EXPERIMENTAL TESTING OF PRECAST CONCRETE CLADDING FOR BUILDING FACADE SYSTEMS

Kurt M. McMullin, P.E., PhD., Dept. of Civil and Environmental Engineering, San Jose State University, San Jose, CA.
Maggie Ortiz, Dept. of Civil and Environmental Engineering, San Jose State University, San Jose, CA.

Abstract

The main test program for the Pathways NEESR-SG project is experimental testing of full-scale façade systems. Six experimental test specimens of precast concrete cladding panels have been cast and the test facility at Berkeley is being built and assembled. Two different test specimens have been designed, an architectural specimen and an engineering specimen. The architectural specimen will be an exact replication of an actual cladding system, including full-scale panels, actual cladding connections, sealed joints and windows. Data will allow for direct linkages between damage states and lateral building drift. The engineering specimen will use identical cladding panels and cladding connections, but will have more access to allow for the instrumentation of the connections so joint sealant and windows will not be installed. Data will allow for force-deformation relationships to be developed for each of the different cladding connections. Experimental testing will be conducted in spring and summer 2011 with data reduction taking place during AY2011/12.

Keywords: precast cladding, experimental testing, seismic performance

INTRODUCTION

Precast concrete cladding with inset windows is one common system for the exterior skin of commercial buildings. Cladding panels are precast at a fabrication yard and delivered to the construction site where they are lifted into place and installed. Typically one spandrel panel covers each perimeter floor beam. Column cover panels are then installed in front of each column, sometimes supported by the spandrel cladding panels or alternatively may be connected directly to the structural frame. Punch out windows are installed to fill in the region framed by the spandrel panels on adjoining floors and column covers on the adjoining columns. Cladding systems are relatively similar whether installed on steel frame structures or concrete frame structures.

Cladding systems have changed continuously as new materials and new manufacturing processes have resulted in technological advances. Hegel [5] provides a typical cladding panel and connection layout from the 1980's. The use of spandrel beams and cantilevered column panel arrangement and the connection configurations and locations appear similar to current practice. Hegel explains that each connection is intended to have a single role: bearing connections support the weight of the panel, push-pull connections resist the out-of-plane forces, and shear connections transfer the horizontal forces from the panel to the building frame. Hegel suggests that the use of slotted holes or bending of steel connections can allow the building to deflect laterally without undue interference from the cladding system.

Hegel [5] explains how the arrangement of connections for precast panels has remained relatively constant. This system uses bearing connections at the end of each spandrel panel, push-pull connections at ends and midspan of spandrel panels, bearing connections at the base of column covers, and push-pull connections at the top of column covers.

Damage to building facade has been reported in engineering reconnaissance reports, but the discussion and the detailed features of the system damaged are often discussed only briefly. This shortage of documented performance in past earthquakes makes it challenging to make accurate predictions of life-cycle costs and therefore engineers are in need of quantified information to make informed decisions for performance based design. Notable cladding damage has been reported from the 1964 Anchorage [1,2], 1971 San Fernando [3], 1976 Fruilli, Italy, 1978 Miyagiken-Oki, 1987 Whittier Narrows [1], 1995 Hyogoken-Nambu, and 2001 Nisqually earthquakes.

PAST EXPERIMENTAL TESTING OF CLADDING PANELS

Testing of precast concrete cladding that has been published is limited. Component tests of push-pull connections and lateral seismic connections have been completed [6]. These tests determined force-deformation relationships for the individual connections. While limited published data is available from past testing of cladding systems, some notable testing has been found. Rihal [9] tested a full-scale in-plane loading on a full-story solid precast concrete panel. Rihal reported a maximum lateral force of 1.2 kips for a drift ratio of 0.0117 for the panel tested. This panel had push-pull connections at the top with oversized holes of 2.5 inch diameter. A preliminary study of the dynamics of precast concrete panels has also been reported [8]. Wang [10] tested a multistory multi-bay steel frame with various types of cladding in a full-scale, cyclic loaded test. In this study cladding systems from the United State and Japan were compared and contrasted. Although the Japanese system appears to have performed better, the general consensus from the United States was that the system was too complex and expensive and that the benefit of such a high performance was not worth the added initial cost.

Based upon this past work, nonlinear modeling techniques have been developed using SAP commercial software. This modeling has allowed for initial studies of performance levels of cladding systems [8]. From this past work, the main needs of the current experimental testing were identified: to expand the database of connection force-deformation relationships, to improve the modeling techniques of the system, and to identify system wide issues not seen in component or single-panel testing.

CURRENT RESEARCH PROGRAM

Building upon these past studies, the current NEESR project attempts to answer the research question: what is the relationship between lateral drift of a building and economic damage to the building façade system. The five-year project is focused on experimental testing using the nees@berkeley site as well as simultaneous analytical studies being conducted at both San Jose State University and U.C. Berkeley. Additional research objectives include the influence of building drift on vertical plumbing risers, application of new technologies to detect earthquake damage to the risers, adaptive reuse of damaged cladding panels for alternatives to traditional disposal, and the ability of an innovative undergraduate program to recruit and prepare students for future graduate studies. Table 1 contains the timeline for the tasks involved with this project.

Table 1. Project Timeline

Sept. 2004	Initial discussion of large-scale testing of precast cladding between P.I. and co-researchers
March 2006	Proposal submitted to National Science Foundation for financial support
Sept. 2006	Contract initiated to begin research project.
Jan. 2007	Cladding system designed for prototype building – SAC 9-story LA Building
Sept. 2007	Analytical modeling of Test Specimen initiated.
Dec. 2007	OpenSEES modeling of prototype building initiated.
June 2008	Experimental test matrix altered from two two-story tests to four one-story specimens.
May 2009	OpenSEES modeling of prototype building concluded.
July 2009	Nonlinear modeling of test specimen concluded.
Sept. 2009	Test matrix expanded to six specimens.
March 2010	Detailing of final cladding panel specimens completed.
May 2010	Contracting of panel construction let.
Sept. 2010	Casting of cladding panels completed.
Oct. 2010	Contracting of steel support frame let.
Jan. 2011	Installation of steel support frame initiated.
July 2011	Specimen 1 tested.
Sept. 2011	Specimen 2 tested.
Feb. 2012	Completion of final testing (Test 6)
Sept. 2012	Contract with National Science Foundation expires.

PLANNED TEST PROGRAM

A series of six full-scale tests are scheduled for the second half of 2011. Table 2 provides the test matrix for the experiments. Figures 1 and 2 show the interior and exterior views of the larger Ground Level panel sizes that will be tested. Figure 3 shows the detailing of Panel C2, the return panel for the test. Two different panel heights will be tested: one represents the Ground Level of the prototype building (where the column covers are significantly taller) and the other represents the Typical Level. Ground Level column covers are commonly taller for two primary reasons: 1) there is no spandrel beam at the sidewalk level and 2) the first floor of an office building is often significantly taller than the typical story height for architectural reasons. A second variable of the testing is the loading protocol. Both loading protocols will use displacement control. To allow for future implementation of performance based design, four tests will use the ATC-58 loading protocol [4], composed of cyclic loading with increasing displacement amplitude. These tests are expected to provide accurate representation of the damage caused by the initial application of a certain drift level. To allow for better correlation with analytical study, the second protocol will represent the displacement time history of the upper level of the story during a ground motion excitation of the steel frame. The third variable considered will be the cladding system configuration. Four of the tests will consider the cladding alone, while the other two will explore the interaction of the cladding with the windows and the joint sealant.

Table 2. Test Matrix

Specimen – Test Date	Building Level	Loading Protocol	System Configuration
1 – July 13, 2011	Ground Level	ATC-58	Precast concrete panels
2 – Aug. 31, 2011		Displacement Time History	Precast concrete panels
3		ATC-58	Precast concrete panels, windows, joint sealant
4	Typical Level	ATC-58	Precast concrete panels
5		Displacement Time History	Precast concrete panels
6		ATC-58	Precast concrete panels, windows, joint sealant

Figure 1. Exterior Elevation of Ground Level Test Specimen

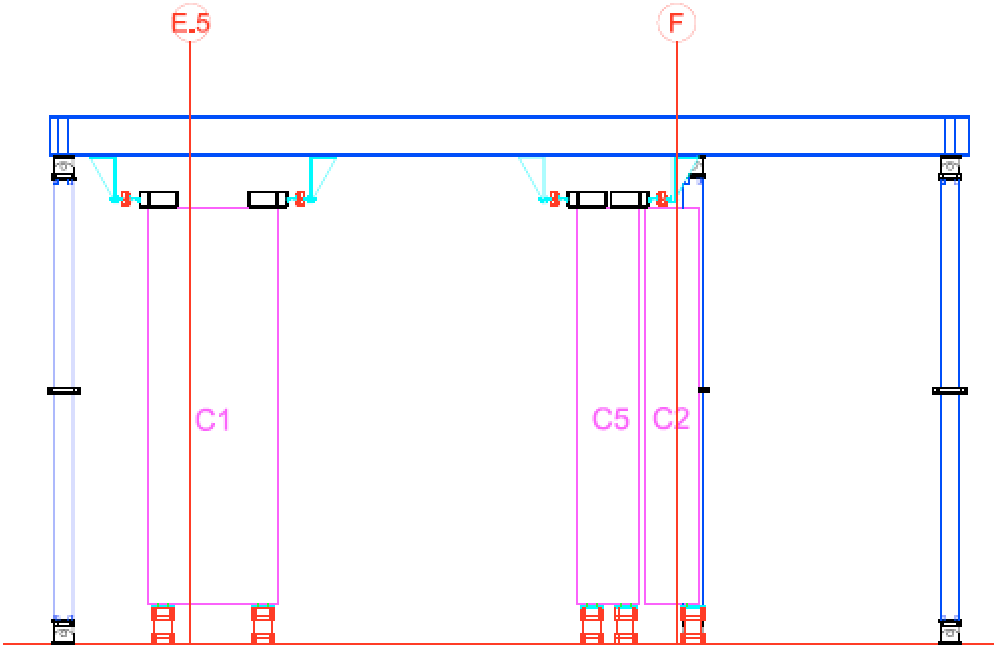


Figure 2. Interior Elevation View of the Ground Level Specimen

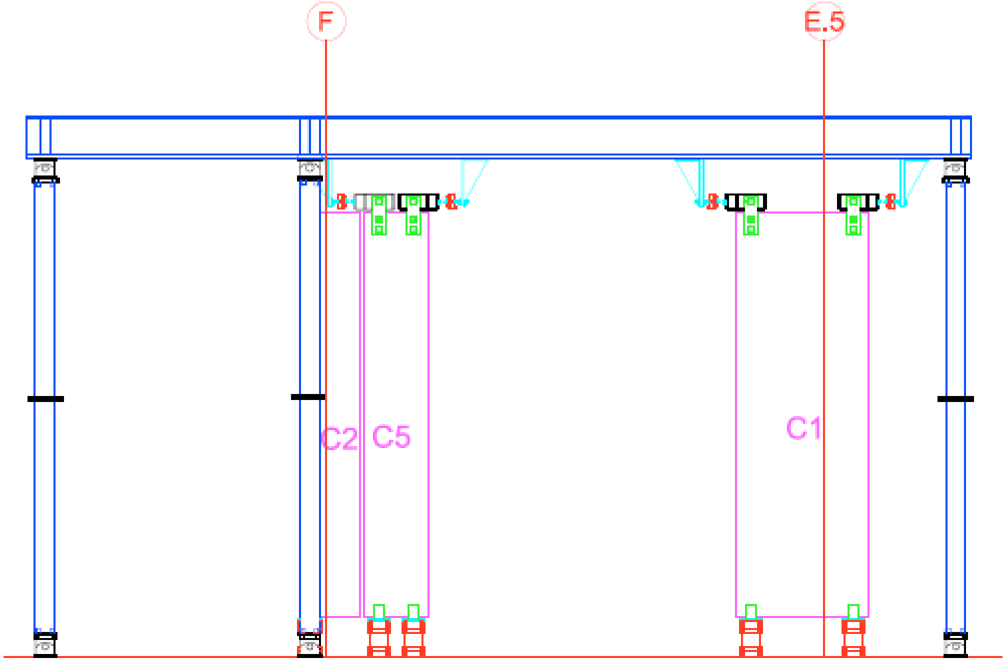
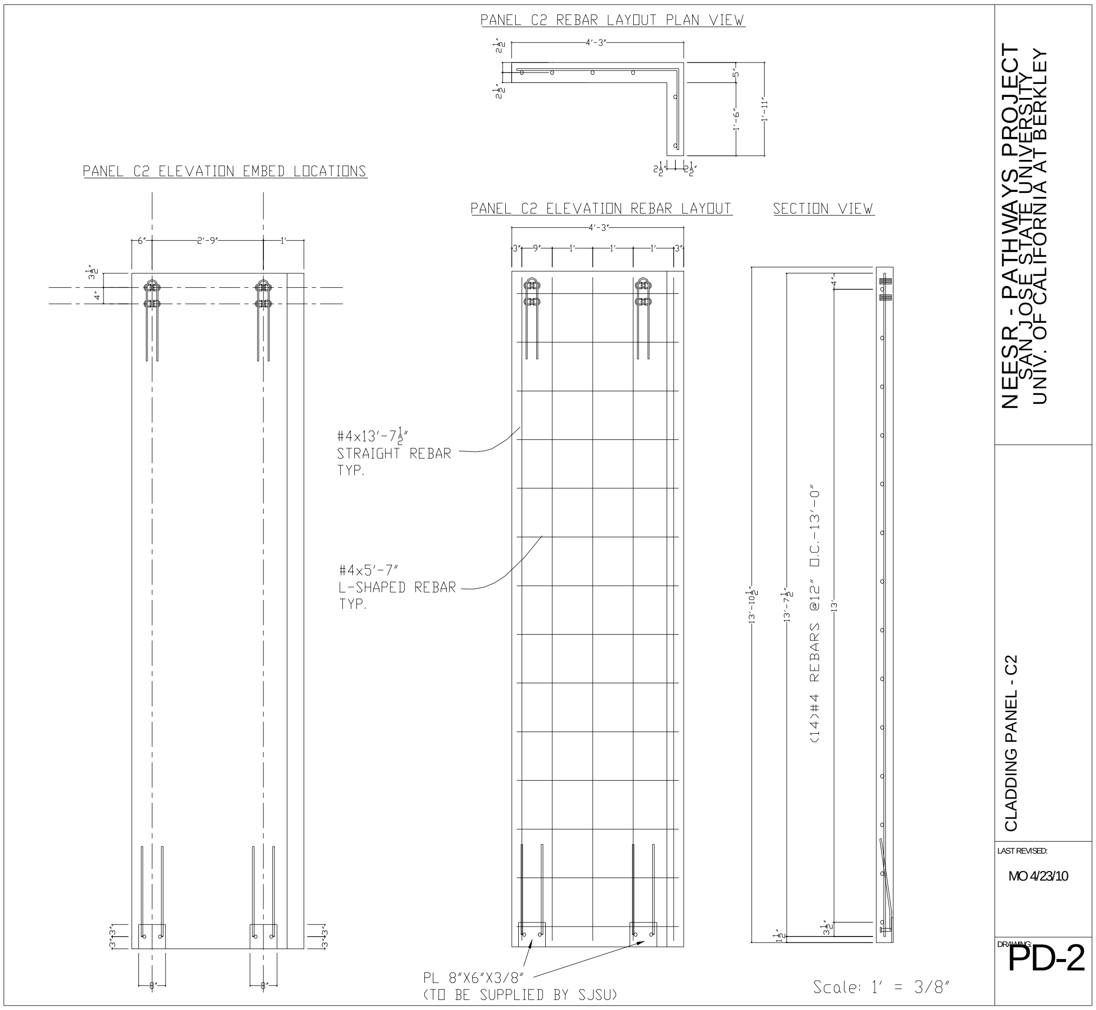


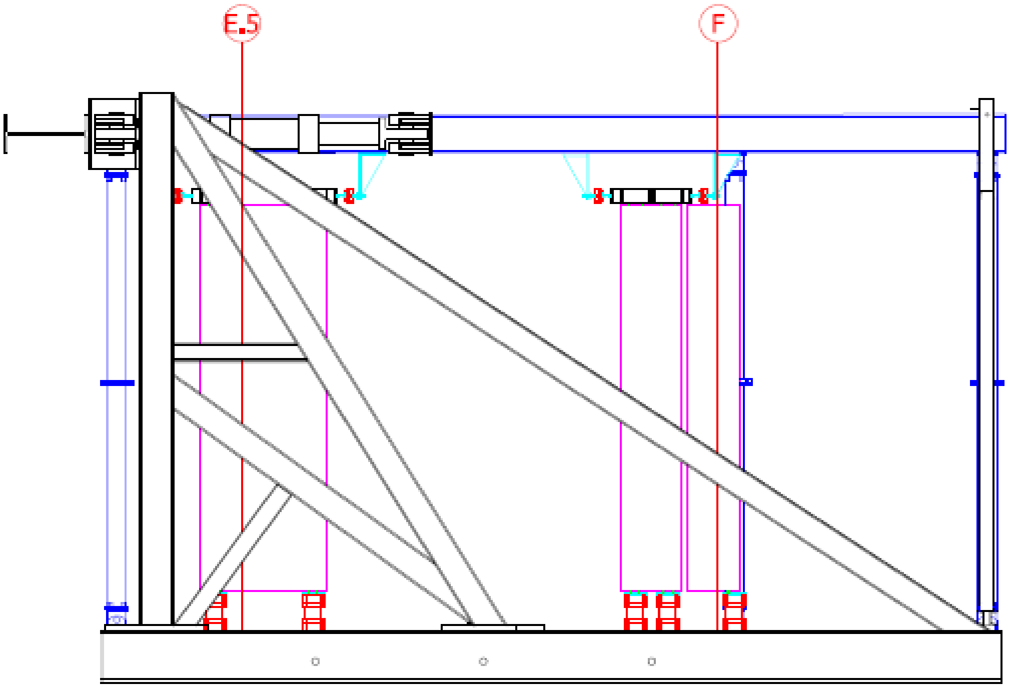
Figure 3. Detail Drawing of Panel C2, the Return Panel



TEST FEATURES

Several aspects of the test have been designed to capture the critical data required for the research. An articulated steel frame will be assembled to support the concrete cladding panels. Although representing the structural system of a moment-resisting frame, the articulation will allow for the drift of the stories without causing resistance in the frame, hence the concrete panels will experience a displacement loading comparable to the motion of adjoining floors of a building swaying during an earthquake. This frame and the test specimen will be assembled in the Reaction Frame of the nees@berkeley equipment site, as shown in Figure 4.

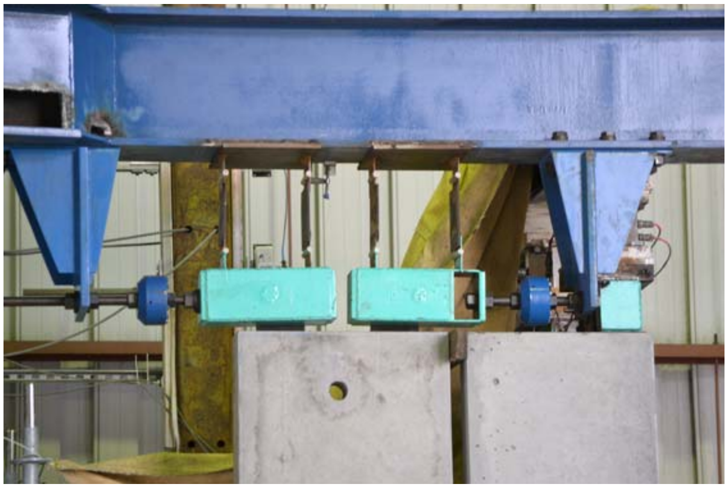
Figure 4. Exterior Elevation of Ground Level Test Specimen installed in Reaction Frame



There are two main objectives for the testing: determining the damage that will occur as a function of lateral drift and determining the force-deformation relationships for the connections between the adjoining concrete panels and between the panels and the steel frame. To accurately define damage events, two architectural specimens (Specimen 3 and 6) will be built as accurately to actual construction as possible. These specimens will include panels as well as finishing with joint sealant to accurately represent the complete facade system. The other four specimens (Specimen 1, 2, 4 and 5) will not have joint sealant installed so as to isolate exact values of forces acting on the panels. All six tests will be monitored for overall pushover forces and deflections to allow for direct comparison of the influence of the modifications between the two specimen designs.

Simulating the movement of a building level during an earthquake presents challenges for accurate experimental testing. Figure 5 shows the load path at the top of the experimental test specimen. The blue beam at the top is attached to the reaction frame with two actuators that simulate the horizontal movement of the floor beam. In the cladding design of the prototype building, only the spandrel panels attach directly to the structural system. To simulate the spandrel panels, the green spandrel boxes in Figure 5 were fabricated. These boxes are made of steel frame and filled with concrete. A coil nut embed in the green box supports the coil rod used in the slotted connection. To monitor the force in an individual slotted connection, each panel connection is attached to a single spandrel box and each spandrel box is connected to the steel support frame using a load cell (blue cylinder in Figure 5).

Figure 5. Attachment of Top of Panel to Support Frame (blue beam represents floor beam, the blue bracket and the green box simulate the spandrel panel above the column cover panel)



The connections of precast concrete cladding systems tend to control the overall behavior of the system. This assumption has been confirmed with the nonlinear modeling of both the specimen and the prototype building. The connections for this test project were designed by an engineer for a local precast cladding manufacturer and were fabricated by a shop familiar with connection fabrication for commercial construction. The tops of the column cover panels use horizontal slotted connections to allow for lateral deflection of the building stories. Figure 6 shows one of the slotted connections (CD-6) prior to testing. The base connections of the panels are designed to have vertical plates welded to a steel plate embedded in the panel. Figure 7 shows one of the welded connections (CD-1) prior to testing. Figure 7 simulates the connection of a column cover to the foundation. In the prototype building design, the column cover is relatively rigidly connected to the foundation since lateral movement of the structure is expected to occur at the top of the column cover. In an actual building, the vertical plate is shop welded to a horizontal plate attached to the foundation concrete and field welded to the column cover embed. To simulate the fixity of the connection while allowing for measurement of applied forces, the test specimen uses a thicker base plate which is bolted to the 5-directional load cell.

Figure 6. Slotted Connection at Top of Column Cover Panels (in-plane lateral loading causes upper bolt to slide horizontally in the slotted steel plate)

Figure 7. Welded Plate Connection at Base of Column Cover (welded vertical plate represents connection of cladding panel to foundation, for testing, the vertical plate is welded to a flat horizontal plate that is bolted to the load cell to measure forces and bending moments)

Simultaneously with the slotted connection traveling to the end of the slot, the vertical seismic joint between the panels is expected to close and panel-to-panel contact will occur. Figure 8 shows the seismic joint for Specimen 1 prior to testing.

Figure 8. Seismic Joint at Corner Assembly (vertical seismic joint between panels will close when the return panel moves in the U1 direction)

The primary work completed in the past year has been the finalization of the test matrix, detailing of individual components of the test specimen and supporting frame, contracting and construction of the test specimen, supporting frame, and experimental components, and detailed design of the instrumentation plan, with particular focus on the displacement channels. The test matrix has gone through several revisions over the course of the project as analytical study and experimental limitations have clarified the usefulness of various parameters of the test specimen. The original concept was to build two two-story test specimens with complete cladding coverage including spandrel panels and column covers. Two primary advances in understanding caused for the revision of this concept: 1) spandrel panels are expected to have limited deformation during lateral movement because they tend to follow the lateral displacement of the supporting floor, and 2) lateral testing of two-story specimens provide limitations because the instability of one floor will result in premature conclusion of the test of the other floor. For these two advances, the test matrix went through three main configurations before converging on the matrix listed in Table 2.

DETAILING OF INDIVIDUAL COMPONENTS

Significant work in the past year was applied to moving global specimen designs to construction-level detailed shop drawings. Prior years work had resulted in global identification of the panel geometry, panel connection configurations, and the punch-out window layout. Additional prior work had developed reinforcement requirements for the concrete. However, to allow for construction by third-party suppliers, detailed drawings of individual panels were made showing precise geometric information and steel reinforcement layouts. Similarly, detailed drawings of the supporting steel frame were made at an individual-component scale. The steel frame needed to be adjustable to allow for column components to be adjusted for the two different heights of specimens. In addition, the elimination of the spandrel cladding panel resulted in the need to make experimental-test components that would simulate the critical geometric and material features of the spandrel panel while allowing for accurate measurement of the forces in the load path from the panel to the supporting frame. In addition, final designation of a laboratory test space resulted in minor adjustments to the steel frame to accommodate existing frame reaction points.

CONTRACTING AND CONSTRUCTION OF INDIVIDUAL COMPONENTS

The size and complexity of the project required industry-level expertise in the construction of many of the individual components. Of primary concern was the recreation of accurate precast concrete panel construction that would represent common American commercial real estate development. The size and weight of the panels are also conducive to industry construction to allow for large-scale batch mixing of concrete, repetitive use of forms, and consistent material testing. The steel connections that connect the concrete panels together are expected to provide the inelastic deformation during the testing. To ensure that the steel used in the connections of different specimens was consistent, the connection plates were fabricated by students in the university steel shop. In addition to maintaining consistency of material, the work also provided hands-on experience for eight engineering students, with the expectation that such hands-on fabrication work will strengthen their future engineering decision-making abilities far beyond the experiences obtained in traditional classroom education. Significant steel-fabrication work was required to develop the articulated steel support frame. By careful consideration of the necessary kinematics, the frame was designed to use rigid steel columns and beams with existing steel clevis connections. The large amount of welding and the large cross-sections involved required an industry fabricator to be subcontracted for this work. In addition, several small component pieces are required to complete the testing arrangement, including out-of-plane bracing, connections to the load cells, and shim plates. For these items, engineering student fabrication work was utilized where the level of sophistication and the complexity of the fabrication work allowed. Contracting of the external work was completed according to federal guidelines. Multiple-bid solicitations were used and the low-cost bidder was selected.

INSTRUMENTATION PLAN

To capture useful data for complex structural testing, a variety of instruments are required, including, load cells, displacement transducers, strain gauges, still camera, video camera, and visual observation. Fourteen load cells are to be used on the specimen to measure critical forces in the load path. One experimental concern for the testing of façade is the mixture of large-size specimens with relatively small-level forces. Two actuators will apply lateral load to the specimen and each will hold a uniaxial load cell. The reactions at the base of the panels are expected to contain varying complexity of forces. The return panel (Panel C2) is the most complex as the applied loads from the loading beam and the potential pounding at the vertical seismic joint must be resisted at the base by two flat-plate connections. At the top and base of this panel, five-direction load cells will be used to record axial force, two horizontal shears, and the two corresponding bending moments. Figure 9 shows a typical five-direction load cell installed below the base connection. The flat panels (Panel C1 and C5) will have less complex reactions and these panels will have two-directional load cells at the base (measuring vertical force and in-plane horizontal shear) and one-directional load cells at the top (measuring in-plane horizontal shear).

Figure 9. Five-Directional Load Cell at Base of Panel

Displacement transducers will be used to record two categories of data: the movement of the precast panels in 3D space, and the relative movement at each steel connection. For the movement of the panels in 3D space, threaded rods were embedded in each panel approximately 10 inches from each corner of the panel. The rods will support three displacement transducers, to record either absolute displacement measured from a support off of the test specimen, or relative displacement measured between two adjoining rods. These readings will allow detection of how panels rotate, twist and/or tilt when two adjoining floors of a building displace laterally. Figures 10 and 11 show the displacement transducers being installed to record this 3D spatial movement. Relative movement at the connections will be measured using displacement transducers also. For each connection, the relative displacement will be recorded in three directions related to the local coordinate system (U1 is in-plane horizontal displacement, U2 is vertical displacement, and U3 is out-of-plane horizontal displacement; in-plane is defined by the exterior surface of the panel, for the return panel this is the longer horizontal leg of the angle). In critical directions, the relative displacement will be measured between the concrete panel and the connecting plate and between the connecting plate and the supporting reaction. For all other directions, the relative displacement will be measured between the concrete panel and the supporting reaction. The purpose of this connection displacement data is to be able to plot force-displacement relationships for use in analytical models of cladding systems.

Figure 10. Installation of Relative Movement Transducers at Connection CD-1.

Figure 11. Installation of Wire Transducers for Measurement of Global Movement of Panel

Small amounts of additional instrumentation will be used for specific needs. Strain gauges will be mounted on the bracing frame to monitor potential out-of-plane movement of the support frame. Laser scanning will be conducted of a slotted connection to collect digital displacement data at critical points of the testing. Digital still and video will be collected to observe progress during the testing but also to document the various levels of damage observed at varying levels of drift. Cameras will be positioned to observe the overall specimen, the movement at the slotted connection at the top of the panels, the expected weld fracture at the base of the panels, the expected inelastic bending of the plate at the top of the return panel, and the possible weld and/or plate damage at the base of the return panel.

DAMAGE DOCUMENTATION

One of the prime goals of the research is clarification of the damage to building façade due to lateral drift of adjoining stories. To reach this goal, identification of potential damage events and the monitoring of the associated building interstory drift correlated to each damage event is crucial. For the precast cladding and steel connections, 33 different damage events have been initially defined and will be monitored. These vary from minor damage, such as bolt slip, that will occur early in the testing to potential collapse, such as panel instability. While not all damage events are likely to occur in the testing, each event that does occur will have the associated drift recorded. At the end of the test program, this data will be presented in a fragility curve format, where the probability of occurrence is a function of the interstory drift. Since this damage is likely to be better correlated with either interstory displacement and/or column panel drift, the fragility curves will also be determined with these two domain axes. This fragility data is expected to be exported to performance based design protocols to allow for better incorporation of façade damage into life-time cost studies.

CONCLUSIONS

Preliminary conclusions have been determined based upon the research completed to date. Component level experimental testing has been completed and reported in the published literature in the past but system level evaluation has been minimal. Seismic behavior is expected to be governed by the steel connections that support panels, in particular the slotted connections at the tops of column covers. The corner seismic joint of a cladding system is likely to result in panel-to-panel contact at large interstory drifts due to the incompatible movement of adjoining panels.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 0619157. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. Mark Hildebrand, PE, President and Chief Engineer, and Bob Steed, Project Manager of Willis Construction of San Juan Bautista, CA provided technical assistance on the construction of the concrete panels and steel details for the experiments. Their assistance is greatly appreciated.
The authors also appreciate the assistance of the following research students: doctoral students Jeff Hunt and Clement Barthes, masters students Phoung Le, Hoang Nguyen, Kai Cheung, Pooja Nagar, Amarjeet Saini, Lokesh Patel, Siddaiah Yarra and Gjyotheeswara Reddy, and undergraduate students Cecilia Luu, Juan Ramirez, Sal Rodriquez, and Tatsuo Kishimoto. Lab technicians Patrick Joice and Robert Cerney and lab managers Don Clyde and Shakzhod Takhirov have also made significant contribution to the project.

REFERENCES

1. Arnold, Chris (2009). Seismic Safety of the Building Envelope. Building Systems Development Inc. http://www.wbdg.org/resources/env_seismicsafety.php?r=envelope June 23, 2011.
2. Ayres, Marx J., Brown, F.R. and Sun, T.Y. (1973), "Nonstructural Damage to Buildings." *The Great Alaska Earthquake of 1964. Engineering.* Washington, D.C.: National Academy of Sciences, pp. 346.
3. Ayres, Marx J. and Sun, T.Y. (1971), "Nonstructural Damage." *The San Fernando Earthquake of February 9, 1971. Vol. 1B.* Washington, D.C.: National Oceanic and Atmospheric Administration, pp. 735.
4. Bachman, R. E., Hamburger, R.O., Comartin, C. D., Rojahn, C., and Whittaker, A. S., 2003, "ATC-58 Framework for Performance-Based Design of Nonstructural Components", *Proceedings of ATC-29-2 Seminar on Seismic Design, Performance, and Retrofit of Nonstructural Components in Critical Facilities, ATC-29-2 Report,* Applied Technology Council, Redwood City, California, pp. 49-61.
5. Hegel, Richard L. (1989). "Connections of cladding to multi-story structures." *Proceedings: Architectural Precast Concrete Cladding – It's Contribution to Lateral Resistance of Buildings.* PCI, November 8-9, Chicago, pp. 192-201.
6. McMullin, K. M., Choi, C., Chan, K. and Wong, Y. (2004). "Seismic performance states of precast concrete cladding connections." Oral Presentation *13th World Conference on Earthquake Engineering*. Vancouver, B.C. Aug.
7. McMullin, K. M., Wong, Y., and Kwong, A. (2003). "Damage thresholds and performance levels of precast cladding systems." *Proceedings of Seminar on Seismic Design, Repair and Retrofit of Nonstructural Components on Critical Facilities*, Applied Technology Council Project 29-2, Los Angeles, April.
8. Merrick, D., McMullin, K. M., Hildebrand, M. and Kwong, A. (2003). "In-Situ Vibration Characteristics of Precast Cladding Panels." *2003 Structures Congress and Exposition*. Seattle, WA.
9. Rihal, Satwant S. (1989). "Earthquake resistance and behavior of architectural precast cladding and connections." *Proceedings: Architectural Precast Concrete Cladding – It's Contribution to Lateral Resistance of Buildings.* PCI, November 8-9, Chicago, pp. 110-140.
10. Wang, M. L. (1986). "Nonstructural Element Test Phase – U.S.-Japan Cooperative Research Project on a Full Scale Steel Test Frame." Center for Environmental Design Research, University of California, Berkeley.