NEES RESEARCH ON HYBRID MASONRY STRUCTURAL SYSTEMS

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ABSTRACT

Research on a new structural concept for seismically resistant buildings known as hybrid masonry is described. As part of the National Network for Earthquake Engineering Simulation (NEES) sponsored by the USA National Science Foundation, a multi-university research investigation is being done to identify and demonstrate earthquake resistance of this form of construction. An overview of coordinated research at the University of Illinois at Urbana-Champaign (UIUC), Rice University and the University of Hawaii at Manoa (UHM) is presented. Exploratory studies at UIUC have found that lateral strength of hybrid masonry is sufficient to resist seismic demand forces for buildings as tall as nine stories in high seismic zones. Experimental research at UHM has examined the force and deformation capacity of steel connector plates that are used to attach a reinforced concrete masonry panel to a surrounding steel frame, and the strength of steel-masonry interfaces. Work at Rice University has developed computational models that simulate lateral force-deflection behaviour of hybrid masonry. Large-scale tests of two-story, one-bay hybrid masonry frames at UIUC have provided benchmark data on strength, stiffness and ductility of sample structures subjected to repeated reversals of lateral displacements. Brief summaries of these studies are presented herein to serve as an overview.

Hybrid masonry has the potential to be a practical and economic form of construction in seismic regions. Such potential can be realized once research is done to further develop design and construction practices. This paper outlines how this research can be used to transform current seismic design practice, and by so doing, make structural masonry more competitive in regions of moderate and high seismicity.

KEYWORDS: reinforced concrete masonry, earthquake, shear walls, structural steel frames

INTRODUCTION

Lateral-load resistance of reinforced masonry shear walls is well known. Specially reinforced masonry shear walls are regularly used in high seismic zones. Strength design provisions of current building codes such as the Masonry Standards Joint Committee (TMS, 2011) address requirements for shear and flexural strength of such walls and ways to ensure ductility by limiting reinforcement amounts and/or using boundary elements. Seismic force reduction factors, R, in the current ASCE 7 (2010) code are as high as 5.5 for specially reinforced masonry shear walls indicating that seismic deformation capacity can be as good as that for walls constructed of reinforced concrete. However, for low-rise office or residential construction, steel braced frames are many times preferred over shear walls because of the speed of erection and integration of trades.

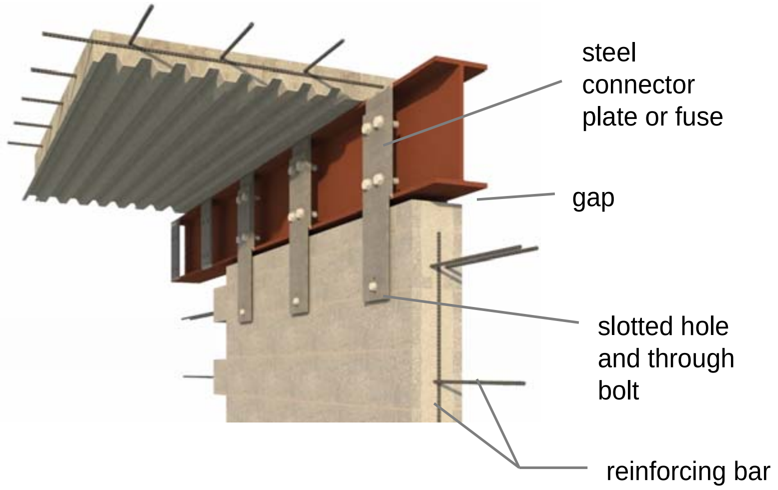

Figure 1: Type I Hybrid Masonry Detail (from IMI)

A new construction method known as hybrid masonry replaces conventional steel bracing with reinforced masonry structural panels. Since these panels may also be used as the backup for brick veneer around the building perimeter, economies in materials and labour are evident. As well, the good seismic strength and ductility of reinforced masonry shear walls can be taken advantage of through proper detailing of reinforcement and anchorage to the steel frame. In addition, masonry panels can be attached to a steel frame with innovative fuse connectors that limit structural damage to the masonry, or conversely strong connector plates (Figure 1) that mobilize energy dissipation through yielding of panel reinforcement. Panels may also be bonded to steel beams at their top and bottom, and possibly at their side edges with grouted stud interfaces to simulate continuous multi-story shear walls with superior strength, stiffness and deformation capacity through composite action with steel members. Papers by Abrams and Biggs (2012) and Biggs (2013) provide additional information on the construction and design of hybrid masonry.

To explore and confirm the feasibility of using hybrid masonry systems in various seismic zones, a research program is underway that is funded through the National Science Foundation of the United States. This paper provides an overview of the research tasks and serves as an umbrella to other papers in this conference (Biggs, 2013; Asselin et.al., 2013; Aoki and Robertson, 2013; and Gregor and Fahnestock., 2013) that describe each task in further detail.

EXPLORATORY STUDIES

A number of different studies were performed at the start of the project to explore characteristics of hybrid systems subjected to lateral earthquake loadings. Simple computational models were used to examine stress distributions with various aspect ratios and conditions of frame confinement (Eidini and Abrams, 2011). The Bentley RAM Elements software was used for this purpose following an extensive evaluation of its modelling assumptions for hybrid masonry. One example of these results is shown in Figure 2 where distributions of vertical stresses resulting from lateral forces applied to a four-story hybrid system are shown. The stress plot to the left is for Type I hybrid masonry where each masonry panel is connected to the steel frames with connector plates as shown in Figure 1. The plot in the center is for Type IIa systems where masonry panels are anchored to the beam above with grout and steel studs. The plot to the right is for Type IIIa systems where panels are anchored to steel frame members around their entire perimeter. Vertical stresses indicate that Type I systems resist lateral force as a series of isolated single-story cantilevered walls whereas Type IIIa systems emulate a continuous four-story tall shear wall. Stresses for Type IIa are between those for Type I and IIIa as expected.

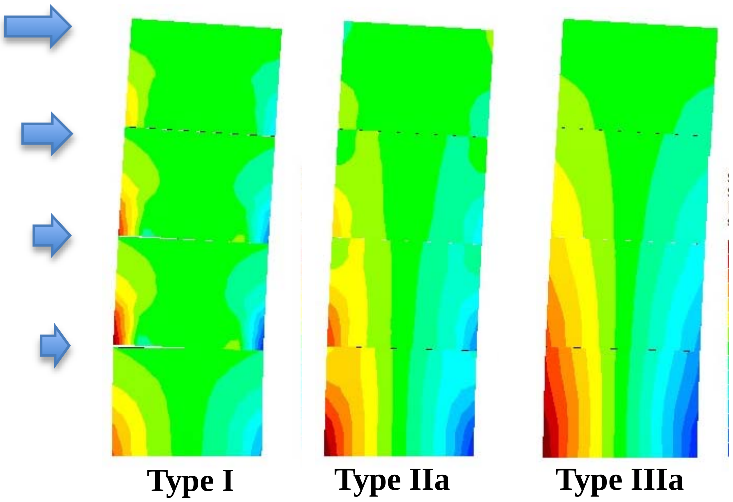

Figure 2: Vertical Stresses for 4-Story Hybrid Systems

A second exploratory study examined the feasibility of using Type I hybrid masonry in various seismic zones in the USA (Asselin et. al. 2012, 2013). The premise for this study was the equivalent base shear method as prescribed in ASCE 7-10 (2010), which relies on national seismic hazard maps per USGS. Using connector strengths per experimental work at the University of Hawaii at Manoa (Johnson, et al., 2011) and standard building configurations per the SAC research program on steel buildings, and a minimum connector spacing of 16 inches, the number of bays requiring masonry panels was estimated (Figure 3). This study demonstrated the feasibility of using hybrid masonry for buildings as tall as nine stories in high seismic zones. This investigation was extended, using static push-over analyses, to explore ductility demands for connector plates which were compared with ductility capacities as measured with the UHM tests. Again, hybrid masonry was found to be a feasible alternative to braced-frame or shear wall construction. Based on these and other exploratory studies, a set of design recommendations for seismic design of hybrid masonry are being formulated which will serve as the basis for trial designs.

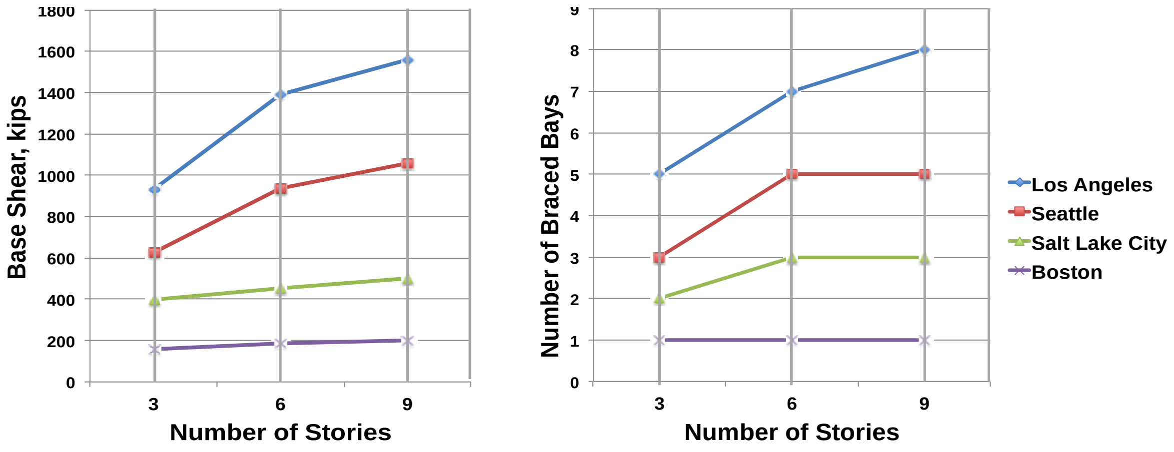

Figure 3: Estimated Number of Braced Bays

CONNECTOR TESTS

Tests of steel connectors attached to masonry panels at the University of Hawaii at Manoa (UHM) provide information on strength, stiffness and ductility needed for design of the large-scale tests done at Illinois (see later description), and explore how best to detail such connectors to behave as energy dissipating fuses, or conversely, with sufficient strength to develop plastic action in reinforced masonry panels. For Type I hybrid masonry, two types of connectors have been developed: one to act as a ductile fuse that can be replaced after an intense earthquake, and the other as a strong connector (termed “link plate”) that relies on ductility of the masonry shear panel to withstand seismic actions but adds flexibility to the stiff masonry panels. Steel connector plates were subjected to cyclic loading with increasing drift levels to determine their response to earthquake shaking. Connector plates installed in three full-scale 8” CMU masonry wall panels were tested as shown in Figure 4.

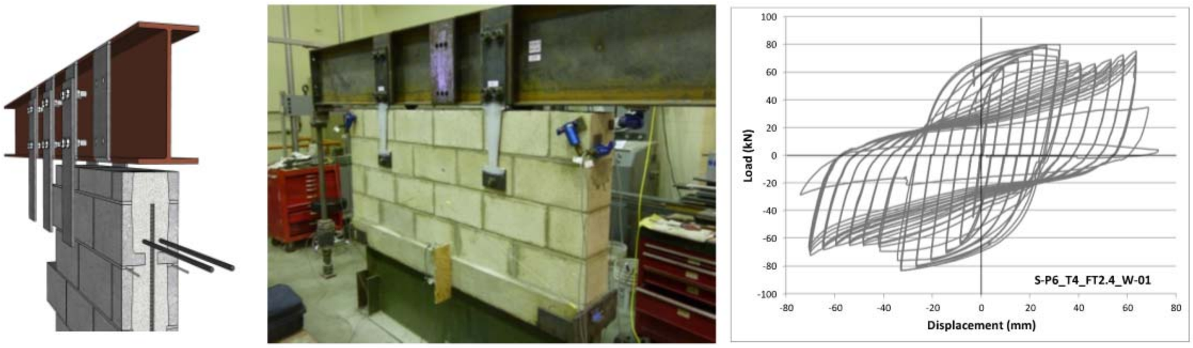

Figure 4. Testing of Fuse and Link Connectors at UHM

Various numbers and sizes of connector plates were investigated to verify that performance of multiple connectors could be extrapolated from the performance of an individual connector. Each masonry wall was constructed over a steel beam with vertical dowels welded to the top flange of the beam. The top of the masonry wall was connected to another horizontal steel beam using either fuse or link connectors. Cyclic horizontal loads were applied to this top beam using a 300-kip, 30-inch stroke hydraulic actuator to induce in-plane shear and bending in the masonry wall. Each wall was used for multiple cyclic load tests, starting with high ductility connector details, and culminating in link plates that induced failure of the masonry wall. Design procedures for both fuse and link plates have been developed based on these experimental results. As a result of this connector development program, connector plates with appropriate size and configuration have been selected for the large-scale tests at Illinois described later.

The connection between the fuse or link plates and the masonry wall is made using a single bolt, which is placed through a masonry panel. Current masonry design codes do not provide design procedures to prescribe edge distances for these through bolts. In order to quantify the bolt break-out capacity based on bolt location and masonry wall reinforcement, a series of masonry specimens were tested at UHM (Aoki and Robertson, 2013).

In order to evaluate the use of headed studs for the steel to masonry connection in Type II and III hybrid masonry, two full-scale 8” CMU masonry walls have been tested at UHM (Aoki and Robertson, 2013). The test setup used for the Type I connector evaluation was also used for these tests, except that the connection between the top steel beam and the masonry wall was made using headed studs embedded in grout instead of the connector plates. These tests have confirmed what stud spacing is necessary to transfer the story shear to a masonry panel.

Detailed information on the series of connector tests at UHM can be found in Goodnight et. al. (2011), Ozaki-Train, et. al. (2011), Mitsuyuki, et. al. (2012) and Aoki and Robertson (2012).

COMPUTATIONAL SIMULATIONS

One purpose of the large-scale testing is to provide benchmark data for calibration of numerical simulation models. Once calibrated, these models can be used to extrapolate laboratory findings to a much larger scope of structural configurations through parametric studies. From basic principles, such simulation models have been developed at Rice University (Stanciulescu and Gao 2011a, b). One sample of results is shown in Figure 5, which correlates contours of computed damage indices with observed damage of a single-story reinforced concrete masonry panel tested by Benson Shing as part of the TeCCMaR research program (Shing et al., 1990). Simulated damage patterns correlated well with the experiments.

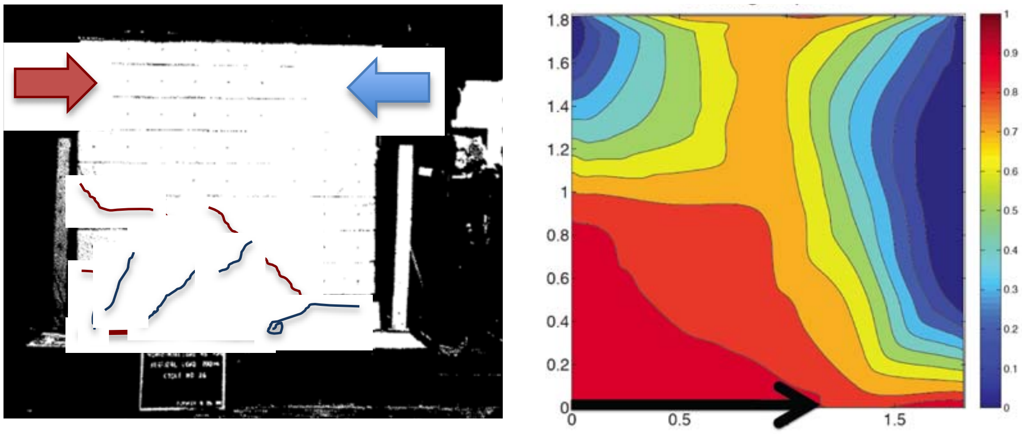

Figure 5: Correlation of Damage Indices with Shing Experiments

Simulation models will be calibrated with measured force-deflection relations from the Illinois experiments, as well as with non-contact measurements of movements of a series of LED nodes attached to the masonry test panel (see next section). This comparison may not be exact because of local effects of cracking in the masonry and load-reversal hysteretic effects, but it will be useful in learning of the precision limits of modeling masonry and understanding overall behavior of the test structure. Experimental data will also be compared with results obtained using commercial software that has recently been developed for design of hybrid masonry structures. Further descriptions of the computational models can be found in Stanciulescu and Gao (2011a, b).

LARGE-SCALE TESTING

A series of large-scale tests of two-story hybrid masonry structures (Figure 6) is underway at the University of Illinois using the NEES MUST-SIM site. Experimental parameters include the type of hybrid masonry (as defined by the boundary conditions around the perimeter of a panel as noted previously) and the height-to-length aspect ratio of a masonry panel. Masonry panels were constructed with fully grouted 8-inch concrete block reinforced in accordance with amounts of reinforcement consistent with that specified for specially reinforced concrete masonry shear walls per the MSJC (TMS, 2011). The base story consists of 12 courses of block while the upper story has 10 courses so that the upper story will incur less damage and not need to be replaced from one test to another.

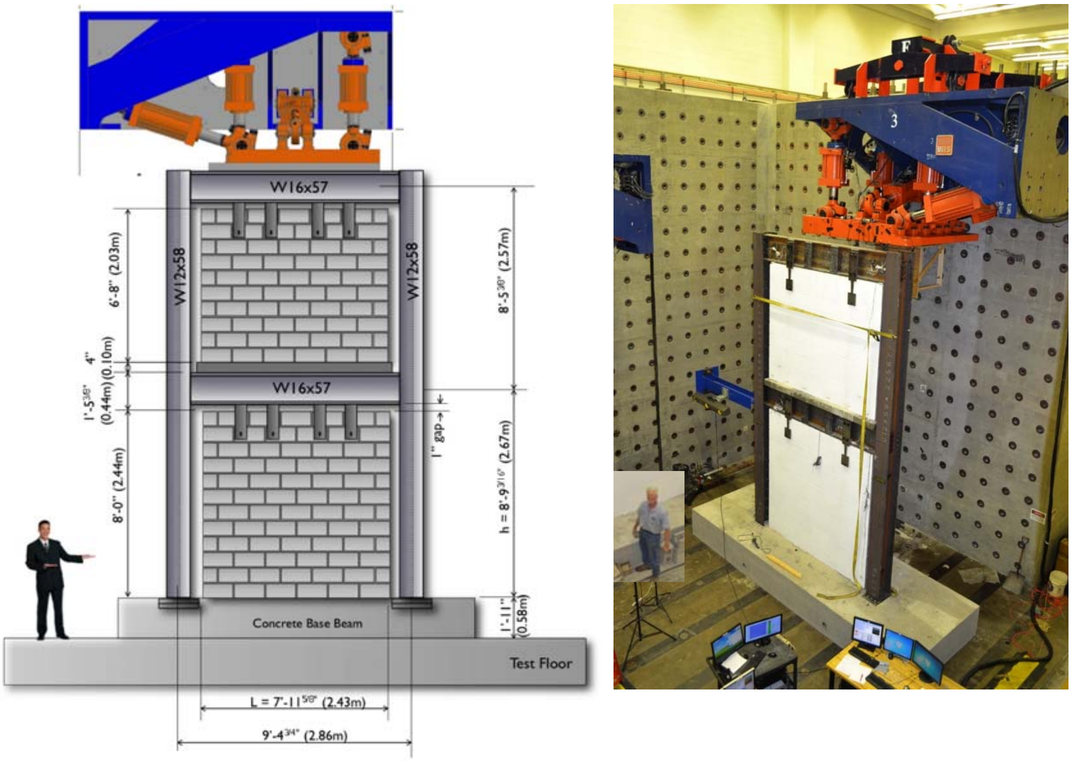

Figure 6. Large-Scale Hybrid Masonry Test Structure at UIUC

Forces and displacements are applied at the top of the structure with a unique Load and Boundary Condition Box (LBCB) capable of imposing six degrees of freedom (three translations and three rotations). The test sequence includes a series of repeated and reversed horizontal in-plane displacements at the top of the structure while a constant vertical force representing gravity loads is applied. Forces are controlled so that no moment is applied at the top of the structure. Loadings are applied at rates that are essentially static.

Instrumentation includes measurement of applied forces and displacements, strains in the reinforcement and steel members, and x-y deformations of a series of LED sensors attached to the masonry on an eight-inch grid. These data provide information to depict the load-displacement hysteretic relations for the overall test structure, the transfer of forces between the masonry and steel frame, and the in-plane distortions of a masonry panel.

The first three test structures were Type I hybrid masonry where masonry panels at both stories were attached to the steel frame with steel connector plates (see Figure 1). These plates had vertical slotted holes so that bolts could resist only horizontal forces and any vertical loads were transferred through the steel beams to the steel columns. Starting with two pairs of relatively weak 4-inch plates (termed "fuse plates") tests replicated previous tests done at UHM (similar to that shown in Figure 4) where damage was limited to that of the fuse plate. Because of the large flexibility of these fuse plates, significant interactions occurred with the steel frame forcing the largest displacement demands on the second-story fuses. Lateral story drifts approached 4%. These weak fuse plates were then replaced with stronger 6-inch fuse plates for the second test structure. The increase in lateral stiffness with this second structure was obvious with far less interaction with the frame than the first structure. The increase in applied lateral force for this test resulted in cracking of some bed-joints near the base of the first-story panel due to flexure. These first two tests demonstrated the favourable flexibility and energy dissipation characteristics of the fuse connections. For the third test structure, a series of four pairs of strong plates (termed "link plates") replaced the fuse plates to test the strength and ductility of the reinforced masonry base-story panel. These tests demonstrated similar behaviour to that observed with other experiments for single-story reinforced masonry shear walls such as Shing, et.al. (1990). Vertical reinforcement was strained past yield near the base, some face shells spalled near the toe, and some limited sliding occurred at the base.

Subsequent testing of four other test structures will be done using prefabricated base-story masonry panels attached to the steel frame with different boundary conditions. The fourth test structure will be similar to the third, but the base-story panel will be reinforced as an intermediate reinforced shear wall. The fifth test structure will be constructed with a fully grouted, steel stud connection at the top of each panel (Type II hybrid masonry) while subsequent test structures will be constructed with grouted stud connections at the top and sides of a panel (Type III). The need to anchor vertical reinforcing bars will be explored for some of these tests by eliminating this type of anchorage at the base of the first-story panel. More information on the large-scale testing can be found in Gregor, et. al. (2011) and Gregor and Fahnestock (2013).

MAJOR RESEARCH FINDINGS

Findings from this coordinated research program include:

a) The feasibility of using hybrid masonry for buildings up to 9 stories tall in moderate and high seismic zones.

b) An improved understanding of how structural masonry panels interact with a structural steel frame for various degrees of frame confinement (gaps on top of panel and on sides) and anchorage of masonry panels to beams (welded reinforcing bars or no tie down).

c) Damage and behavioural patterns in reinforced masonry panels as well as the connector plates under reversed cyclic lateral loadings.

d) Seismic strength and deformation capacity of hybrid masonry systems.

e) How commercial software (Bentley RAM Elements) depicts such behaviour.

f) How steel connector plates deform and how the surrounding masonry stresses react to such forces.

g) Identification of the simplest simulation model capable of capturing salient features of hybrid masonry structural systems including nonlinear behaviour of reinforced masonry panels and nonlinear contact with the surrounding frame.

h) Confirmation of recommended design provisions for seismic design of hybrid masonry buildings.

i) Overall demonstrations of constructability and seismic performance of hybrid masonry.

CONCLUDING REMARKS

Design of masonry construction has largely followed traditional criteria initially established for gravity loadings or in accordance with architectural constraints. Checks for seismic resistance or performance then followed these initial designs. However, this design process can be reversed. Design and construction methods that explicitly reflect intended seismic performance can be introduced as a primary concern. Hybrid masonry lends itself well to such a concept because the building system can be tuned to perform in a desired manner for a specific earthquake intensity level. Performance-based design concepts for earthquake-resistant design can easily be adapted to this innovative form of construction that blends design of two traditional systems.

With the use of ductile and relatively weak steel connector plates, masonry structures can respond with greater flexibility, longer fundamental periods of vibration, less damage and lower repair costs. Or conversely, masonry panels can be bonded to steel columns and beams with grouted stud connections to act compositely. These systems may be superior to a specially reinforced masonry shear wall because of the greater strength and confinement offered by the steel columns acting as boundary elements. Moreover, overly restrictive maximum reinforcement limits set by the current MSJC code, can be waived since toe compressive stress in the wall panel is reduced with attachment to the adjacent steel column.

With either design approach, reinforced masonry panels can be designed using existing provisions of the MSJC for flexure or shear. In addition, the steel frame can be designed using current specifications given by AISC. Because deformation capacity for specially reinforced masonry shear walls and for steel frames is well recognized, response modification factors (R) for hybrid masonry systems can exceed five or six, making them competitive to alternate design solutions in either material or reinforced concrete.

The potential for hybrid masonry as an earthquake-resistant solution has been well demonstrated through this coordinated research project. Whereas further research is needed to develop new design criteria, recommended practices and code provisions, the acceptance of hybrid masonry as a seismic-design solution by design professionals is imminent.

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