Experimental Testing of Precast Concrete Cladding
for Building Façade Systems

Kurt M. McMullin, Eugenia Tai and Tu-An Ma
San Jose State University

Abstract: Since 1998, San Jose State University has conducted research into the seismic behavior of building façade systems, particularly the precast concrete cladding systems. This research has combined full-scale experimental studies and component experimental studies of connections. In addition, the research team has been active contributors to two full-scale experimental tests of complete building systems including precast concrete façade panels. The testing has been combined with the development of structural analysis models to simulate seismic behavior. The primary findings to date have been that modern precast concrete cladding façade systems perform well when loaded to displacement levels less than the original design displacement. New understanding of cladding performance will allow precast fabricators to provide higher performing systems in the future.

Background. Building façade has several critical roles. It is the environmental barrier between the interior and exterior functions of a building. The façade is often one of the primary architectural design elements of the structure resulting in a critical aesthetic role. The façade can have various structural roles, from providing the main structural support for gravity loads and lateral forces to having a nonstructural role of providing gravity support only for itself and distributing wind forces from the skin of the building to the main structure.

Over time, the interaction between the main structural system of common building designs and the façade has changed. Traditional construction had the exterior surface of the building as the primary if not sole vertical structural elements. With the advent of curtain wall construction in the 1800’s, façade became a nonstructural element that was supported by the main structural system of the building. This separation of the role of façade from the main structure has continued, particularly as the size and shape of the vertical load carrying elements have been reduced.

Some researchers propose the return of a larger structural role for façade system, including the use of curtain wall type façade systems to provide the full lateral resistance of the building. This paper reports the study of more traditional design, where the façade is considered not to support any portion of the main structure, but to work as a nonstructural element providing load to the main structure while successfully performing other roles. This traditional design remains popular for multiple reasons, one of which is the clarity of each designer’s role in the process. The architect specifies the elevation features, both shape, color, texture and window design, the structural engineer specifies the size and shape of structural elements and the precast façade engineer specifies the panel layout, panel structure, and panel materials.

Precast Cladding Systems: 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. 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.

The photograph shows the installation of panels on the King Library at San Jose State University in 2002. Panels are typically held in place at each story level with the weight of the panel supported by the lower level beams, similar to curtain wall systems.

In another style of panel layout, spandrel panels cover the floor beams while column cover panels define and highlight the vertical columns of the structural frame.

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 how the arrangement of connections for precast panels has remained relatively constant. Hegel explains that each structure-to-panel 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.

Precast concrete façade systems can be assembled in many ways. A common method in California is the use of panels covering the spandrel beams and column covers used over the columns, as highlighted in red.

At the corner of the building, a return panel is usually cast that covers portions of two of the exterior elevations.
To maintain a consistent column panel width for the entire building elevation, the return panel often has an adjoining half-width column cover that is roughly half the lineal length of the main column cover.

To complete the building enclosure, window units are often installed between column cover panels. The window units are usually supported by the façade spandrel panel below.

The joints between panels are critical to the success of the façade. These joints are typically 0.75 inches wide around all edges of the panels. The joints allow for tolerance variation in the precast assemblies. The joints also allow thermal expansion and contraction of the façade without damage. In addition, the façade must allow for movement of the main structure, either lateral movement due to wind or earthquake, or vertical movement due to foundation settlement. However the joints do cause challenges. They must be water-tight and resist air movement. The typical finish for the joint is a sealant.

Precast concrete cladding facades are primarily assemblies of large rigid concrete blocks, rigid glass windows, and relatively flexible steel connections. One aspect of the evolution of structural engineering is the continuous movement toward more flexible building frames, particularly to counteract the potential damage from major earthquakes.
Bassler et al (1992) reports general design features of cladding systems and the means to allow for structural movement. They discuss the differences between using rocking assemblies or swaying assemblies 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.

Between the return panels and the adjoining column covers, a seismic joint is installed to allow for the two exterior elevations of the building to move independently during an earthquake.

**VERTICAL SEISMIC JOINT**

A final installation might look like the adjoining picture, where the vertical seismic joint is visible between the return panel on the left and the half-width column cover on the right.
During an earthquake in the direction of the building elevation containing the seismic joint, the in-plane panels move with the supporting structural floor, the level below. However, the out-of-plane panels tilt into the building.

Without proper detailing and knowledge of the necessary joint width, pounding between the panels can occur during major earthquakes. Current building code requirements typically require a seismic joint of at least two inches to allow for suitable performance during a major earthquake.

**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) conducted a full-scale in-plane loading experiment on a full-story solid precast concrete panel. 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 States 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.

Since 1998, a research initiative at San Jose State has focused on experimental testing to allow for input of structural analysis software. The primary goal of the research is the development of input data to be used for Performance Based Earthquake Engineering design of commercial buildings. This concept uses life-cycle cost analysis to minimize total costs of a building. The design criteria is to match the potential higher initial investment for higher quality, more robust new construction versus the lower expected costs for repairs after future earthquakes. The challenge is that to implement these types of design theories, requires a large investment of research to define the expected damage and potential repair costs that various building components may experience.
Component testing of steel connections used for the support of concrete panels was the focus of the first several years of research at San Jose State as stated before. Steel connections usually have specific roles in façade systems, push-pull connections to resist forces in and out of the building, bearing connections that support the weight of the panel, and lateral seismic connections that resist horizontal seismic forces.

The connection shown has all three force resisting components. The leveling bolt in the assembly supports the gravity load. The coil rod and tube provide a push-pull connection to resist out-of-plane loading. The 25 mm plate resists in-plane shear.

**Current Research Program:** Building upon these past studies, three connected projects have recently been completed to qualitatively and quantitatively measure the damage to precast cladding systems under seismic loading. All three testing program receive primary funding from the National Science Foundation. Additional funding has been received from the Charles Pankow Foundation, San Jose State University and multiple industry partners. There are two main objectives for the testing: determining the damage that will occur as a function of lateral drift and/or acceleration and determining the force-deformation relationships for the connections between the adjoining concrete panels and between the panels and the steel frame.

As the timeline of Table 1 indicates, the current research is the evaluation of three large scale experimental studies. The Pathways Project at UC Berkeley has completed static loading of six full-scale experiments under simulated displacement-controlled seismic loading. The advantage of static testing is that systems can be loaded to near-collapse levels of displacement to evaluate how the system will perform under extreme overloading. The E–Defense testing and the UC San Diego testing were both single full-scale, complete-structure specimens which were loaded using shake table facilities that reproduce the actual recorded motion of the ground during past earthquakes. The advantage of shake table testing is that the true acceleration and dynamic environment can be developed in three-dimensional space. Through these coordinated test programs, a wealth of data has been collected, including quantitative data about displacements, accelerations and forces as well as qualitative data in video, photographic and experiential formats.

All three test programs had similar features. The following photos show the overall form and size of each of the test layouts. Many of the features of the test program were defined by other aspects of the overall test program. All cladding systems were based upon current US precast cladding design practice and were built and tested under laboratory conditions. Critical aspects of all the cladding systems were built by industry personnel to ensure the quality and condition matched those seen in actual commercial building construction. 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.

Test Specimen 4 of Pathways Project at the nees@berkeley lab facility. Test specimen is three precast concrete panels representing the corner bay of the typical floor of a building. In the front of the picture is the return column cover panel. Sitting next to it is a flat half-width column cover panel. Toward the back of the picture on the left is a flat full-width column cover panel.

Precast concrete specimens for the TIPS Project at the E~Defense lab facility. On the left is Panel P-1, a return column cover panel. On the right is Panel P-2, a flat, half-width column cover panel. Both panels were designed in the US and cast in Japan. The steel connections were designed and fabricated in the US, according to common US building design practice.

Precast concrete specimens for the NEES Structural/Nonstructural test specimen. Full bay panels are installed on the top two floors of the building, on all four elevations. The photo shows the transverse elevation of the building, the single bay direction. All panels were designed and fabricated by a California precast fabrication company.

However, due to the constraints defined by other aspects of each of test programs, each of the test specimens also had unique characteristics, particularly in the detailing of the steel connections that connect the panels to the structural frame. The Pathways project had a primary focus on cladding and hence most of the design characteristics of the experiment were
determined by the cladding. Using the SAC 9-story LA Building as a preliminary schematic, a cladding system using spandrel panels and supported column covers were tested. The test program was six individual tests with each test containing three panels. The E~Defense (TIPS) project used an existing steel frame test structure and included two panels on a frame that would be shaken in all three directions. The UC San Diego (Structural/Non-structural) project 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.

Results from Testing: The primary findings to date have been that well designed and fabricated precast panel systems perform very well during seismic loading. The only significant damage observed in the testing has been as a result of lateral displacements far above the design displacements. Various panels have been loaded in both static and dynamic protocols and the damage observed at displacements below the design displacement have been minimal. All the cladding systems represent modern design features by American fabricators in seismic zones.

Damage was observed during the static loading tests when displacements above the design displacement were applied. The photos below show representative photographs of some common damage patterns in the testing completed. The most common post-design-displacement damage has been the cracking of the concrete panels due to flexure, particularly in the flat half-width panel. This damage has coincided with cracking and loosening of the steel embeds in the interior face of the panels, particularly at the base of the panels. The slotted connection at the top of the panel were made with the nut on the slotted rod being placed finger tight, no wrench was used to tighten or install this nut. The threads of the bolt were then sealed to prevent loosening of the nut. With this finger-tight nut, the slotted connections performed as intended, with minimal resistance to movement. This was observed in both the horizontal slotted connections of the Pathways project and the vertically slotted connections of the E~Defense project.

![Photograph of common damage patterns](image)

Cracking of the exterior face of the panel occurred once the design displacement was exceeded. In the adjoining photo, flexural cracking of the panel due to the horizontal force applied at the top results in horizontal cracks starting at each vertical edge of the panel. As the crack progresses across the width of the panel, it begins to curve downward due to the presence of large shear stresses in the concrete.
On the interior face of the panel, severe damage occurs around the steel plates that support the weight of the panel. This connection at the base of a panel is a large steel plate cast into the concrete that has been field-welded to the smaller plate that would connect to the structural frame. Seismic loading has resulted in severe cracking of the concrete, potentially causing the embed to break loose of the panel.

The slotted connections at the top of the panels performed well. The horizontal slot is intended to allow the building floor above to move horizontally while the panel below remains essentially in place. At displacements far above the design displacement, the coil rod has traveled the full length of the slot, resulting in the steel plate beginning to rotate and applying horizontal shear to the panel.

Rotation of the slotted connection plate can lead to severe damage such as fracture of one of the coil rods. Fracture of the coil rods results in a potential collapse of the panel, resulting in high risk of potential life threatening dangers.
**Computer Simulation:** One major outcome from the experimental testing is better understanding of the behavior of panel systems and quantitative data to compare to computer simulation.

For successful computer simulation, the façade design from a structure is isolated from the entire assembly. With proper relationships defining the force-deflection behavior of each element, a computer simulation can be developed as shown below. This simulation allows for prediction of the actual tested specimen as well as variation of different parameters to allow for investigation into the sensitivity of each item.

The resulting model allows for both linear and nonlinear response to both static pushover types of loading as well as the cyclic loading expected during an earthquake.
Individual connections can be modeled in the simulation once the force-deflection behavior is defined. The experimental output of the adjoining graph shows how slotted connections respond to cyclic experimental loading. The connection slides very smoothly over the length of the slot and then resists significant force once the slot length is exceeded.

Supplemental Research Initiatives. Beyond the main focus on precast concrete cladding, the research work has also provided abilities to study related topics.

Window Performance. Window glass was a façade material also tested during the project. Two of the specimens at UC Berkeley were built with complete façade systems including both the precast concrete cladding and inset window units.

Experiment 3 of the Pathways Project contained a full window inset between the two flat column cover panels. During testing, the loading moved the blue beam horizontally, in the plane of the window glazing.
As the lateral movement increased, the main damage to the window units were fracture of the F-Clip used to connect the window frame to the structure (yellow plate above in the adjoining photo). Surprisingly, none of the window panes in any experiment every cracked, even when story displacements of four inches were applied to the window unit.

What were seen during the testing were movement of the glazing in the rubber gasket and relative movement between the various framing members. At the end of the experiment, there were multiple open gap between the units that would allow air movement into a building.

One window assembly was retrieved and taken to San Jose State, where it was mounted in a special frame and pushed laterally until it was damaged. During this test, the frame became very heavily bent and damaged.
After several inches of lateral displacement, the glass panes finally shattered when the tempered glass failed. The double-pane windows often had one pane fail at a displacement lower than the other pane. The conclusion of the window testing was that modern systems are able to absorb very large distortions due to lateral loading without breakage of glass.

Instability of the entire window unit after severe loading was a concern. During the original testing, the frames often accommodated lateral building drift by fracture of the F-Clip connecting the window unit to the building. Since the static loading was in the plane of the window, the frame remained standing, due to cantilever action of the vertical aluminum mullions from the base of the unit. During an earthquake, out-of-plane acceleration after these F-Clips fracture may cause the entire assembly to fall from the building. This potential is a concern, but it was not seen during the in-plane loading tests.

**Adaptive Reuse.** A payload research task is the study of potential adaptation of damaged cladding panels for alternative use. Panels can be unusable for three common reasons, either they are mis-manufactured originally or they are damaged during extreme loading or they are removed from a structure due to renovation and changes to the main structure. For any of these reasons, the owner is presented with a significant cost of demolition and disposal. With current requirements about the disposal of concrete with embedded steel rebar, the cost of discarding these damaged panels has become significant. Recycling of concrete via crushing has become a common alternative, particularly for panels that have been miscast and are fabrication waste. However, recycling does have limits due to energy requirements and the need for matching aggregate with building design limitations.

To explore alternatives, one case study was implemented as to a potential reuse of the panels in their entirety. The case study was to take panels damaged during the experimental testing, perform moderate trimming of heavily damaged portions, and installing the panels at a local non-profit undergoing renovation work. The goal was to replace the planned slab-on-grade hardscape with a layout of panels closely spaced.
The concept for the Adaptive Reuse case study was that if panels were damaged during an earthquake or blast event, the damaged items would be ‘harvested’ by removing the panels from the building.

Minor modification to the panels would likely need to be done. Flat column covers could be used as pavers. Return panels could be used as portions of a raised stage. The design concept was to replace a new slab-on-grade hardscape surface.

Final installation would include installation of shear rods to hold the panels in place. Panels would be arranged to allow for strips of similar width column covers and then enclosed in a cast-in-place ring to hold the panels in place.

Work Forthcoming: As the research initiative continues, work will focus primarily on four areas: data reduction, computer modeling, component testing, and research dissemination. Data reduction is expected to be a significant task as data has been collected in both quantitative and qualitative formats.

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 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.

Building upon the full scale system tests, San Jose State is expanding upon the connection component tests. The current work is to expand the knowledge about the effect of lateral load on the coil rod push-pull connections. The full scale experiments have shown that correct detailing of these connections shows high potential to use their ductile capacity to use flexural yielding as a means of reducing the size of the seismic joint. Hence a series of experiments are using various levels of displacement to define the fracture limit state of the connections.

The test setup is used to apply lateral force to the coil rod by extending and retracting the actuator. By applying constant displacement cycles of loading, a predictive formula is to be developed to allow precast fabrication engineers the ability to predict suitable performance for the rods.

Fracture consistently occurs at a region of concentrated yielding at one end of the rod. While a fracture of the rod would result in potential collapse of a panel and is thus unacceptable, predicting the fracture limit state would allow the precast fabricator to make suitable decisions about the proper detailing of connections.
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.

**Conclusions.** The primary conclusion has been that current precast concrete facade systems designed for seismic motion perform very well when displaced up to the level that was expected during design. Additional conclusions are:

1. When displaced significantly beyond the design displacement, the prevalent form of damage seen was cracking of the concrete, both due to flexural of the panel and around connection embeds.
2. Modern window systems performed very well during testing. Damage was seen to the aluminum connection between the structure and the window frame. Glass panes slid in the gaskets and frames distorted to a level that left visible gaps in the assembly, but glass breakage only occurred after extremely large levels of story drift.
3. Damage of panels seems closely related to the size of the seismic joint. Modern designs usually contain very large width of joints. Concern about the successful performance of older systems with narrow joints does appear to be a concern.
4. Detailing of cladding connections to allow ductile yielding during major earthquakes has the potential to develop suitable performance of commercial buildings with narrower seismic joints.
5. Computer simulation of nonlinear behavior of cladding is suitable for flexible rod systems where yielding controls the behavior but modeling slotted connections using traditional commercially available software is limited in capability.
6. Adaptive reuse shows potential for replacing the tradition options of disposal or crushing for recycling. However the case study showed that using the panels in lieu of a slab-on-grade hardscape is challenging due to fit up and placement issues. Higher potential would be the use of panels as independent entities, where a large structural component is needed, such as a tank foundation, a set if spaced pavers, or riprap for erosion protection.

**Acknowledgements:** This material is based upon work supported by the National Science Foundation under Grant Nos. CMMI-0619157, CMMI-1113275, and CMMI-0936505. Additional funding for testing has been provided by the Charles Pankow Foundation and the Precast Concrete Institute. Industry engineering personnel contributed many hours of work to complete the design, construction, experimental program and interpretation of the experimental results. 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, other sponsors, or assisting industry groups.
Related References:


NEES TIPS/E-Defense Seismic Isolation Test Program.  


Table 1. Timeline of Façade Research at San Jose State University

<table>
<thead>
<tr>
<th>Year</th>
<th>Work Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>Initial literature research into building façade systems and their performance during seismic events.</td>
</tr>
<tr>
<td>2002</td>
<td>Development of initial nonlinear computer simulation models to evaluate performance of cladding system behavior.</td>
</tr>
<tr>
<td>2002</td>
<td>Initial proposal submitted to National Science Foundation for research funding.</td>
</tr>
<tr>
<td>2005</td>
<td>NEESR funding proposal submitted to National Science Foundation to support full-scale testing at UC Berkeley test facilities.</td>
</tr>
<tr>
<td>2006</td>
<td>NEESR funding approved and official start of Pathways Project.</td>
</tr>
<tr>
<td>2010</td>
<td>Initial collaboration with experimental programs at E~Defense and at UC San Diego</td>
</tr>
<tr>
<td>2011-12</td>
<td>Testing phase of Pathways Project at UC Berkeley.</td>
</tr>
<tr>
<td>2011</td>
<td>Experimental testing at E~Defense</td>
</tr>
<tr>
<td>2012</td>
<td>Experimental testing at UC San Diego</td>
</tr>
<tr>
<td>2012</td>
<td>Adaptive reuse test case completed.</td>
</tr>
<tr>
<td>2012</td>
<td>Window glass testing conducted at San Jose State.</td>
</tr>
<tr>
<td>2012-13</td>
<td>Component testing of precast cladding connections conducted at San Jose State.</td>
</tr>
</tbody>
</table>