Performance-Based Design of Masonry and Masonry Veneer

By Richard E. Klingner, Ph.D., P.E., P. Benson Shing, Ph.D., W. Mark McGinley, P.E., David I. McLean, Ph.D., P.E., Hussein Okail, and Seongwoo Jo

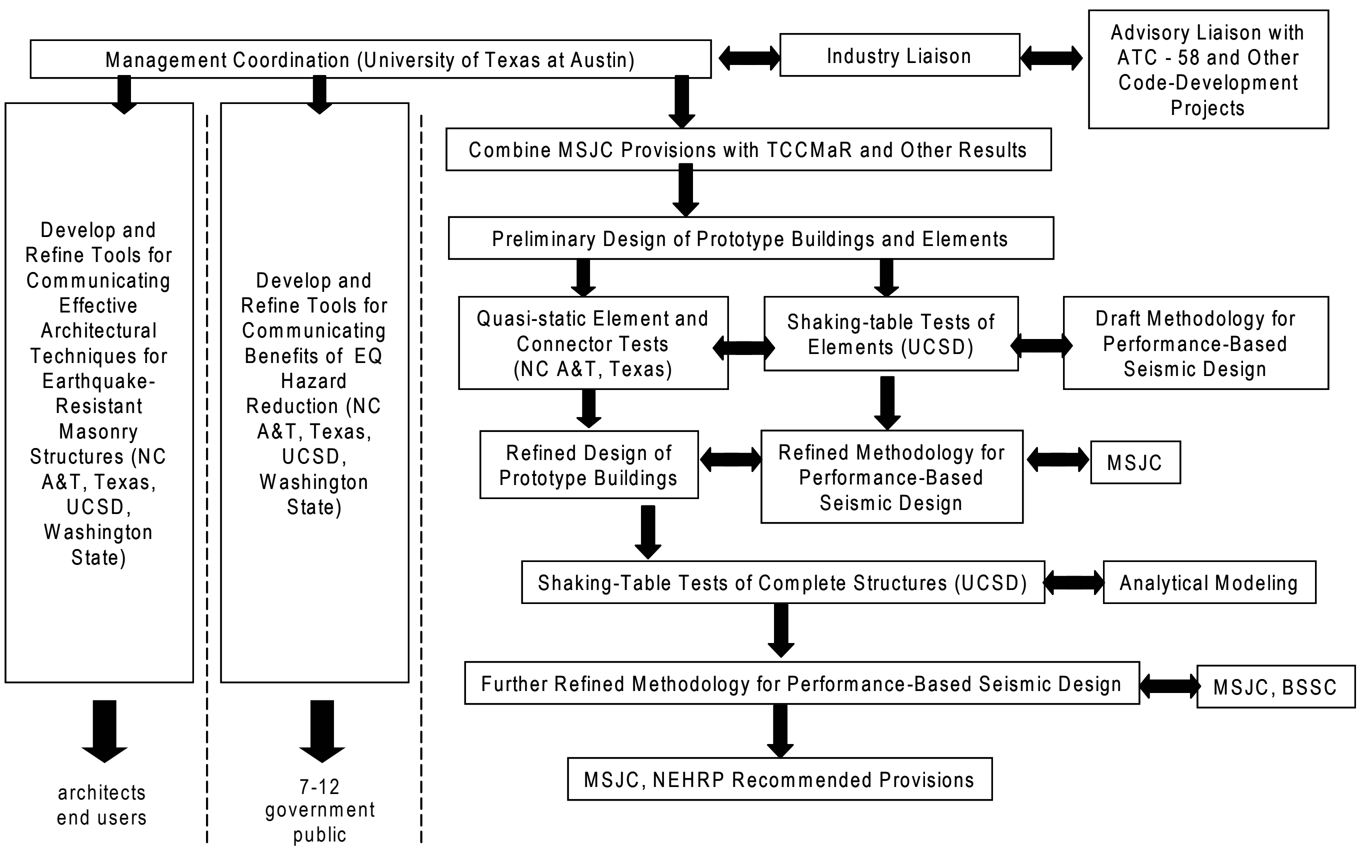
With the support of the Network for Earthquake Engineering Simulation (NEES) program, the US National Science Foundation (NSF) is sponsoring a research project on Performance-based Design of Masonry. The goals of the project are to develop performance-based design provisions for masonry veneer and masonry veneer connectors, and to educate the profession and the public in this area. The project focuses on new masonry construction rather than existing masonry construction.

The project participants include the following:

- The University of Texas at Austin (Richard E. Klingner, Seongwoo Jo);
- The University of California at San Diego (Benson Shing, Hussein Okail);
- Washington State University (David McLean, Katherine Keane, Charlena Grimes); and
- North Carolina A&T State University (W. Mark McGinley, University of Louisville, under contract).

In addition to direct funding and equipment support from the NSF NEES program, the project is receiving financial and in-kind support from many segments of the masonry industry. The project also benefits from the expertise of masonry industry partners, shown in *Table 1*.

OVERALL ORGANIZATION AND WORK PLAN OF NSF NEES MASONRY PROJECT



Overall organization and work plan of NSF NEES small group project on performance-based design of masonry.

Seismic Response of Low-Rise Buildings with Masonry Veneer

Prototypical low-rise buildings with masonry veneer are shown in *Figures 1* and *2*.

Under earthquake loads, walls oriented perpendicular to the direction of ground motion behave as vertically spanning beams, excited at the bottom by the foundation slab and at the top by the roof diaphragm. Their inertial forces contribute to the response of the diaphragm. Walls oriented parallel to the direction of ground motion transmit the diaphragm reactions to the foundation, and act as shear walls. The roof diaphragm is generally flexible compared to the shear walls.

The veneer and the backing are joined by connectors. Examples of these are shown in *Figure 3*. Earthquake loading produces forces in the connectors. The connectors are generally stiff in axial tension, flexible in axial compression, and of variable stiffness in horizontal and vertical shear.

Table 1: Masonry Industry Partners on NSF NEES Masonry Project.

NSF NEES INDUSTRY PARTNERS			
Name	**Title**	**Affiliation**	**Expertise**
J. Gregg Borchelt	Vice President, Engineering and Research	Brick Industry Association, Reston, VA	Masonry veneer, masonry structures, earthquake engineering
John Chrysler	Executive Director	Masonry Institute of America, Torrance, CA	Masonry veneer, earthquake engineering, masonry constructability
Jamie Farny	Program Manager, Masonry and Special Products	Portland Cement Association, Skokie, IL	Masonry mortar, masonry standards
Eric Johnson	Director of Engineering	Brick Industry Association Southeast Region, Charlotte, NC	Masonry veneer
Rashod Johnson	President	The Roderick Group, Chicago, IL	Masonry structures, masonry constructability
John Melander	Director of Product Standards and Technology	Portland Cement Association, Skokie, IL	Masonry mortar, masonry standards
Robert Thomas	President	National Concrete Masonry Association, Herndon, VA	Masonry structures, masonry testing
Diane Throop	Director of Engineering	International Masonry Institute, Annapolis, MD	Masonry structures and masonry constructability
Jason Thompson	Director of Engineering	National Concrete Masonry Association, Herndon, VA	masonry structures, earthquake engineering, masonry testing

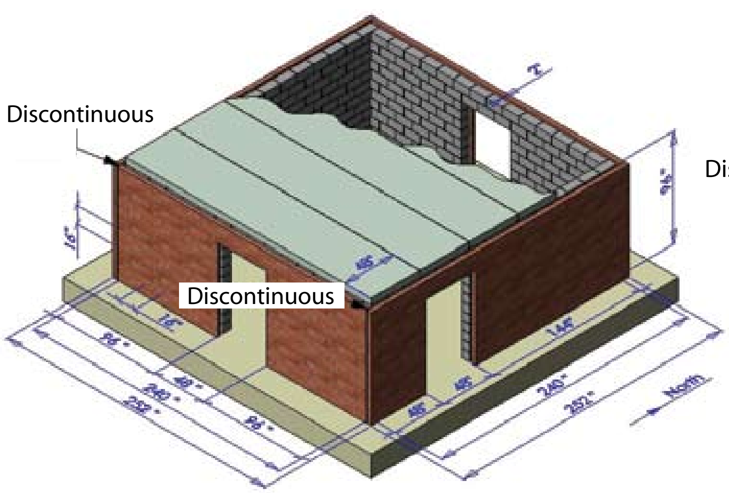


Figure 1: Prototypical wood-stud frame with wood sheathing, connectors and clay masonry veneer, and interior gypsum wallboard.

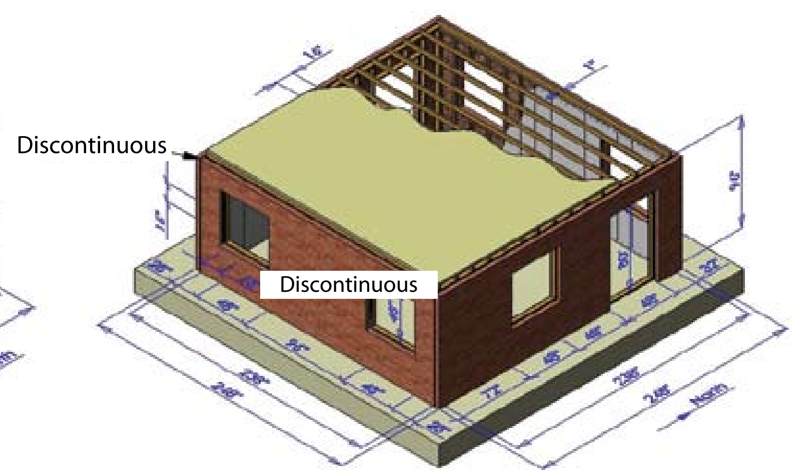


Figure 2: Prototypical low-rise building with concrete masonry backing and masonry veneer.

Corrugated (left) and Rigid (right) Connectors.

Tri-Wire Joint Reinforcement.

Double Eye-and-Pintle Connectors.

Figure 3: Examples of connectors.

Experimental Work

The experimental work on this project consists of the following, each of which is discussed in more detail below:

- quasi-static tests of connectors;
- in-plane, quasi-static tests of veneer over wood studs and over concrete masonry;
- out-of-plane, quasi-static tests of veneer over wood studs and over concrete masonry;
- shaking-table tests of wall segments; and
- shaking-table tests of entire structures.

To permit comparison of the quasi-static and dynamic behavior of wall segments with the dynamic behavior of prototype buildings composed of those same walls, the dimensions and details of the specimens representing entire structures and the specimens representing wall segments are carefully coordinated. The specimens representing entire structures are shown in *Figure 1* and *Figure 2*. The specimens representing wall segments are described in *Table 2* and *Table 3*, and are shown in individual figures later in this paper. Specimens were constructed using locally available materials, according to prevailing local practice and in compliance with the MSJC *Code* and *Specification*. Material strengths were verified by test and will be reported by individual researchers. Specimens at UT Austin and NCA&T were constructed and cured in laboratory space that was heated but not air-conditioned. Specimens at UCSD were constructed and cured out-of-doors. Specimens were cured for at least 28 days before testing.

Table 2: Wood Stud Wall Specimens.

Connectors and Reinforcement	Specimen Description	Loading			
		Quasi-static		Shaking Table	
		In-Plane	Out-of-Plane	In-Plane	Out-of-Plane
Corrugated at 16 in. each way (SDC D). This satisfies current requirements.	4-ft wide by 8-ft high	NCAT Wood 1	NCAT Wood 5	UCSD Wood 1	UCSD Wood 5
	8-ft wide by 8-ft high with 4-ft opening	NCAT Wood 2		UCSD Wood 2	
Corrugated at 16 in. each way with joint reinforcement, mechanically attached (SDC E). This satisfies current requirements.	4-ft wide by 8-ft high		NCAT Wood 6	UCSD Wood 3	UCSD Wood 6
	8-ft wide by 8-ft high with 4-ft opening			UCSD Wood 4 test 1	UCSD Wood 7 UCSD Wood 4 test 2
Corrugated at 16 in. horizontally and 8 in. vertically. This represents an upgraded east-coast solution.	4-ft wide by 8-ft high		NCAT Wood 7		UCSD Wood 8
Rigid at 16 in. horizontally and 24 in. vertically with joint reinforcement (SDC E). This represents a current West Coast solution.	4-ft wide by 8-ft high	NCAT Wood 3	NCAT Wood 8		UCSD Wood 9
	8-ft wide by 8-ft high with 4-ft opening	NCAT Wood 4			UCSD Wood 10

All specimens with wood stud walls use 30 mil EPDM flashing (not self-adhering) at base. All specimens use nominal 4-inch clay units, standard modular (ASTM C216, greater than 75% solid); Type N masonry cement mortar; 7⁄16-inch exterior grade oriented strand board (OSB) fastened by 8d nails 6 inches on center on the edge studs, and 12 inches on center on the intermediate studs; ½-inch gypsum wallboard fastened by drywall screws 4 and 8 inches on centers. Specimens have nominal 2- x 4-inch studs @ 16 inches on centers. All in-plane specimens, except NCAT 1 and NCAT 3, have seismic hold-downs (HDU4-SD2.5) at the panel edge studs. Specimens NCAT 1 and 3 do not have hold-downs, to allow more in-plane movement in the backing, similar to that observed in the field in backing segments not designed as shear walls.

- NCA&T wood-stud specimens use a 2-inch specified air space over OSB for corrugated connectors, because (though not permitted by code) this is the most critical case structurally. NCA&T wood-stud specimens use a 1-inch specified air space over OSB for rigid connectors, because the rigid connectors are fixed in length at 1 inch.
- UCSD wood-stud specimens use a 1-inch specified air space over OSB for corrugated connectors and for rigid connectors, because that best represents current construction.

Figure 4: In-plane, quasi-static, wood-stud specimen (4-ft long) tested at North Carolina A&T State University (NCAT Wood 3).

Table 3: Concrete Masonry Wall Specimens,

CONNECTORS AND REINFORCEMENT	SPECIMEN DESCRIPTION	LOADING			
		Quasi-static		Shaking Table	
		In-Plane	Out-of-Plane	In-Plane	Out-of-Plane
Vertical reinforcement ratio is 0.0011 (two #4 reinforcing bars); horizontal reinforcement ratio is 0.0011 (three #4 reinforcing bars and twelve W1.7 wires). W1.7 joint reinforcement at 16 in. vertically in CMU with W2.8 wire double eye and pintle, spaced at 16 in. horizontally (SDC D)	4-ft wide by 8-ft high	UT CMU 3		UCSD CMU 3	
Vertical reinforcement ratio is 0.0014 (five #4 reinforcing bars); horizontal reinforcement ratio is 0.0011 (three #4 reinforcing bars and twelve W1.7 wires). W1.7 joint reinforcement at 16 in. vertically in CMU with W2.8 wire double eye and pintle, spaced at 16 in. horizontally (SDC D)	8-ft wide by 8-ft high		UT CMU 1		UCSD CMU 1
Vertical reinforcement ratio is 0.0011 (two #4 reinforcing bars); horizontal reinforcement ratio is 0.0011 (three #4 reinforcing bars and twelve W2.8 wires). W1.7 tri-wire ladder-type joint reinforcement at 16 in. vertically with W1.7 cross wires at 16 in. horizontally (SDC E)	4-ft wide by 8-ft high	UT CMU 4 UT CMU 4 (MC)		UCSD CMU 4 UCSD CMU 4 (MC)	
Vertical reinforcement ratio is 0.0014 (five #4 reinforcing bars); horizontal reinforcement ratio is 0.0011 (three #4 reinforcing bars and twelve W1.7 wires). W1.7 tri-wire ladder-type joint reinforcement at 16 in. vertically with W1.7 cross wires at 16 in. horizontally (SDC E)	8-ft wide by 8-ft high		UT CMU 2 UT CMU 2 (MC)		UCSD CMU 2 UCSD CMU 2 (MC)

All specimens with CMU walls use 30 mil EPDM flashing (not self-adhering) at base. All specimens use nominal 8x8x16-inch LWT CMU (ASTM C90); ASTM C270 Type S cement-lime mortar by proportion for CMU wythe and clay wythe; and ASTM C476 coarse grout by proportion. The corresponding masonry cement specimens ("MC") use Type S masonry cement mortar in CMU and clay masonry wythes.

The following air spaces are used:

- UT Austin CMU wall specimens, UT Austin CMU connector specimens, and UCSD CMU specimens use a 2-inch specified air space, because that is typical practice.
- UT Austin CMU wall specimens use nominal 4-inch clay masonry units, standard modular (ASTM C652, 71% solid); UCSD CMU wall specimens use nominal 4-inch clay masonry units (specified as ASTM C216, not 100% solid).
- UT Austin CMU specimens use knock-out units, with every web knocked out except at wall ends. UCSD CMU specimens use A-units throughout, with knock-out units at wall ends. CMU specimens are fully grouted.

In-plane, Quasi-static Tests of Veneer over Wood Studs

In-plane, quasi-static tests were conducted in Summer 2007 at North Carolina A&T State University on veneer over wood studs. The in-plane specimens are described in *Table 2*.

A typical in-plane wood-stud specimen measured either 4 feet or 8 feet in plan by 8 feet high. An example of a 4-foot specimen is shown in *Figure 5*. The 8-foot in-plane, wood-stud specimens had window openings. Detailed results of in-plane tests of wood-stud specimens are described further in work currently being prepared by McGinley.

In-plane, Quasi-static Tests of Veneer over Concrete Masonry

In-plane, quasi-static tests were conducted in Spring 2008 at The University of Texas at Austin on clay masonry veneer over concrete masonry backing. The in-plane specimens are described in *Table 3*. A typical in-plane CMU specimen measured 4 feet in plan and 8 feet high (*Figure 5*).

Results for each in-plane specimen are described in papers being prepared by UT Austin researchers.

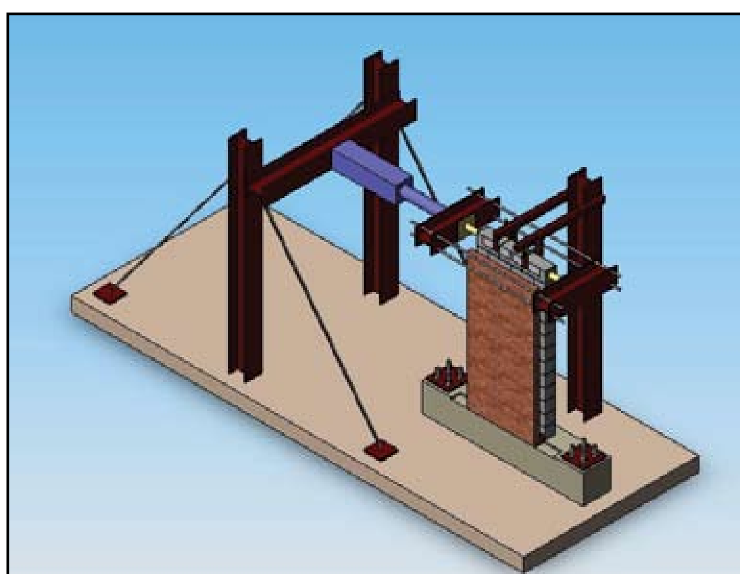


Figure 5: Test setup used for in-plane quasi-static tests of concrete masonry walls with clay masonry veneer at The University of Texas at Austin.

Out-of-plane, Quasi-static Tests of Veneer over Wood Studs and over Concrete Masonry

Out-of-plane, quasi-static tests were conducted in Summer 2007 at North Carolina A&T State University on veneer over wood studs. The out-of-plane specimens are described in *Table 2* and shown in *Figure 6*.

Results of out-of-plane testing of wood-stud specimens are discussed in work currently being prepared by McGinley.

Out-of-plane, Quasi-static Tests of Veneer over Concrete Masonry

Out-of-plane, quasi-static tests were conducted in Summer 2008 at The University of Texas at Austin on veneer over concrete masonry backing. The out-of-plane specimens are described in *Table 3*. A typical out-of-plane CMU specimen measures 8 feet in plan by 8 feet high (*Figure 7*). Results of these tests will be described in work currently being prepared by UT Austin researchers.

Shaking-table Tests of Wall Segments

Shaking-table tests of in- and out-of-plane wall segments replicating the quasi-static specimens described above were conducted in September and October 2007 at the NEES shaking-table site at the University of California at San Diego. The specimens are described in *Table 2* and *Table 3*. In *Figure 8* shows a typical photo of testing of two specimens with window openings (one in-plane and the other out-of-plane) on the outdoor shaking table at the University of California at San Diego.

Specific results from those tests are discussed in papers now being prepared by Okail and Shing. The research group's initial evaluation of test results so far is provided at the end of this article.

Figure 6: Typical out-of-plane, quasi-static specimen with wood-stud backing tested at North Carolina A&T State University.

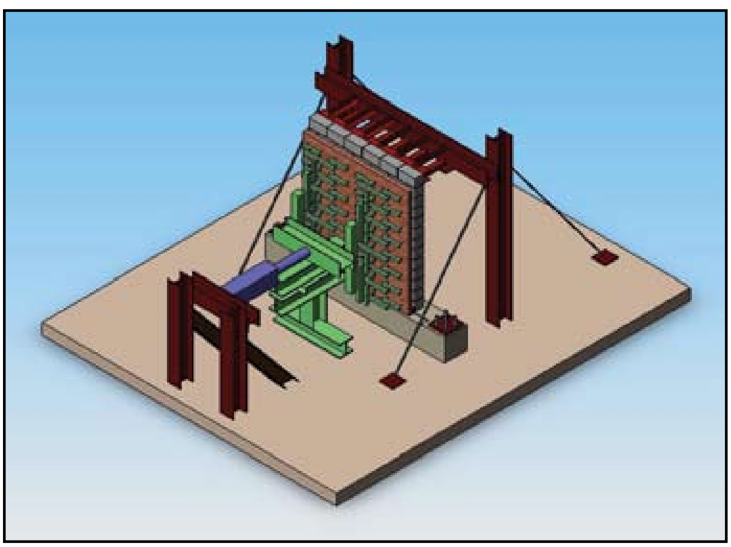


Figure 7: Typical out-of-plane, quasi-static specimen with CMU backing tested at the University of Texas at Austin.

Figure 8: Testing of in- and out-of-plane wall segments on outdoor shaking table at the University of California at San Diego, September 2007.

Shaking-table Tests of Entire Structures

The complete prototype structures shown in *Figure* 2 and *Figure* 3 will be subjected to shaking-table tests in late 2008 at the NEES shaking-table site at the University of California at San Diego. The wood-stud specimen will be tested first. The concrete masonry specimen will then be tested, under two different levels of excitation. It will first be shaken hard enough to seriously damage the veneer. The veneer will then be stripped off; additional mass will be placed on the roof of the specimen; and it will be then be excited more strongly, to examine the collapse behavior of the CMU itself. The aspect ratio of the walls of the CMU specimen has been selected to provide important information about the transition between flexure-dominated and shear-dominated behavior.

Analytical Work

The experimental work described above is being supplemented by analytical modeling. Before testing, each of the specimens described above was modeled on a preliminary basis for design, and in more complex ways for prediction of behavior. An example of this, shown in *Figure 9*, is a finite-element analysis of a masonry veneer panel loaded out-of-plane (University of California at San Diego).

Most Important Information Obtained to Date

The observations made here are tentative, based on preliminary evaluation of shaking-table results from wall segments and the comparison of those results with the results of corresponding quasi-static tests.

Tentative Synthesis of In-plane Behavior

- When masonry veneer is loaded quasi-statically through a wood-stud wall, because the backing is so flexible, a racking displacement field is imposed on the ends of the connectors attached to the backing (see above). For the in-plane wood-stud specimens with window openings, quasi-static tests at North Carolina A&T imply a response consisting primarily of cracking of the veneer wall elements, followed by in-plane rocking of the piers on each side of the openings. Researchers are continuing to investigate the use of existing analytical models for this. The 22-gage connectors are more flexible in-plane than the rigid ones.
- When masonry veneer is loaded quasi-statically through a CMU backing wall, a rocking and racking displacement field is imposed on the end of the connectors embedded in the backing. Those connectors transfer force to the veneer according to their shear stiffness. Because the shear stiffness is low, the connectors can't transfer much force to the veneer, and can't crack the veneer. Veneer response is limited to sliding and rocking. Sliding of the CMU wythe comprises about half the displacement response of the top of the wall.
- When veneer walls are loaded in-plane on the shaking table, the mass of the veneer is excited. The veneer rocks and slides, subjecting the connectors in the top rows to severe reversed cyclic loads, and producing low-cycle fatigue failure.
- The situation is expected to be quite different for the building specimens to be tested . In those specimens, the veneer will have to follow the motion of a backing that is driven by diaphragm mass as well as self-mass.

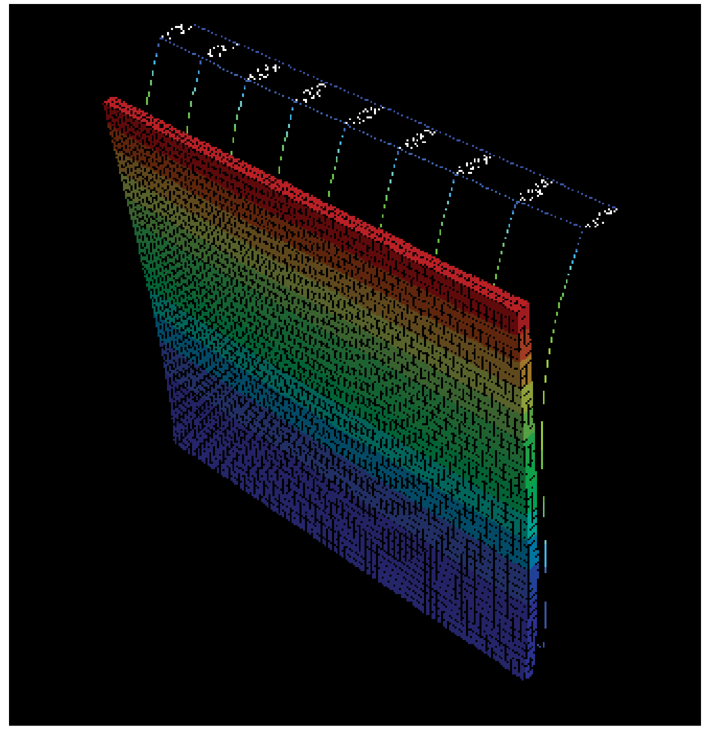


Figure 9: Example of finite element analysis of masonry veneer loaded out-of-plane (University of California at San Diego).

Tentative Synthesis of Out-Of-Plane Behavior

- Out-of-plane response subjects veneer bed joints to flexural tension, and will probably crack one or more veneer bed joints before ultimate capacity is reached.
- Out-of-plane capacity of veneer over wood-stud frames is generally governed by nail extraction, possibly combined with fracture of the connectors in low-cycle fatigue. Stronger nails or screws between the connector and the wood-stud backing can cause the capacity of the wall system to be governed by failure of the connection between connector and veneer at the cracked veneer bed joint.
- Out-of-plane capacity of veneer in CMU specimens is generally governed by failure of the connection between the connector and the veneer at the cracked veneer bed joint. In the CMU specimen with double eye-and-pintle connectors, the pintles pulled out of the eyes along a row of connectors at a load of about 650 lb/connect or (quasi-static) and 400 lb/connector (dynamic). On a preliminary basis, project researchers regard these failure modes as acceptable.
- Under repeated cycles of reversed loading, out-of-plane capacity of veneer over wood-stud or CMU walls may be governed by low-cycle fatigue of veneer connectors. Connectors currently approved by the MSJC Specification vary widely in low-cycle fatigue resistance.

Fundamental Performance and Design Objectives for Veneer

- Life safety is consistent with essentially no falling veneer. Veneer should not be badly damaged under the design earthquake. It can crack, but should not fall off. If this performance objective can be sustained under the maximum considered earthquake (MCE, that would be even better.
- Serviceability is consistent with some maximum permissible cracking (which is not defined at this stage). It should require only minor repair (pointing of some joints).

Summary Results from Shaking-Table Tests on Wall Segments at UCSD

After shaking-table tests of wall segments at UCSD, project researchers believe that these performance objectives are still valid. We believe that they are certainly met by our current design provisions.

- Peak ground accelerations of the Sylmar motion and the Tarzana motion are 0.86 g and 1.9 g respectively. The design earthquake (10% in 50 years, or 476-year return) corresponds to a PGA of 0.69 g, which is about 80% of the Sylmar motion, and about 36% of the Tarzana motion based on the response spectrum of IBC and ASCE 7 for Southern California. The MCE is about 1.5 times design (2% in 50 years, or 2500 year return), corresponding to a PGA of 1.03 g, which is about 120% of the Sylmar motion, and about 54% of the Tarzana motion. This information is summarized in *Table 4*.

Table 4: Relationship between UCSD table motions and code earthquakes.

Description of Earthquake	Multiple of Sylmar	Multiple of Tarzana
Design earthquake (PGA 0.69 g) (10% in 50 years) (476-year return period)	0.80 times Sylmar	0.36 times Tarzana
Maximum considered earthquake (PGA 1.03 g) (2% in 50 years) (2500-year return period)	1.20 times Sylmar	0.54 times Tarzana

- Out-of-plane specimens with clay masonry veneer over CMU behaved as summarized in *Table 5*. A PGA of 2.9 g probably corresponds to response acceleration of about 6 g. Assuming that each connector transmits inertial forces from 1.78 square feet of veneer, and that veneer weighs between 30 and 40 lb/ft^2, the corresponding force per connector is between 300 and 400 pounds per tie. This is consistent with the capacities observed in quasi-static testing elsewhere. Performance in all cases is well in excess of performance objectives.

Table 5: Behavior of out-of-plane specimens with clay masonry veneer over concrete masonry.

Specimen	Description	Behavior	Maximum PGA
UCSD CMU 1	Eye-and-pintle connectors, cement-lime mortar	Failed by bed-joint cracking of veneer and pullout of pintles from eyes in the top row of connectors	2.87 g
UCSD CMU 2	Tri-wire joint reinforcement, cement-lime mortar	Did not fail	> 2.87 g
UCSD CMU 2 MC	Tri-wire joint reinforcement, masonry-cement mortar	Failed by a combination of weld failure of tri-wire joint reinforcement and bed-joint cracking of veneer	2.87 g

- In-plane specimens with clay masonry veneer over concrete masonry behaved as summarized in *Table 6*. Performance in all cases is well in excess of performance objectives. Connector behavior depends on the sliding and rocking response of the veneer, and is more complex than for the out-of-plane case.

Table 6: Behavior of in-of-plane specimens with clay masonry veneer over concrete masonry.

Specimen	Description	Behavior	Maximum PGA
UCSD CMU 3	Eye-and-pintle connectors, cement-lime mortar	Did not fail	> 2.87 g
UCSD CMU 4	Tri-wire joint reinforcement, cement-lime mortar	Failed by a combination of weld failure of tri-wire joint reinforcement and bed-joint cracking of veneer	2.87 g
UCSD CMU 4 MC	Tri-wire joint reinforcement, masonry-cement mortar	Failed by a combination of weld failure of tri-wire joint reinforcement and bed-joint cracking of veneer	2.87 g

- Out-of-plane specimens with clay masonry veneer over wood studs behaved as summarized in *Table 7*. Performance in all cases exceeded performance objectives, and was well in excess of performance objectives except for Specimen UCSD 7X, in which the critical top row of connectors was not installed. Capacity as governed by nail extraction depends on the species grade of the wood, and is quite variable. If predicted capacity of veneer over wood studs is insufficient, and is governed by low nail-extraction capacities, this could be addressed by requiring a reduced connector spacing, or heavier nails, or screws instead of nails.

Table 7: Behavior of out-of-plane specimens with clay masonry veneer over wood studs.

Specimen	Description	Behavior	Maximum PGA
UCSD Wood 5	Corrugated connectors at 16 in. horizontally and vertically	Nail pullout, bed-joint cracking between connectors	2.40 g
UCSD Wood 6	Corrugated connectors at 16 in. horizontally and vertically, joint reinforcement	Nail pullout, bed-joint cracking between connectors, rupture of one connector	2.87 g
UCSD Wood 7 (previously tested UCSD Wood 4)	Window, corrugated connectors at 16 in. horizontally and vertically, joint reinforcement	Nail pullout, bed-joint cracking at sill and pier	2.40 g
UCSD Wood 7X	Window, corrugated connectors at 16 in. horizontally and vertically, joint reinforcement	Nail pullout, bed-joint cracking at lintel (missing top row of connectors)	1.08 g
UCSD Wood 8	Corrugated connectors at 16 in. horizontally and 8 in. vertically	Nail pullout, connector pullout at top row of connectors	2.40 g
UCSD Wood 9	Rigid connectors at 16 in. horizontally and 24 in. vertically, joint reinforcement	Screw pullout, bed-joint cracking, slip at connector hole	1.92 g
UCSD Wood 10	Window, rigid connectors at 16 in. horizontally and 24 in. vertically, joint reinforcement	Screw pullout, bed-joint cracking at pier, slip at connector hole	2.40 g

• In-plane specimens with clay masonry veneer over wood studs behaved as summarized in *Table 8*. Performance in all cases was well in excess of performance objectives. Testing of Specimen UCSD Wood 4 was stopped at a low level of shaking so that the specimen could be re-tested out-of-plane as Specimen UCSD Wood 7. Connector behavior depends on the sliding and rocking response of the veneer, and is more complex than for the out-of-plane case.

Table 8. Behavior of in-plane specimens with clay masonry veneer over wood studs.

Specimen	Description	Behavior	Maximum PGA
UCSD Wood 1	Corrugated connectors at 16 in. horizontally and vertically	No failure; sliding and rocking	> 2.87 g
UCSD Wood 2	Window, corrugated connectors at 16 in. horizontally and vertically	Diagonal cracking and rocking of piers, connector rupture at second run of Tarzana	2.87 g
UCSD Wood 3	Corrugated connectors at 16 in. horizontally and vertically, joint reinforcement	No failure; sliding and rocking	> 2.87 g
UCSD Wood 4	Window, corrugated connectors at 16 in. horizontally and vertically, joint reinforcement	No failure; sliding, pier rocking (test was stopped before failure so specimen could be re-tested out-of-plane as UCSD Wood 7)	1.08 g

Role of Joint Reinforcement

The traditional argument in favor of joint reinforcement is that it will hold pieces of veneer together. This argument may not be correct or even tenable, given that joint reinforcement is ineffective in a cracked bed joint.

As of this date, project researchers have not seen behavior for which the presence or absence of joint reinforcement would be decisive. For the tri-wire specimens, joint reinforcement must obviously be present, so this question is irrelevant. For the eye-and-pintle specimens, we have some evidence (UCSD CMU 1) that cracks form at joint reinforcement, but this may simply be because this is where the connectors are.

We still don't know whether joint reinforcement is beneficial or not. It could help by keeping pieces together, but it also could act as a bond breaker by creating voids or corrosion cells in the bed joints in which it is placed. The more critical difference seems to be among connectors (corrugated versus stiff), and even among different types of corrugated connectors.▪

Acknowledgements

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See next page for references.

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