FULL-SCALE DYNAMIC TESTING OF PRECAST CONCRETE CLADDING PANELS

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ABSTRACT

The seismic performance of precast concrete cladding panels will be one aspect of the Full-Scale Structural and Nonstructural Building System Performance during Earthquakes research project at UC San Diego. The full-scale building frame has been tested in April and May 2012 using the NEES @ UC San Diego Large High Performance Outdoor Shake Table and provide a support structure for the cladding system. The two-bay by one-bay, five-story building has the top two stories of the building fully enclosed with precast concrete cladding. The cladding system was designed and built by precast cladding fabricators in California. A combination of steel cladding connections were used to connect the cladding to the concrete frame structure. These included bearing, sliding and flexing rod connections. The building will be tested under dynamic loading using moderate and large magnitude seismic records. The expected test data will include measurements of the inter story drift, the floor acceleration, the panel accelerations and photographic documentation of the connection behavior and the panel movement. The dynamic testing is being coordinated with static tests of connections to clarify the full range of design parameters of connections to allow for the development of engineering design procedures for practicing engineers.

Keywords: Precast Concrete Cladding, Building Façade, Nonstructural Building Components, Experimental Testing

BACKGROUND

PRECAST CLADDING SYSTEMS

Precast concrete cladding with punch out 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. 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 (1989) 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 (1989, p 193) 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.

Industry groups report general design features of cladding systems (Council, 1992). They discuss the differences between using rocking and swaying to allow the cladding to respond to lateral movement of the building floors. They also provide discussion about joints and sealants as well as common testing procedures for preconstruction and quality control.

PAST EXPERIMENTAL TESTING OF CLADDING PANELS

While limited published data is available from past testing of cladding systems, some notable testing has been found. Rihal (1989, p. 124) 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.

Wang (1986) 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.

CURRENT RESEARCH PROGRAM

Building upon these past studies, an experimental study was recently completed to qualitatively and quantitatively measure the damage to precast cladding systems under seismic loading. The cladding tests are part of the NEESR-SG: Full-Scale Strcutural and Nonstructural Building System Performance research study led by Dr. Tara Hutchinson at the University of California at San Diego as shown in Figure 1. The experiment uses full-story, single-bay or half-bay precast concrete panels with punch-out windows installed in individual panels. In addition to the full-scale testing, connection components tests are being conducted to quantify the force-deflection relationships and energy dissipative characteristics of the steel connections.

Figure 1. Five-Story Concrete Frame Test Specimen.

The primary objective of the project is to determine the viability of existing precast concrete cladding systems to accommodate moderate to major seismic excitation. The cladding system was designed to represent design for seismic regions of the United States. To expand the current knowledge base of performance, innovative concepts in the detailing of connections and the size of the seismic joint between panels were included in the experimental specimens. Lessons learned from the testing will be used to develop design protocols for industry practice with the goal of rapidly disseminating the findings into current industry design.

The cladding research is one component of the overall research program at San Diego, a full-scale representation of modern structural and nonstructural building components tested for the effects of base isolation of the structure. This testing includes façade systems, commercial energy and HVAC systems, hospital and office contents and equipment, and elevator and stair egress systems. The shake table testing includes both base isolated and fixed base structural tests and includes a post-event fire-spread test. The research of the overall project has been discussed in both popular media (Hutchinson, 2012; Full-Scale, 2012) and traditional engineering research dissemination means (Xiang, 2012).

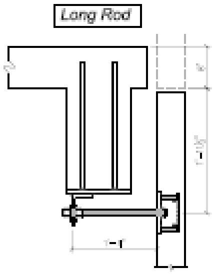
A key benefit of the project is the active involvement of several personnel from the precast concrete industry and the building design industry in the design, execution and evaluation of the testing. The cladding component oversight was provided through a Precast Concrete Advisory Board composed of six members of the Precast Concrete Institute. A sub-committee of this board comprising three PCI fabricators from California were actively involved in every aspect of the research, including the design and detailing of the concrete panels and connections, the fabrication and installation of the physical specimens, the design of the instrumentation for the testing, and the on-site evaluation of the performance of the façade system. It is expected that this group will also be heavily involved in the analysis and review of the experimental data and the preparation and beta-testing of the design protocol.

SUMMARY OF TEST PROGRAMS

Both the dynamic shake table tests and the connection component tests were closely linked to allow more complete understanding of the performance of the system. Figure 1 shows the overall form and size of the main test specimen at the University of California at San Diego. The overall structure is a concrete moment resisting frame with two bays in the direction of shaking. For the building façade, all panels used 5000 psi concrete and Grade 60 reinforcing steel. All steel connection components used Grade 50 steel plate and or angle. All welding was E70XX or equivalent.

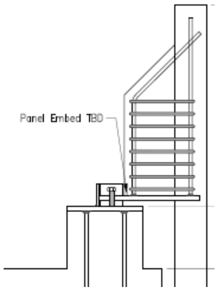
The shake-table testing used a project-specific concrete frame that was completely enclosed by concrete facade on the top two floors and was shaken in a single longitudinal direction. Figure 2 shows some of the individual details connecting the concrete panels to the structural frame. The connection component tests used static loading applied with a single actuator to simulate the relative movement between the cladding panel and the structural support. Table 1 lists the testing protocol for the component tests.

Detail 1 – Flexing Rod



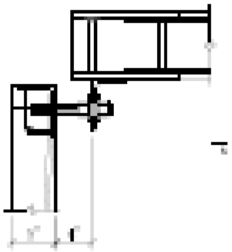
This connection allows relative movement between the panel and structural floor in the U3 direction by the flexibility of the horizontal rod.

Detail 2 – Bearing Connection



This connection resists gravity load by the leveling bolt shown on top of the upturned structural concrete beam. The connections can be modified to resist force in the U1 and U3 directions if desired.

Detail 3 – Slotted Connection



This connection at the top of a panel allows relative movement between the panel and structural floor in the U3 direction because the horizontal rod passes through a horizontal slot in the angle mounted below the floor slab.

Figure 2. Cladding Details on Façade Panels

Table 1: Loading Protocol – Connection Component Tests

No.	**Cyclic Loading Protocol**	**Remarks**
1	ATC-58 – Increasing amplitude with three cycles at each amplitude	Displacement amplitudes increasing by 0.25 inches up to 2.0 inch, by 0.5 inch up to 3.0 inch, and by 1.0 inch until fracture occurs.
2	Constant amplitude cycles	Displacement amplitudes of ± 5.0 inch until fracture occurs

Two component connection details have been tested to date, both of which use coil rod as a push-pull connection configuration. The flexing rod detail (Figure 2, Detail 1) is expected to allow ductile lateral movement in the event that interstory displacements are large enough to cause contact between adjoining panels. The slotted rod connection (Figure 2, Detail 3) allows interstory deflection via a horizontal slot in the angle. Data collected from the projects will be prepared for use in Performance Based Earthquake Engineering design procedures (Bachman, et al., 2003).

WORK COMPLETED

At the time of writing this report, the base-isolation testing of the shake-table tests and the initial component testing has been completed. The shake-table testing is scheduled to be completed by the end of May 2012. Component testing will continue for several months. Data reduction of the testing has started, but has been limited in scope due to the main research focus on completion of the test programs. Analytical modeling of the façade system has been started and has provided detailed information about the expected performance of the cladding.

RESULTS FROM TESTING

The primary findings to date have been that well designed and fabricated precast panel systems perform very well during seismic loading. Initial evaluation of the shake table testing has not reported damage to the panels or connections at the time of writing. Detailed evaluation of the shake table testing will be conducted to confirm this initial assessment. In the component testing, the only damage observed so far in the testing has been as a result of lateral displacements far above the design displacements. Damage was observed during the component tests when displacements above the design displacement were applied.

One desired output from the experimental testing is the force deformation relationship for the connections. Instrumentation on the shake table testing will record forces and accelerations and the accelerations will be converted to equivalent displacements. At the component tests, the instrumentation records forces and displacements directly and results in graphs such as Figures 4, 6 and 7.

Damage to building façade systems are traditionally related to displacement and drift ratio. Drift ratios for cladding panels can be defined in three ways. Inter-story drift ratio is calculated as the lateral deflection divided by the distance between the top of the two floor slabs. Connection drift ratio is defined as the lateral deflection divided by the vertical distance between the horizontal centerlines of the top and bottom connections on a panel. Panel drift ratio is defined as the lateral deflection divided by the physical height of the panel.

Each of these drift ratios have unique uses and features. Inter-story drift ratio is the value most commonly used by building design engineers to quantify suitability of the flexibility of a structure and is the information most commonly designated from the building design team to the precast façade fabricator. However, many design features of the façade system affect the relationship between this global measure of inter-story displacement and the actual rotation of the concrete panel, most critically being the size of any window openings in the building design. The relationship between panel drift ratio and inter-story drift ratio can be determined once the size of the panels has been determined. This relationship can vary from having the two values equal to each other to having the panel ratio nearly double the inter-story drift ratio. Connection drift ratio can be determined once the actual connection design has been determined. The value of the connection drift ratio is usually close to the panel drift ratio since connections are usually located near the top and bottom of the panel.

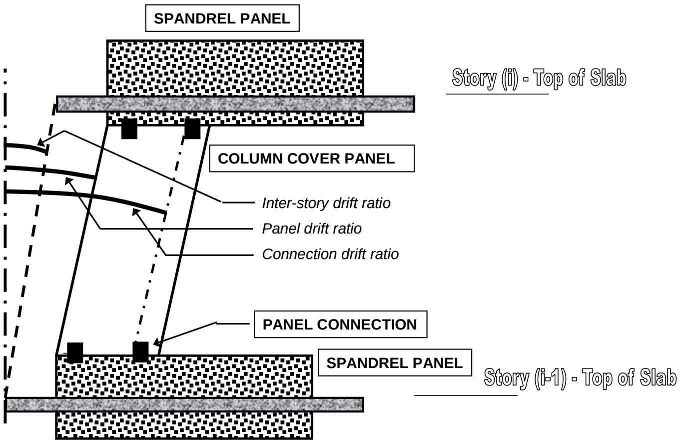


Figure 3. Definition of Drift Ratio

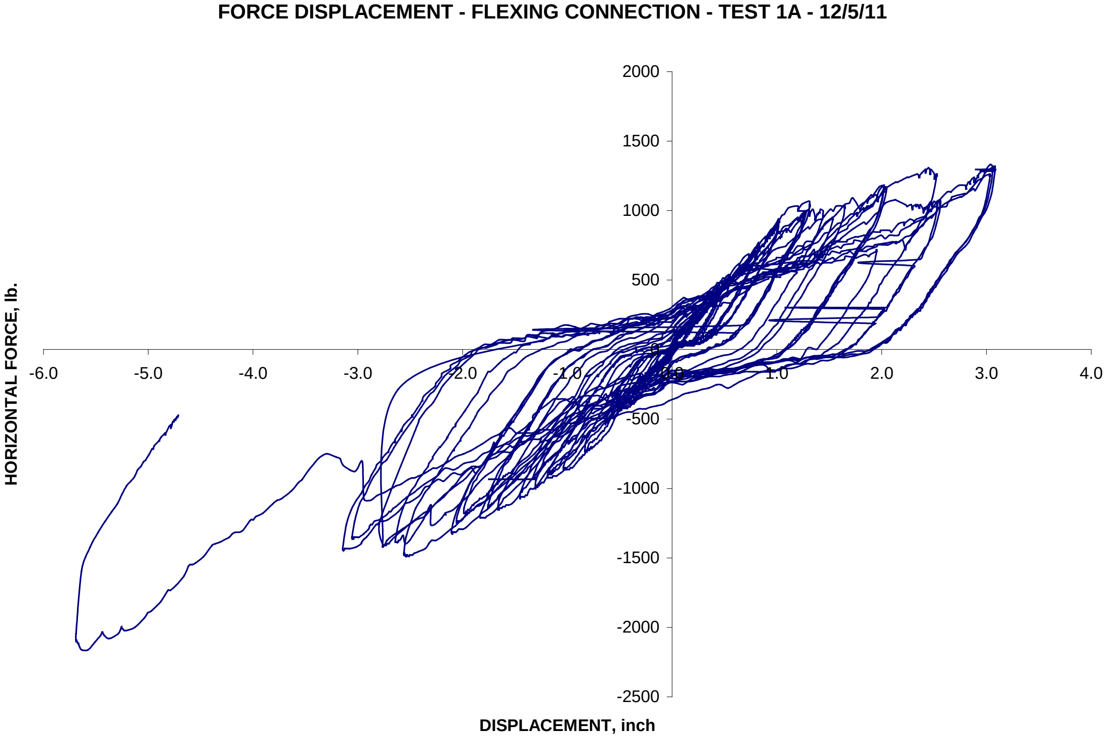


Figure 4. Force-Deformation of Coil Rod Component Test

Figure 5. Component Testing of Flexing Coil Rod Connections

WORK FORTHCOMING

In the following months, work will focus primarily on three areas: data reduction, computer modeling, and research dissemination. Data reduction is expected to be a significant task as data has been collected in both quantitative and qualitative formats. Displacement data is available for both global panel movement and individual connection deformation. Force data is available for both global and individual connections. Photographic documentation of the connection performance will be used to more closely define damage events and align the event with a drift ratio. Fragility curves will be prepared for both global performance levels as well as individual types of damage. Fragility curves will use individual panels as a population. Care must be exhibited in applying these fragility curves to actual projects as the test programs have a high percentage of panels concentrated at the corners of buildings where damage is expected to occur.

Nonlinear modeling is critical to allow for practicing engineers to correlate experimental testing to the wide variety of cladding panel designs in use today. From the research data collected in there and individual component tests, nonlinear link properties for the three

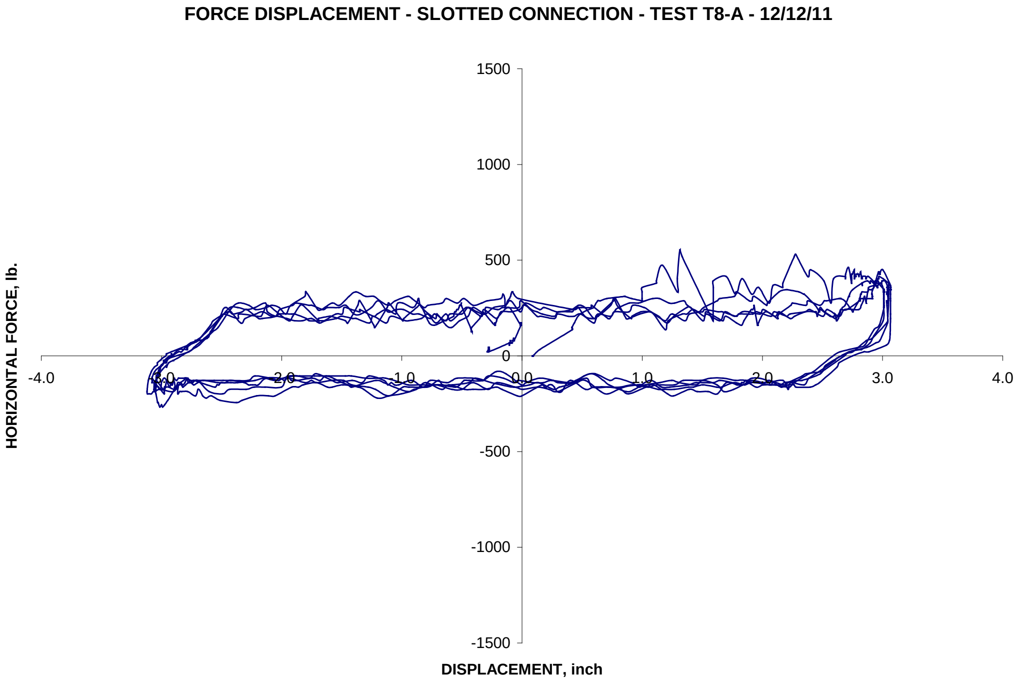


Figure 6. Load-Displacement Graph for ¾x 8 inch Coil Rod with Loose Coil Nut Connection

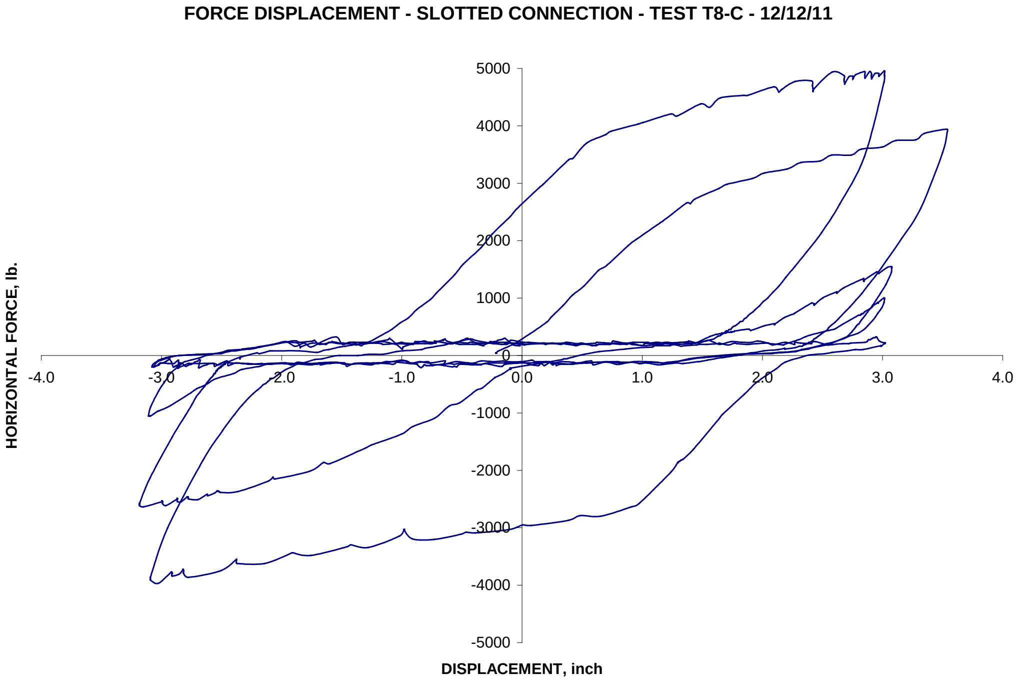


Figure 7. Load-Displacement Graph for ¾x 8 inch Coil Rod with Coil Nut at Finger-Tight Connection

local coordinates are being developed. Using modern software, such as SAP 2000, allows for assembly of these nonlinear links into full façade models. One challenge at the present time is to accurately model damage due to the cracking and crushing of concrete panels.

As experimental data is processed and combined with analytical studies, dissemination of research findings is continual. Project webpages and online repositories of data allow for online access and rapid dispersal. Webinars are in development as well as design procedure documents for fabricator engineering staff.

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