriate seismic retrofit measures can help protect these buildings.

Testing has already been carried out studying the effect of rehabilitating individual pier samples (Erbay and Abrams 2001). However, individual pier tests do not provide a clear picture of how the rehabilitation will affect the overall building system. Because the interactions between various structural components are largely unknown, the testing of an entire building system is necessary to determine the effectiveness of the retrofit.

This project is centered on the shake table testing of a half-scale unreinforced masonry (URM) structure. In this instance, the test structure is constructed of clay-unit masonry. The test model contains important features common to URM buildings such as perforated shear walls and a flexible diaphragm.

This project works in parallel with a static full-scale test being performed at the Georgia Institute of Technology. The building prototype for both of the tests is the same. Individual static full-scale tests do not accurately represent strain rate effects or true inertial force distributions. On the other hand, individual reduced scale dynamic tests are often disregarded due to their reduced size and use of simulated material. However, when both tests are done in parallel, the results become more relevant.

The purpose of this research program is to gauge the effectiveness of various rehabilitation schemes on the seismic performance of an unreinforced masonry building. The purpose of this paper is to introduce the project and its various aspects.

OBJECTIVES

The objectives of the project focus on achieving a better understanding of the earthquake behavior of URM buildings and effectively rehabilitating existing URM buildings. Specific objectives include:

- Assess the effectiveness of selective rehabilitation of individual brick piers on overall system performance. This objective will study the effect of rehabilitating one critical weak pier in a wall or one weak wall in a building on the overall performance of the structure.

- Investigate the effect of tri-directional base motions on the dynamic response of the structure.

- Examine dynamic amplification in systems with flexible diaphragms.

- Verify the extrapolation of individual component behavior to the overall response of the building system.
- Examine the relative effectiveness of different rehabilitation approaches.
- Aid in the development of rehabilitation guidelines.
- By comparing the test results with the static full-scale test, make general observations comparing static and dynamic testing, and full and half-scale modeling.

DESCRIPTION OF TEST STRUCTURE

The test structure, shown in Figure 1, is designed to reveal behavioral tendencies that meet the objectives of the project. Walls A and B are designed to study the effects of rehabilitating a weak pier on the overall performance of the structure. Walls A and B are identical in configuration in order to provide uniformity and consistency in the structure. Walls 1 and 2 are designed to examine the effects of rehabilitating a weak wall that works in parallel with a strong wall. The flexible diaphragm will deliver the same horizontal load to each wall, independent of the walls' relative strengths or stiffnesses. Therefore, effects of strengthening the weak wall on system performance are accentuated. These kinds of wall/pier combinations are also typical of actual construction.

The diaphragms at both the second floor and roof levels are wood floor decking. The diaphragms are simply supported by walls A & B. Each diaphragm is designed to obtain frequency ratios between the wall and the diaphragm that realistically emulate prototypes. This will allow a distinction between the motions of the diaphragms and the walls. Each diaphragm is loaded with lead ingots, to further reduce its frequency and increase the weight of the structure.

The specimen will be mortared to a concrete base girder. The base girder was designed to remain stiff during the test and simply connects the test specimen to the shake table. The bricks used in this test are 9.67cm x 4.6cm x 2.86cm (3.81" x 1.81" x 1.13"), this is half scale of common U.S. size bricks 19.37cm x 9.2cm x 5.72cm (7.625" x 3.625" x 2.25"). Walls A and B are 3 wythes thick, walls 1 and 2 are two wythes thick. The joints are also half-scale at 0.5cm (1/4") thick. The mortar used is an N (1:1:6) type mortar.

A common problem in reduced scale testing is that in creating a scale model, not all of the properties can be scaled. In order to make a model that is half-scale, half scale bricks are used. However, the bricks possess the same material properties as the full-scale bricks. Consequently the gravity stress versus the material strength relationship is not constant. In order to remedy this complication additional weight is placed on the floors to add more stress in the walls. This is important for masonry construction because the lateral strength of the piers is based, in part, on the vertical stress in the piers.

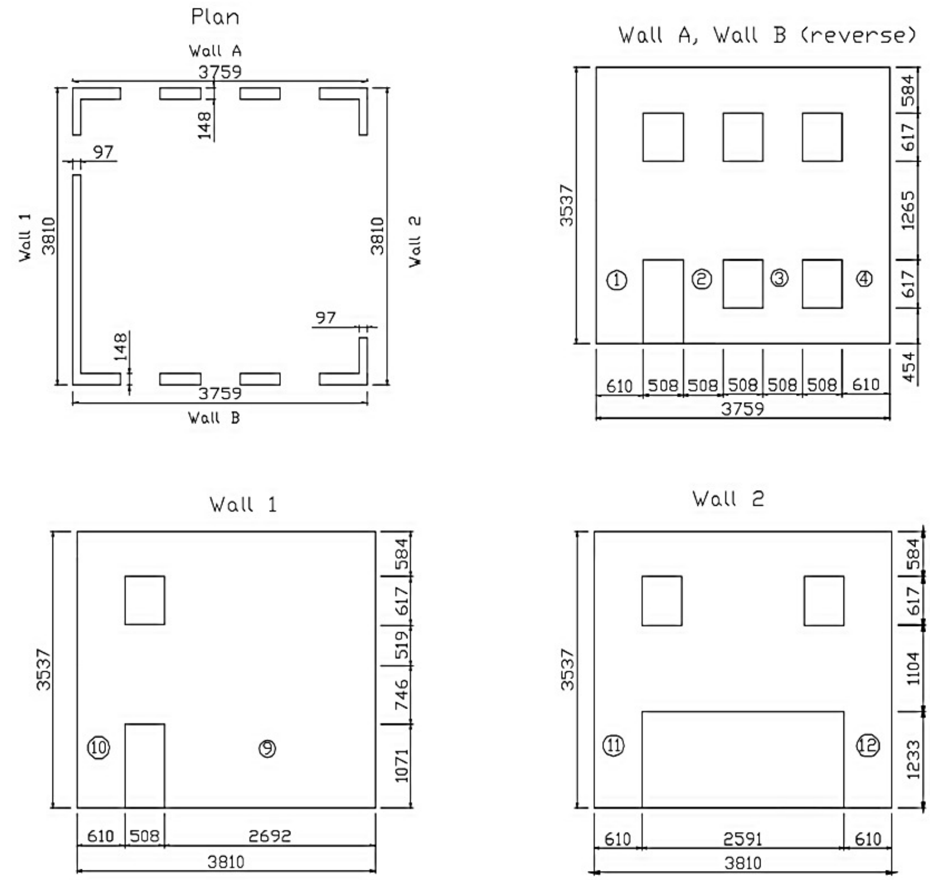

Figure 1. Layout of test specimen (all units in millimeters)

It is not feasible to model the full amount of gravity stress in the walls. However this does not pose a serious concern. This type of model is accurate while the material is in the elastic range therefore the crack patterns will still be similar. In the inelastic range, the modeling of gravity stress does affect the accuracy of the model. However the point of this test is to study the global response characteristics and to evaluate the retrofit measures. Since, the model will show similar crack patterns, the response of the cracked model will contain the same global characteristics of the full-scale model even though the inelastic responses will occur at lower levels of lateral load.

INSTRUMENTATION

The primary objective of this test is to gauge the effectiveness of rehabilitation schemes on a masonry structure. Accelerometers, displacement transducers, and strain gauges will all be used to record the state of the model during testing.

Accelerometers are fastened to the specimen to record accelerations in all three directions during the test. Accelerometers are placed in the center and edges of the diaphragms in order to record the motions of the diaphragm and determine the forces transmitted to the walls. Accelerometers are also placed in the center and edges of the walls at each floor level to record the motions of the walls. These accelerometers are used to determine the story stiffnessess and the relative force distributions between the walls. They also indicate any torsional motions due to the asymmetry in the model. In addition reference accelerometers are installed at the base of the specimen to record the base motion.

Displacement transducers are placed in similar places to record the displacements of the walls and diaphragms. Some displacement transducers are attached between a fixed datum and the story levels to determine the story drift. In addition displacement transducers will be placed along the first story piers to determine the strains and deformations in the piers. Strain gauges will be used to record the state of stress in the FRP (fiber reinforced polymer) reinforcement.

PRELIMINARY ANALYSES

A simple initial analysis examined the expected strength of the piers in the model. The analysis assumed a first story mechanism and used the FEMA 273 (1997) provisions to determine the basic capacity of the piers. Based on the initial analyses (see Table 1), all of the piers in the structure should eventually rock when subjected to earthquake motions. Using FEMA 273 guidelines, the estimated combined lateral strength of walls A and B is approximately 52 kN (12 kips), the strength of walls 1 and 2 are approximately 16 kN (3.6 kips). An acceleration of approximately 0.2 g's is estimated to be sufficient to start rocking the piers. The rehabilitated structure can be expected to see significant damage within the anticipated shake table acceleration limit of 1.5 – 2.0 g's.

The specimen was also analyzed with a 3-D finite element model. Initial results from this model agree with the results form the FEMA 273 analysis. Later, in-depth analysis will be useful in determining how the expected stress distributions in the walls compare to the actual distributions measured in the test.

Table 1. Initial calculations based on FEMA 273

Pier	Length (mm)	Effective height (mm)	Bed Joint Sliding (kN)	Rocking (kN)	Diagonal Tension (kN)	Toe Crushing (kN)
1	610	1071	22.2	1.9	13.7	2.1
2	508	617	19.9	4.4	18.8	4.8
3	508	617	21.5	6.8	21.3	7.4
4	610	617	27.4	12.7	33.8	13.9
9	2692	3200	66.5	5.6	61.9	6.2
10	610	1071	15.0	1.7	9.5	1.9
11	610	1071	17.6	4.4	12.3	4.8
12	610	1071	17.6	4.4	12.3	4.8

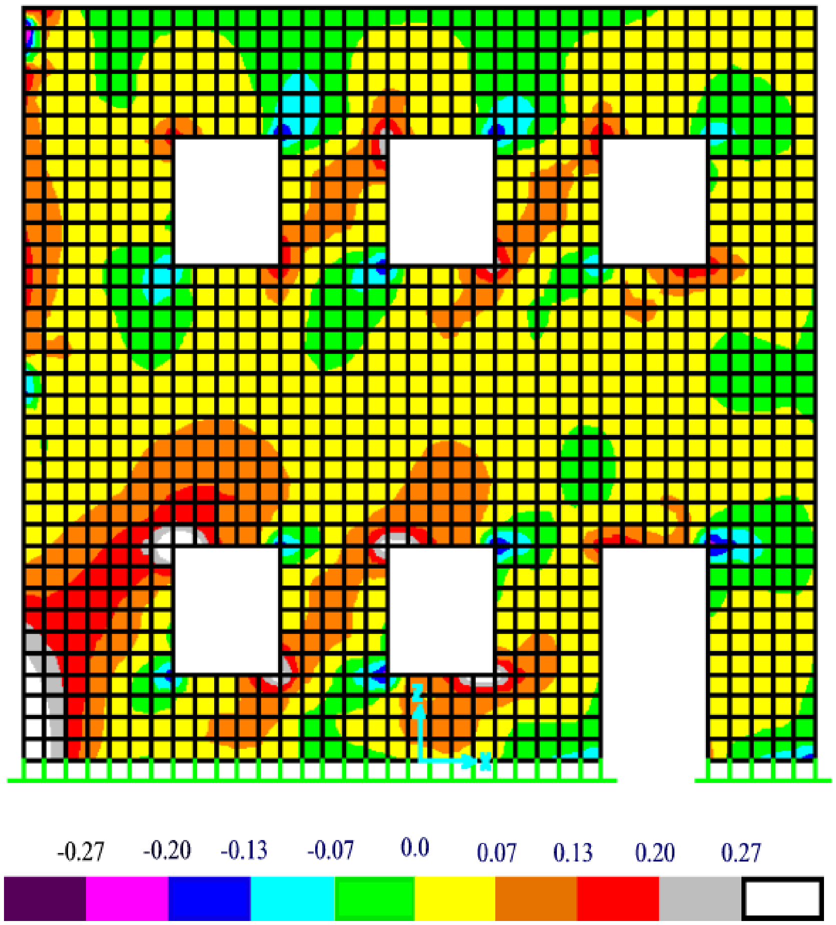

Figure 2. Principal stresses in wall B (units in MPa)

Figure 2 shows the maximum principal stresses in wall B. The stresses were determined from a SAP 2000 analysis with equivalent lateral loads at 0.2g's. Across the lower piers there are diagonal bands of high stress. For the band with the highest stresses, the majority of the band has stresses lower than 0.14 MPa (20psi), which means it does not reach the diagonal tension strength of the masonry of 0.27 MPa (40psi). Therefore the piers should not crack in diagonal tension. There are regions of very high stress of 0.27 MPa (40 psi) located at the corners of the piers. These stresses are much greater than the tensile strength of the masonry of 0.1 MPa (15psi), therefore the model is likely to crack in these regions. These types of cracks are consistent with rocking of the pier. The initial results from the FEM analysis agree with the FEMA 273 analysis in that all of the piers will rock at approximately 0.2g's.

RETROFIT SCHEME

The retrofit scheme involves the placement of FRP (fiber reinforced polymer) straps on the critical piers. The straps are placed in such a way as to maximize strength while minimizing the amount of material needed, see Figure 3. The increase in strength of the pier is a function of the FRP strength and the volume of FRP used.

The vertical straps in the diagram add to the bed joint sliding strength of the pier by providing clamping force and some additional shear resistance. The strap is full height because the shear is constant through the height of the pier. The vertical straps also add to the rocking strength by providing tensional strength across any possible cracks. The cross straps add to the material at the critical corners thereby adding even more strength in those locations. Also, they increase the strength in diagonal cracking by forcing the crack to develop on the outside edge of the fibers rather than through the middle. Furthermore they help hold the pier together and keep it from falling out.

The FRP can generally increase the strength of the pier to the diagonal cracking strength. However FRP does little to add to the toe crushing strength so that generally serves as the upper bound of the strength of the piers. Based on tests at CERL (Construction Engineering Research Laboratory), the straps should increase the strength of the pier 10 to 50 percent.

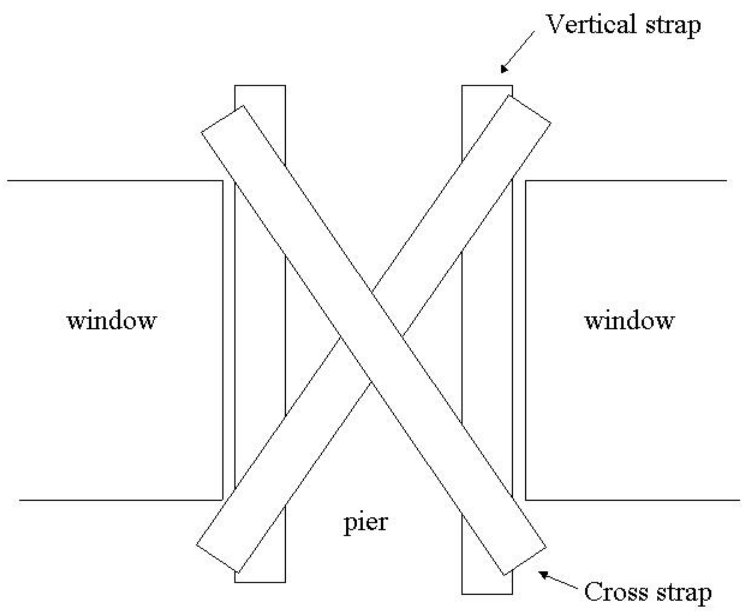

Figure 3. Placement of FRP

PROPOSED TEST PROCEDURE

The testing of the model begins with free vibration tests in all three directions to determine the natural period of the model in those directions. Scaled earthquake ground motions are then run through the model in each of the horizontal directions separately to determine the response from the walls. This provides a basis for comparison with one-directional dynamic testing. The motions are small enough as to not to cause significant damage to the structure. Finally the model is tested tri-directionally to determine the three-dimensional response of the structure. These motions are significant enough to cause some damage to the structure. The model is then retrofitted per the described retrofit techniques. The same earthquake ground motions are then run at higher amplitudes to determine the effects of the retrofit scheme. Finally the structure is tested until it becomes severely damaged.

SUMMARY

An introduction to a dynamic testing program on a half-scale unreinforced masonry building has been presented. Reasons for the design and preliminary analysis have been discussed. Various retrofit schemes intended to strengthen the building have also been introduced. The data collection setup and testing procedure have been outlined. Results of the testing program should be presented at the conference.

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