Seismic Response of Unreinforced Masonry Buildings

by Daniel Abrams

Abstract and Background

Currently, there are two documents that provide guidance to the engineering profession on how to make a seismic evaluation of an unreinforced masonry building system. In Appendix Chapter C of the Federal Emergency Management Agency (FEMA) 178 report (1992) an evaluation procedure is described which is based on earlier National Science Foundation sponsored research with the ABK project. A similar evaluation procedure is given in Appendix Chapter 1 of the UCBC (1991) which is based on working stresses rather than strengths as is done with the FEMA 178 procedures. Each procedure is aimed at a single specific type of building configuration: low-rise buildings with unreinforced clay-unit masonry walls and flexible floors and roofs. A new document is presently being developed by FEMA and the Building Seismic Safety Council (BSSC) through contract to the Applied Technology Council (ATC) that will attempt to incorporate the UCBC and FEMA 178 methodologies for rehabilitated building systems containing unreinforced masonry with new elements of other construction materials such as steel, concrete or timber. Furthermore, the new guidelines will make a first attempt at a performance based design which will demand a more complete knowledge of the overall force-deflection characteristics of structural components.

To provide the necessary theoretical information for the new guidelines, the NCEER Building Project is taking a close look at the basic response mechanisms for unreinforced masonry bearing wall buildings with flexible diaphragms. In addition, research on masonry infill-frame systems will furnish information needed for the development of provisions for modeling stiffness and strengths of infill panels.

This paper presents an overview of structural engineering research supported by NCEER on seismic response and behavior of unreinforced masonry buildings. Included are research projects related to improving engineering methods for seismic evaluation and rehabilitation of masonry bearing wall and infill-frame building systems.

Collaboration

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Objectives and Approach

The objective of the NCEER masonry building project is to improve the understanding of how masonry bearing wall and infill-frame systems respond to earthquake shaking. The goal of the research is to improve present methods for seismic evaluation and rehabilitation of both bearing wall and infill-frame systems. A number of research projects have been completed or are underway to provide the data necessary to change present engineering procedures for estimating the seismic resistance of these two types of systems.

Seismic behavior of unreinforced masonry (URM) building systems is researched using methods that are common with other types of building structures. Basic research methods include (a) experimental investigations in laboratories, (b) development of computational models, and (c) sensitivity studies of building response. The experimental studies are based on static tests of large-scale test specimens or dynamic tests of reduced-scale structures on earthquake simulators. Computational models are developed using the experimental data as benchmark information. Once calibrated, the models are used to extrapolate what is seen in the laboratory to a large class of buildings and seismic motions so that parametric studies of earthquake response can be made.

This research task is part of NCEER's Building Project. Task numbers are: 92-3107, 92-3108, 92-3109, 92-3110, 92-3111, 93-3110, 93-3111, 93-3112, and 93-3113.

Introduction

Much of the nation's building stock consists of structures that are constructed with masonry. Many of these buildings are exposed to potential seismic hazards, and vulnerable to even moderate intensity earthquakes. Masonry bearing wall buildings predate the turn of the century and were not designed to resist earthquake forces.Their performance in recent earthquakes has been poor. Masonry infill panels in steel or concrete frame buildings represent a newer form of construction, yet these components were not generally engineered as structural elements although they do stiffen a frame system appreciably, and resist stress during seismic events. Little or no guidance is given to structural engineers in existing design documents regarding how to consider infill panels as acting with their surrounding frames.

Accomplishments

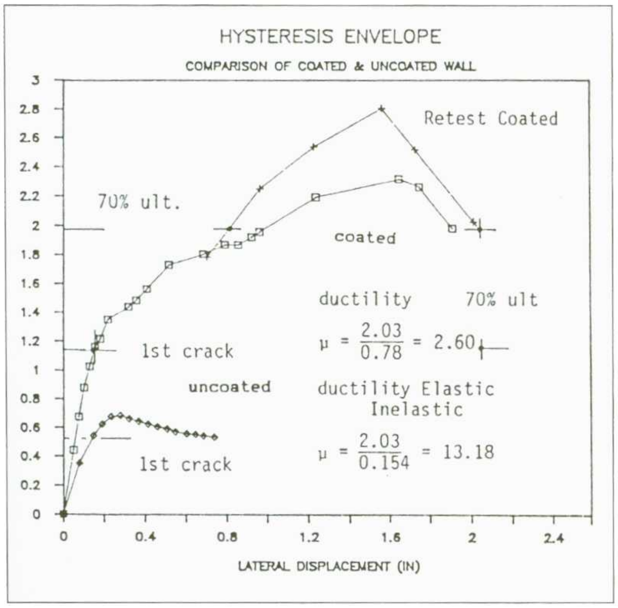
Research accomplishments for NCEER masonry projects are grouped in three basic areas:

- enhancing seismic strength of unreinforced masonry clay brick walls;
- evaluating seismic response of unreinforced masonry bearing wall systems; and
- understanding seismic behavior of unreinforced masonry infill panels.

Results from NCEER projects in each of these three categories are summarized in this section.

Enhancing Seismic Strength of URM Clay Brick Walls

The effectiveness of a ferrocement coating procedure has been proven through a series of



■ **Figure 1**

Comparison of Load-Deflection Relations for Coated and Uncoated URM Walls

experiments on unreinforced clay-unit masonry walls. The rehabilitation method consists of parging a one-half inch thick layer of cement plaster over one or both surfaces of a brick wall. Two layers of wire mesh (No. 19 gage with 1/2 inch mesh) are embedded in the coating. Steel bolts (1/4 inch diameter spaced at 12 inches) are used to prevent delaminations of the coating from a masonry wall.

Test walls were subjected to static and dynamic lateral forces that were applied normal and transverse to their plane. The rehabilitation procedure was found to be an effective measure for improving the seismic resistance of URM brick masonry for both in-plane and out-of-plane bending. As noted in figure 1, the initial stiffness was much larger for coated walls than for uncoated walls (generally by a factor of two or more). Wall strength was also increased considerably with the coating (generally by a factor of three or more). Energy dissipation capacity for a coated wall was as much as three times that for an unstrengthened in-plane wall, and six times that for an unstrengthened out-of-plane wall. The variation of damping factor with seismic intensity remained more stable for the coated walls during the later test phases. For in-plane action, the failure mode changed from flexural combined with sliding or rocking motion to simply flexural with the coating technique. More information on the rehabilitation method and the research results can be found in Reinhorn et. al. (1985) and Prawel et.al. (1986, 1988, May 1990, June 1990, 1991 and 1994).

Based on results of the NCEER study, the rehabilitation method was tested for unreinforced clay-unit masonry infill panels by another researcher (Angel, et. al., 1994). The method was found to increase the transverse strength of non-perforated infill panels by at least a factor of three times.

Evaluating Seismic Response of URM Bearing Wall Systems

At the University of Illinois at Urbana-Champaign, a series of unreinforced clay-unit masonry building systems have been constructed at a reduced scale for the sole purpose of testing to failure with simulated seismic motions (figure 2). The test structures are two stories tall and consist of two perforated brick walls that resist base motions in parallel, and are tied together with flexible diaphragms. In addition, end walls are

■ **Figure 2**

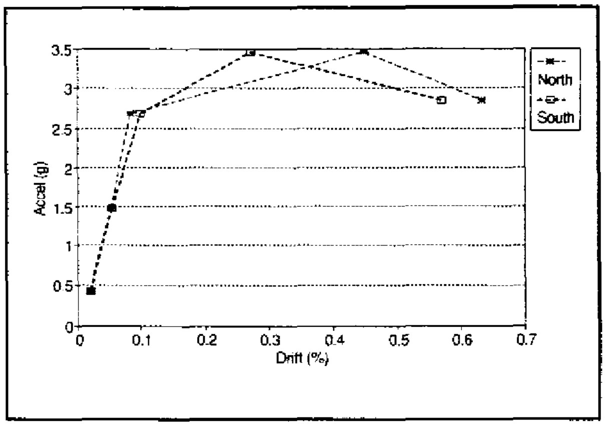
Reduced-Scale URM Bearing Wall Structure on Shaking Table

provided to examine resistance to transverse inertial forces and flange effects for in-plane walls. The primary experimental parameter between the two test structures is the configuration of door and window openings in the walls which results in piers that are governed by shear, flexure or rocking mechanisms.

The research builds on previous NSF sponsored projects done at Illinois. A number of laboratory tests of unreinforced brick walls (Abrams, July 1992 and Abrams and Shah, December 1992) indicated that walls failing in shear or flexure could respond as ductile elements because of the influence of vertical compressive stress. Studies of instrumented unreinforced masonry buildings during the Loma Prieta earthquake (Tena-Colunga and Abrams, December, 1992a and b) suggested that properly constructed and rehabilitated masonry buildings could withstand moderate seismic shaking, and that analysis methods could estimate their dynamic response. In addition, the research is being coordinated with a companion project at the University of Pavia in Italy where a full-scale version of one of the Illinois shaking table test structures is being subjected to static reversals of lateral force (Calvi et. al., 1994). Flexible diaphragm effects, deflected shapes and lateral force distributions observed from the shaking table tests were studied before deciding how to load the full-scale structure in Pavia.

Measured dynamic response of the two Illinois shaking table test structures have resulted in the following conclusions. Supporting information can be found in Abrams and Costley (1994) and Costley, Abrams and Calvi (1994).

Amplification ratios for the shaking table structures were similar to those observed with actual instrumented buildings during the Loma Prieta earthquake. It was found that in-plane masonry shear walls can amplify ground motions by a factor of two and flexible roof diaphragms can amplify ground motions by a factor of four.



■ Figure 3
Measured Relation between Seismic Force and Building Deflection

The overall relation between base acceleration and top-level deflection (figure 3) revealed that response of the test structures was ductile despite the presence of shear or flexural cracks.

Pier rocking was the prevalent mechanism for one in-plane wall with door openings. The maximum story shear was easily estimated by summing static rocking capacities of each pier suggesting that a simple calculation method could be used to assess story shear strength.

Lateral forces attracted to the masonry shear walls were a direct result of the vibrating diaphragms. In addition, inertial forces from the masonry elements were applied to the walls, but at a higher frequency than the diaphragm frequency. Thus, the two wall forces were generally out of phase, and as a result, the test structures were able to resist much higher earthquake motions than predicted using conventional equivalent lateral force or spectral response methods that are common for use with stiffer diaphragm systems. Moreover, the applicability of the current "push over" method of analysis appears to be questionable for such flexible diaphragm systems that vibrate at two separate frequencies.

The commonly assumed triangular force distribution is not applicable to flexible diaphragm systems. Because the mass and flexibility of the roof and floor diaphragms were nearly equal, and the stiffness of the shear walls was large relative to the diaphragm stiffness, maximum amplitudes of lateral force at the first and second levels were nearly the same, and many times in synchronization with each other. This suggested that lateral forces should be distributed in accordance with the relative mass amounts without concern for height.

Lateral seismic forces resisted by a single wall are dependent on the strength of adjacent walls. Because the diaphragm forces were shared equally by the two parallel walls, the lateral force attracted to the stronger wall was limited to the strength of the weaker wall.

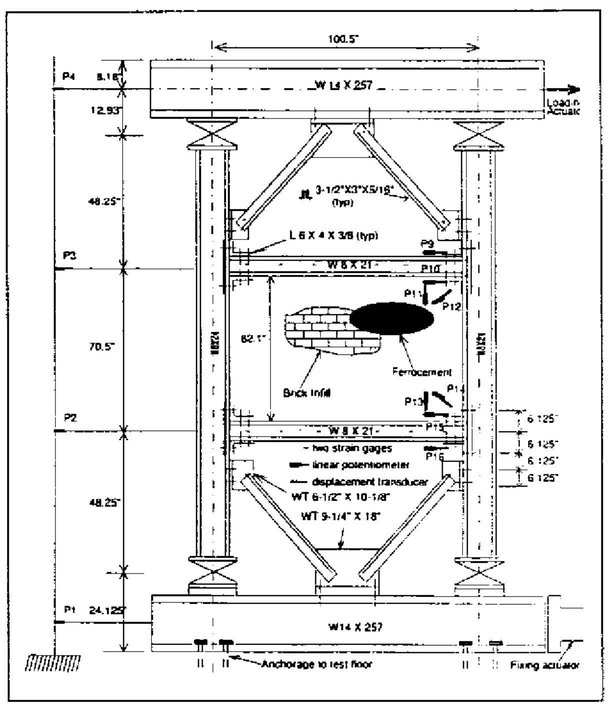
Further research is being done to correlate measured response with estimates based on numerical models.

Understanding Seismic Behavior of URM Infill Panels

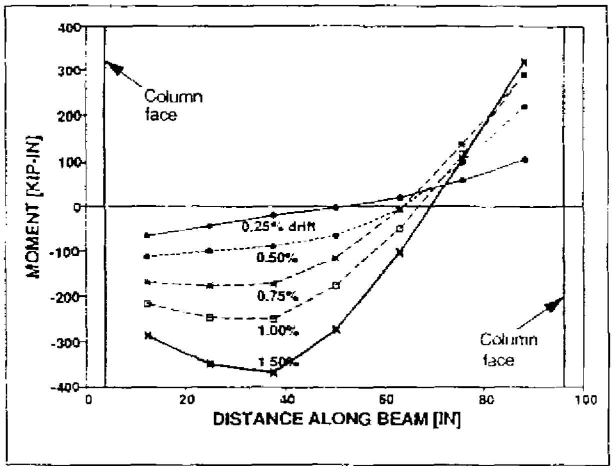
Masonry panels constructed of clay bricks, concrete blocks, or a composite of both, are often placed within structural frames of reinforced concrete or steel. Their purpose is to isolate a room from sound, temperature or weather rather than serve as a stiffening element for a frame. Despite this, infill panels do sense stress and strain when a frame system is subjected to lateral forces. Their relatively high in-plane stiffness can attract significant lateral story shears to the frame-infill system which may exceed their panel strength. Upon cracking, the large infill shear forces may be transferred to the frame elements which in most cases will be designed for much lower lateral forces. Furthermore, partial restraint of a column member by a lower portion of an infill panel may create a shorter span for the member to bend along. In such cases, the full flexural capacity of the column member cannot be developed before it fails in diagonal tension. In any case, seismic evaluations of frame systems must consider the effects of the masonry infill panels in stiffening the system as well as reducing the overall deformation capacity. Three parallel laboratory research projects on infills are or have been supported under the NCEER Building Project. Results from each study will be incorporated in the development of the "FEMA/BSSC/ATC Guidelines for Seismic Rehabilitation of Existing Buildings."

University at Buffalo

The first is a project at the University at Buffalo where a series of brick infilled steel frames were tested to examine basic force interactions between a frame and an infill panel as well as retrofit methods for strengthening the infill panel (Mander et. al., 1993 and 1994). A series of test specimens (figure 4) were subjected to static reversals of lateral force applied parallel to the plane of the infill panels. The first specimen was tested, then repaired using a ferrocement overlay and then retested. A second undamaged specimen was rehabilitated using the same procedure before testing. The third specimen was tested much like the first specimen with the exception that



■ **Figure 4**
Test Specimen with Steel Frame and Brick Infill Panel



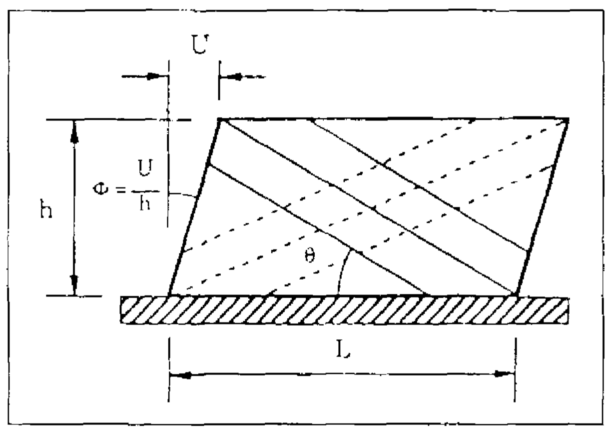
■ **Figure 5**
Moment Diagrams Implied from Beam Strains for Infill Specimen

the overlay was enhanced with diagonal reinforcement. Test results showed that the infill panels behaved in a ductile manner because of the confinement offered by the surrounding steel frame. It was found that ductility could be enhanced with the use of a ferrocement overlay, particularly if it is used with diagonal reinforcement. However, bricks were loosened relative to the frame with cyclic loading and were feared to fall out when subjected to transverse loadings. For this reason, two test specimens were placed on a shaking table and subjected to accelerations normal to the infill plane. Contray to the concern, the tests showed that out-of-plane strength of the infill panels could be quite high because of arching action. Specimens were difficult to fail even with accelerations exceeding 10g's.

Steel strains were measured along the frame members, and were used to infer curvatures and bending moment distributions (figure 5) Using a finite difference method, contact stresses between the frame members and an infill panel were determined from the bending moments Using this unique information on contact stresses, equivalent strut and tie mechanisms were formulated to represent the in-plane stiffness of an infill panel

Cornell University

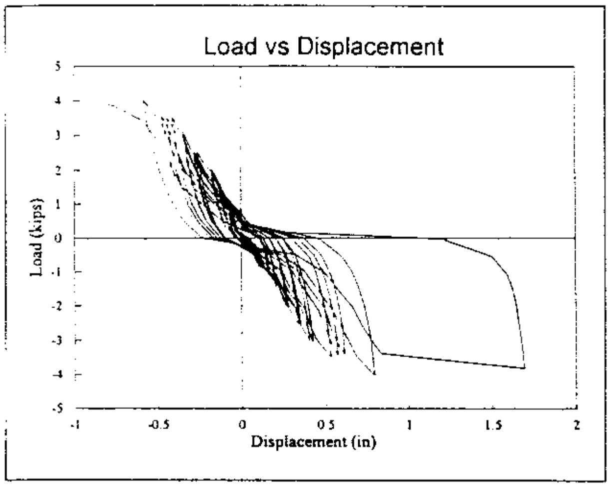
The second infill research project is an ongoing study at Cornell University that examines in-plane behavior of infills in lightly reinforced concrete frames and semi-rigidly connected frames (Chrysostomou et. al , 1992; Gergely et. al, 1993, February 1994 and June 1994; and Mosalam et. al., 1993). The experimental phase of the project is largely centered about verification of analysis methods that can be used to evaluate a frame-infill system. Two analytical formulations are being examined for in-plane panel behavior: (a) a simple multi-strut analogy and (b) nonlinear macro finite element models. With the first model, in-plane behavior of the frame-infill system is represented with three compression struts (figure 6). One strut is on the diagonal of a panel while the other two struts are off center to model panel stiffness after corner crushing occurs With the second model, an infill panel is represented as a continuum with finite elements. The DIANA



■ **Figure 6**
Three Strut Analogy for In-Plane Infill Behavior

program is used to model cracking and plastification as well as geometrical discontinuities such as interface conditions between the panel and surrounding frame.

At Cornell, laboratory experiments are run on concrete masonry infills with steel frames.Test specimens are constructed at one-quarter scale,



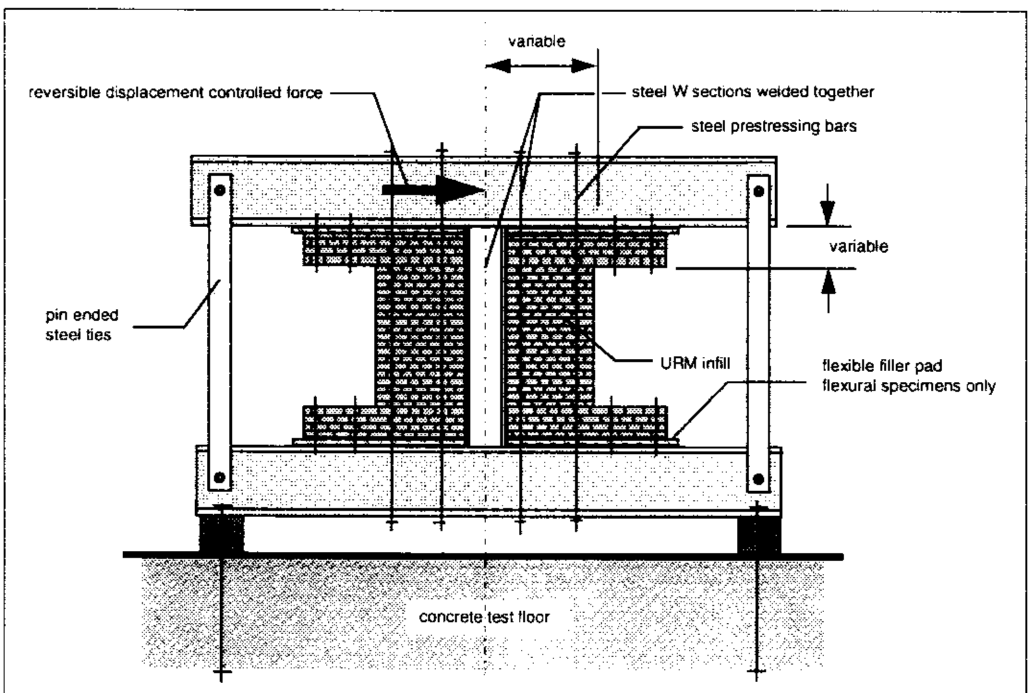
■ **Figure 7**
Measured Relation between Lateral Force and Infill Deformation

consist of single story, one and two-bays, and are subjected to static reversals of lateral force. A typical force-deflection curve is shown in figure 7 that demonstrates the pinched behavior of the hysteresis relation. Considerable separation occurred between the frame and the infill panel away from the panel corners confirming the notion that the frame was braced by equivalent compression struts.

Future work will investigate infills with reinforced concrete frames and include infill panels with openings.

University of Illinois at Urbana-Champaign

The third infill research project is in its first stage at Illinois. A series of test specimens are being subjected to static force reversals to examine basic modeling parameters needed to evaluate the seismic behavior of steel frame buildings with open brick infills or cladding. The experimental study will generate data needed by structural engineers to model stiffness increases for steel frame members and joints that are attributable to unreinforced brick masonry infills and cladding. Three sets of test specimens are planned that will reveal: (a) the increase in flexural stiffness for a cladded steel member, (b) the strut action provided by a partial masonry infill across a story height, and (c) the increase in beam-to-column connection stiffness. The test setup shown



■ **Figure 8**
Infill Braced Steel Frame Test Specimen

in figure 8 will be used to determine how a partial brick infill panel can flex with a steel column. Another test setup will be used to study the moment-rotation relations for cladded steel connections.

Conclusion

Structural engineering research in the area of earthquake resistance of unreinforced masonry construction is challenging because most URM existing buildings were not engineered at the time of their construction. The NCEER Building Project is attempting to fill the gap between present engineering procedures and what is known about the behavior of masonry elements subjected to reversed and repeated loadings, and complete three-dimensional systems comprised of them. Information gleaned from laboratory and computational studies will be of great worth for emerging codes and guidelines for seismic evaluation and rehabilitation of these existing systems.

Personnel and Institutions

NCEER masonry research is a collaborative effort between investigators at the State University of New York at Buffalo, Cornell University and the University of Illinois at Urbana-Champaign.

Methods of rehabilitating unreinforced masonry (URM) walls using ferrocement cement plaster coatings were studied at the University at Buffalo by Professor Sherwood Prawel. Static and dynamic tests were run on sample wall panels that had been strengthened to various degrees using the method.

Research on bearing wall structures is being done at Illinois under the direction of the author. Two-story URM bearing wall systems constructed at approximately 3/8ths scale are subjected to simulated earthquake motions on a shaking table. The purpose of the project is to study nonlinear dynamic response of URM clay brick walls linked by flexible floor or roof diaphragms so that methods of seismic evaluation can be improved.

Three NCEER projects are examining behavior of URM infill panels in structural frames. At the University at Buffalo, Professor John Mander has tested a series of brick infill panels encased in steel frames to examine basic resistance mechanisms as well as repair methods.The behavior of concrete block infill panels confined by reinforced concrete and steel frames is being studied at Cornell by Professors Peter Gergely and Richard White. Reduced-scale specimens are being subjected to static loads in an effort to develop a new strut analogy which can be used by engineers to assess the in-plane lateral stiffness of an infill panel. At Illinois, research is being done to study the interaction of open brick masonry infills with steel frames. Professor Stephen Schneider is running a series of experiments to quantify the stiffening action that an infill with openings can have on steel frame members and connections.

Technical References

Enhancing Seismic Strength of URM Clay Brick Walls

Angel, R., Abrams, D.P., Shapiro, D., Uzarski, J., and Webster, M., "Behavior of Reinforced Concrete Frames with Masonry Infills," Structural Research Series No. 589, University of Illinois at Urbana-Champaign, UILU ENG 94-2005, March 1994, 183 pp.

Prawel, S.P., Reinhorn, A.M., and Kunnath, S.K., "Seismic Retrofit and Repair of Structural Masonry Walls using External Coatings," Proceedings, Third U.S. Conference on Earthquake Engineering, Charleston, South Carolina, August 1986.

Prawel, S.P., Reinhorn, A.M., and Qazi, S.A., "Upgrading the Resistance of Unreinforced Masonry Using Ferrocement Coatings," Proceedings, 8th International Brick/Block Masonry Conference, Dublin, Ireland, September 1988.

Prawel, S.P. and Lee, H.H., "The Performance of Upgraded Brick Masonry Piers Subjected to In-Plane Motion," Proceedings, Fourth U.S. National Conference on Earthquake Engineering, Palm Springs, California, May 1990.

Prawel, S.P., and Lee, H.H., "The Performance of Upgraded Brick Masonry Piers subjected to Out-of-Plane Motion," Proceedings, Fifth North American Masonry Conference, University of Illinois at Urbana-Champaign, June 1990, pp. 411-427.

Prawel, S.P., and Lee, H.H., "Ferrocement as a Surface Coating for the Seismic Upgrading of Old Unreinforced Brick Masonry Walls: Hysteretic Modeling," Proceedings, 9th International Brick/Block Masonry Conference, Berlin, Germany, October 1991, pp. 929-939.

Prawel, S.P., "Research on the Seismic Performance of Repaired URM Walls," Proceedings, US-Italian Workshop on Guidelines for Seismic Evaluation and Rehabilitation of Unreinforced Masonry Buildings, University of Pavia, June 1994.

Reinhorn, A.M., Prawel, S.P., and Jia, Z.H., "Experimental Study on External Ferrocement Coating for Masonry Walls," Journal of Ferrocement, Vol. 15, July 1985, pp. 247.

NEHRP Handbook for the Seismic Evaluation of Existing Buildings, Appendix Chapter C: Evaluation of Unreinforced Bearing Wall Buildings, Federal Emergency Management Agency Report 178, June 1992, pp. C-1 to C-21.

Tena-Colunga, A., and Abrams, D.P., "Response of an Unreinforced Masonry Building during the Loma Prieta Earthquake, Structural Research Series No. 576, Department of Civil Engineering, University of Illinois at Urbana-Champaign, December 1992a, 288 pp.

Tena-Colunga, A., and Abrams, D.P., "Response of an Instrumented Masonry Shear Wall Building with Flexible Diaphragms during the Loma Prieta Earthquake, Structural Research Series No. 577, Department of Civil Engineering, University of Illinois at Urbana-Champaign, December 1992b, 114 pp.

Uniform Code for Building Preservation, Appendix Chapter 1: Seismic Strengthening Provisions for Unreinforced Masonry Bearing Wall Buildings, International Conference of Building Officials, Whittier, California, 1991, pp. 21-33.

Evaluating Seismic Response of URM Bearing Wall Systems

Abrams, D.P., "Strength and Behavior of Unreinforced Masonry Elements," Proceedings, Tenth World Conference on Earthquake Engineering, Madrid, July 1992, pp. 3475-3480.

Abrams, D.P., and Shah, N., "Cyclic Load Testing of Unreinforced Masonry Walls," Advanced Construction Technology Center Report No. 92-26-10, University of Illinois at Urbana-Champaign, December 1992, 46 pp.

Abrams, D.P. and Costley, A.C., "Dynamic Response Measurements for URM Building Systems," Proceedings, US-Italian Workshop on Guidelines for Seismic Evaluation and Rehabilitation of Unreinforced Masonry Buildings, University of Pavia, June 1994.

Calvi, G.M., Magenes, G., Pavese, A., and Abrams, D.P., "Large-Scale Seismic Testing of an Unreinforced Brick Masonry Building," Proceedings. Fifth U.S. National Conference on Earthquake Engineering. Chicago, July 1994. 10 pp.

Costley, A.C., Abrams, D.P., and Calvi, G.M., "Shaking Table Testing of an Unreinforced Brick Masonry Building," Proceedings, Fifth U.S. National Conference on Earthquake Engineering, Chicago, July 1994, 9pp.

Understanding Seismic Behavior of URM Infill Panels

Chrysostomou, C.Z., Gergely, P., and Abel, J.F., "Nonlinear Seismic Response of Infilled Steel Frames," Proceedings, Tenth World Conference on Earthquake Engineering, Madrid, Spain, July 1992, pp. 4435-4442.

Gergely, P., White, R.N., Zawilinski, D., and Mosalam, K., "The Interaction of Masonry Infills and Steel or Concrete Frames," Proceedings, 1993 National Earthquake Conference, Memphis, May 1993, Vol. II, pp. 183-191.

Gergely, P., White, R.N., and Mosalam, K., "Evaluation and Modeling of Infilled Frames," Proceedings, NCEER Workshop on Seismic Response of Masonry Infills, Technical Report NCEER-94-0004, San Francisco, February 1994, pp. 1-51 to 1-56.

Gergely, P., and Hamburger, R., "Simplified Methods for Evaluation of Rehabilitated Buildings," Proceedings, US-Italy Workshop on Guidelines for Seismic Evaluation and Rehabilitation of Unreinforced Masonry Buildings, Technical Report NCEER-94-0021, University of Pavia, June 1994, pp. 4-3 to 4-16.

Mander, J.B., Nair, B., Wojtowski, K., and Ma, J., "The Seismic Performance of Brick Infilled Steel Frames with and without Retrofit," Technical Report NCEER-93-0001, National Center for Earthquake Engineering Research, Buffalo, New York, January 1993.

Mander, J.B., Aycardi, L.E., and Kim, D.K., "Physical and Analytical Modeling of Brick Infilled Steel Frames," Proceedings, NCEER Workshop on Seismic Response of Masonry Infills, Technical Report NCEER-94-0004, San Francisco, February 1994, pp. 1-21 to 1-26.

Mosalam, K.M., Gergely, P., White, R.N., and Zawilinski, D., "The Behavior of Frames with Concrete Block Walls," Proceedings, First Egyptian Conference on Earthquake Engineering, Hurghada, Egypt, December 1993, pp. 283-292.