DEFINING FRACTURE LIMIT STATES OF COIL RODS FOR PRECAST CONCRETE CLADDING PANELS

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ABSTRACT

Steel coil rods resisting axial tension or compression are often used as push-pull connections for precast concrete building facade panels. During earthquakes or wind storms, these rods often must flex to allow inter-story movement of the building while supporting axial load. Experimental component testing has been conducted on ¾-inch coil rods and inserts to define the fracture limit state for bending. Experimental testing with cyclic loading at constant peak displacement was used to determine the number of cycles resisted prior to the fracture of the rod. A rigid-beam-with-inelastic-links model for plastic rotation at both ends of the rods can be used to define a failure limit state relationship. This relationship between plastic hinge rotation and number of cycles of loading was seen to be consistent for rods of 12-inch and 16-inch lengths. During 2013, this testing will expand to include longer specimens as well as 1-inch diameter rods. The derived relationship and experimental test data will be used to support an industry-developed design guideline procedure for precast fabricators to detail connections for lateral movement.

Keywords: Designing and testing related to seismic, research, Precast Concrete Cladding, Building Façade, Nonstructural Building Components, Experimental Testing

Summary: Experimental testing defined the inelastic bending that will cause fracture of steel coil rods used as push-pull connections in precast concrete building facade systems. Plastic rotation of the rods is related to the number of cycles of lateral displacement that the rod resists prior to fracture.

BACKGROUND

Precast concrete cladding facade 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. 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. 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.

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. 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. McMullin et al (2013) report testing of a preliminary series of coil rod tests that are used as the preliminary information for the current paper. Previous testing of coil rods has shown that brittle fracture is a potential failure mode, particularly when the lateral displacement of the panel exceeds the design-level displacement as shown in Figure 1.

Figure 1. Fracture of Coil Rod Supporting Plate for Slotted Connection (McMullin, 2013).

Coil rods are a convenient method of developing both sliding and flexing precast concrete connections that resist out-of-plane forces on the panel while allowing in-plane movement of the panel to allow for interstory drift due to earthquakes, windstorms or thermal movement as shown in Figure 2. Coil rods are economical; they are usually manufactured from mild steel rod and have threads rolled into the rod. The challenge is that the cold-working of the rolling process can produce high-strength, low-ductility material on the exterior surface of the rod. The mixture of low-strength, high-ductility inner core with an exterior rolled thread has not been studied for engineering performance. No national standards have been located that define the chemical composition, the mechanical properties or the manufacturing process for coil rods. Due to the lack of nationally defined engineering standards, engineers have been reluctant to use coil rod except in exceedingly conservative applications.

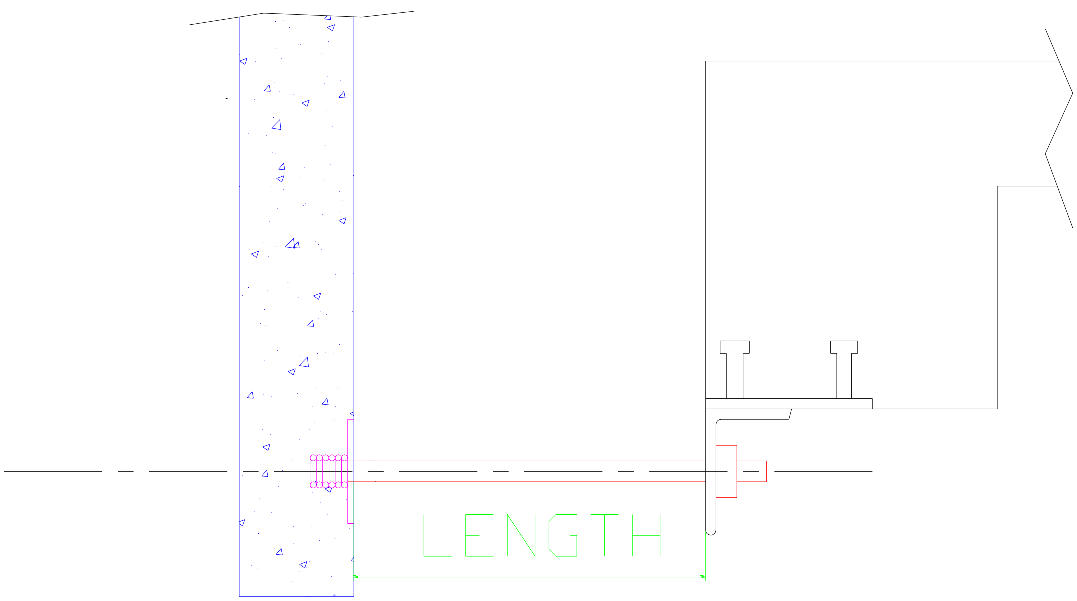


Figure 2. Cladding Detail for Façade Panels

CURRENT TEST PROGRAM

Testing of coil rod component tests continue from those reported at the last PCI Convention (McMullin, 2012). Table 1 provides a test matrix of the materials and goals of the testing. Figure 3 shows the layout of the test specimen and the testing set-up. In Figure 3, a concrete block is hung from the loading beam. The block represents a panel and was cast with a coil rod insert embedded into the upper surface of the block. A coil rod of specified length is installed in the top of the concrete block and attached to a steel angle attached to the bottom of the loading beam. The weight of the block is supported by the coil rod to represent the axial tension commonly existing in a push-pull connection due to dead load. The block is held from lateral movement by shear keys bolted to the steel reaction frame. Between the shear keys and the block are teflon pads to allow for frictionless sliding of the block up and down. This frictionless sliding represents the free movement of a panel into and out from the structure due to lateral movement of the panel. All coil rods tested were purchased from commercial local suppliers in California under the designation of low strength steel. Coil rods were cut to length at the research lab. Steel plates, concrete blocks and concrete embeds were made by local precast fabricators from typical materials to represent common California cladding panel manufacturing. The concrete block and embed were used for multiple tests but fresh coil rod was used on each experiment.

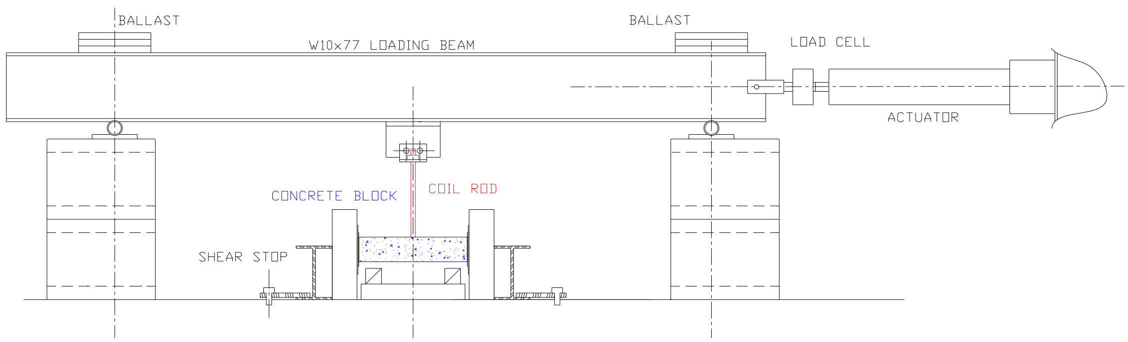
Table 1. Specimen Test Matrix – Flexing Rod Detail Component Tests

Series	Materials Tested	Loading Protocols Applied	Research Objective
2011	3/4-coil rod, lengths of 12, 16 and 20 inches	LP1, LP2	Define upper bound fracture displacement limit state for installations in system-level experiments.
2012	3/4-coil rod, lengths of 12 and 16 inches	LP2	Define fracture limit state as a function of peak displacement.
2013	1-inch coil rod, lengths of 16 and 20 inches.		

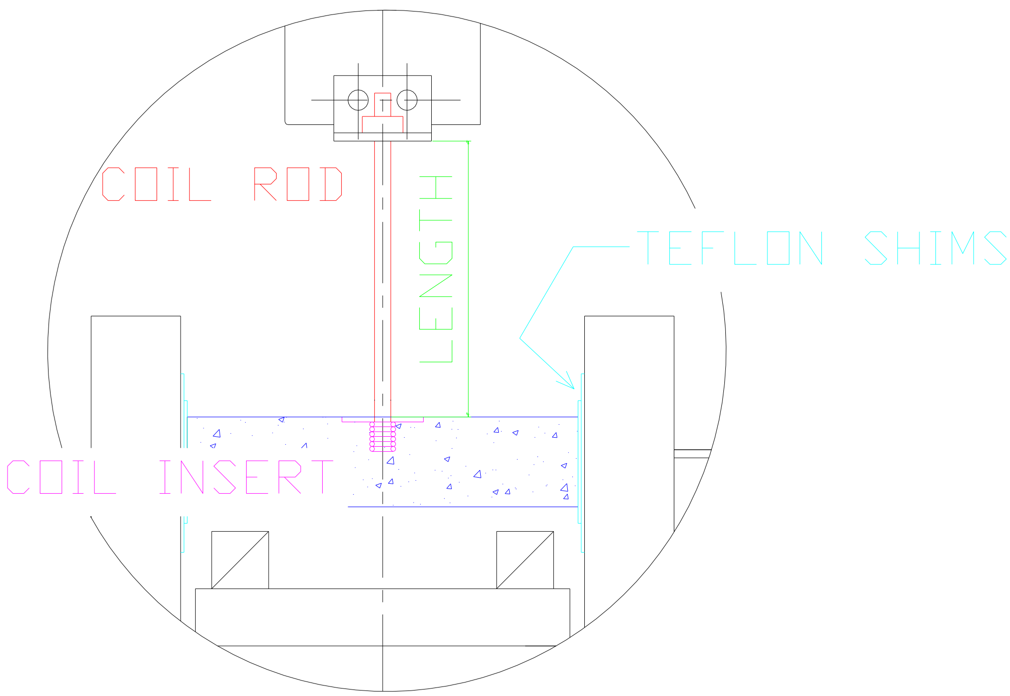
Various loading protocols have been applied to allow for a wide application of experimental results. Lateral movement of the loading beam is achieved by extending or contracting the actuator. This lateral movement induces a bending of the rod to simulate the flexural response expected due to in-plane movement of the concrete panel. Table 2 lists the testing protocol and specimen design for the component tests. Instrumentation measured the actuator force, the horizontal displacement of the loading beam, and the rotation of the concrete block. Because the block could not be held exactly horizontal, the rotation of the block was monitored to accurately measure the total transverse bending of the coil rod.

Table 2: Loading Protocol – Connection Component Tests

No.	Cyclic Loading Protocol	Remarks
LP1	ATC-58 – Increasing amplitude with three cycles at each amplitude (Bachman et al, 2003).	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.
LP2	Constant amplitude cycles	Constant amplitude displacement cycles until fracture occurs



a) Global Set-Up



b) Specimen Detail

Figure 3. Test Arrangement

RESULTS FROM TESTING

The primary findings to date have been that well designed coil rod connections perform well during simulated seismic loading. Damage was observed during the component tests when displacements above the design displacement were applied. Figures 4 and 5 show the behavior of a ¾ inch coil rod observed during testing. As Figure 4 shows, the coil rod is able to achieve considerable flexural bending prior to fracture. Several cycles of large amplitude loading were resisted prior to fracture. Figure 5 shows the final fractured coil rod. Fracture usually occurred at the nut to the steel plate on the structure side of the connection but occasionally occurred at the face of the concrete block at the embed. Fracture always was preceded by severe bending of the rod at both ends of the length, and concentrated over a short length of the threads. After fracture, the concrete block dropped several inches as the coil rod provided the only vertical support for the block.

Figure 4. Fracture of 3/4-inch Coil Rod, 16-inch long Specimen

Figure 5. Close-Up of Fracture Surface of Coil Rod in Figure 5.

One desired output from the experimental testing is the force deformation relationship for the connections. Figure 6 shows a typical component test result. The hysteretic behavior is rather constant with a slight decrease in the maximum force resisted for each consecutive cycle of loading. Most specimens had minimal slip observed during loading, however a few specimens did experience rather large levels of slip at the building end of the coil rod. Apparently horizontal friction and potential binding of the rod and plates prevented the coil rod from sliding relative to the support angle.

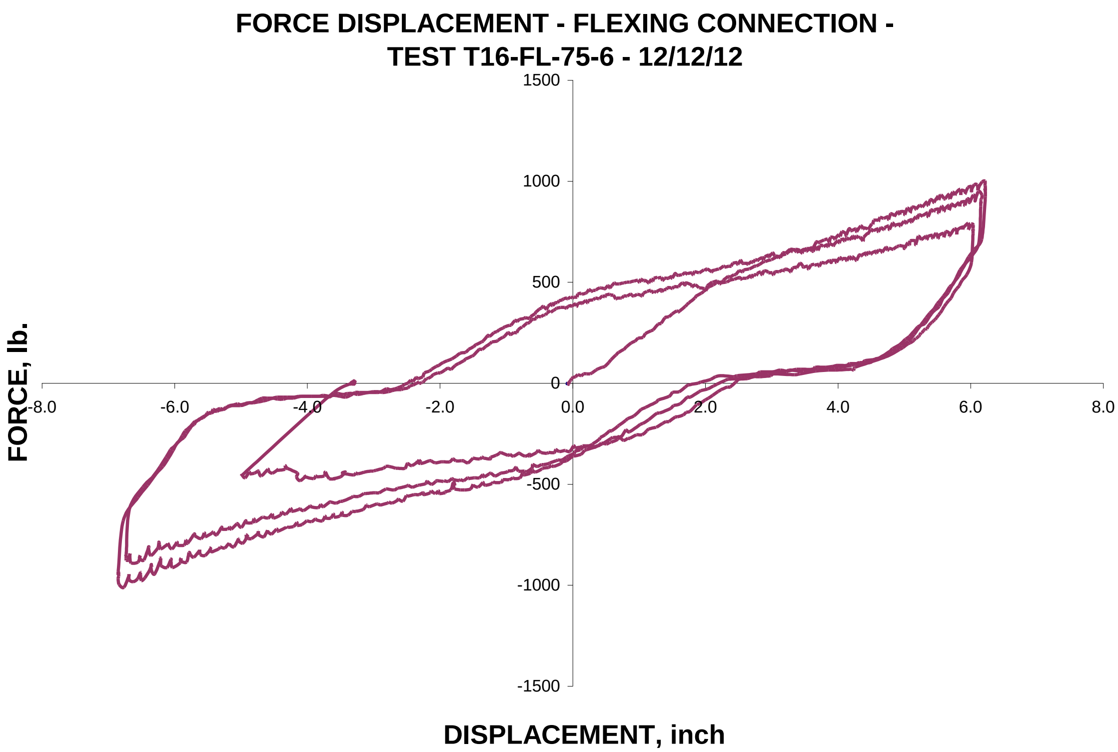


Figure 6. Typical Force-Displacement Graph of ¾-inch Coil Rod Specimen with Length of 12 inches.

ANALYTICAL MODELING

The goal of experimental testing is to develop analytical models that precast engineers can use to predict mechanical behavior to allow for accurate prediction of the coil rod behavior. The Phase I in this process is to develop basic models of individual components elements that can then be used in Phase II where the component elements are installed into more complex system-level model for evaluation of multi-panel behavior and/or structure-panel interaction.

A simple rigid-bar, concentrated-inelastic hinge (RBCIH) element is proposed based upon the experimental testing. Observation of the coil rod, particularly at large lateral displacement as shown in Figure 4, indicates that the main portion of the bar remains elastic and relatively undeformed throughout the testing. Inelastic behavior is concentrated in a short segment of the rod at both the panel and the support ends of the rod. Figure 7 shows a simplified assumption about the force-displacement element. The rod is assumed to remain undeformed at the two ends and have plastic hinges form at both ends. The rotation of each hinge would then be related to the horizontal displacement as shown in the figure.

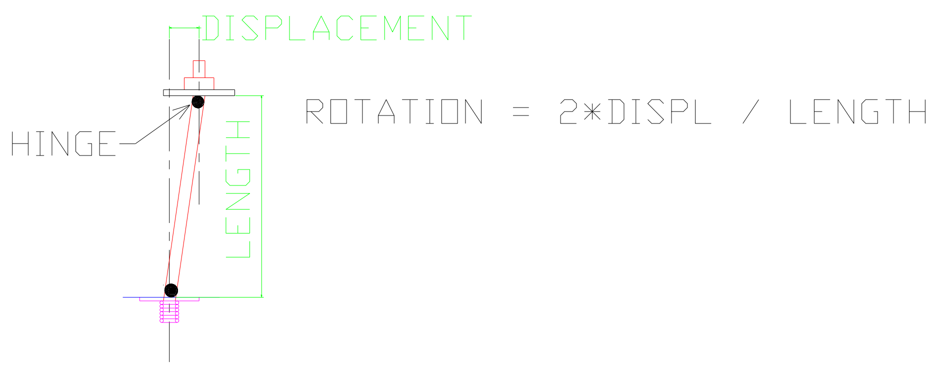


Figure 7. Proposed Rigid Bar Concentrated Inelastic Hinge (RBCIH) Model for Coil Rod Behavior.

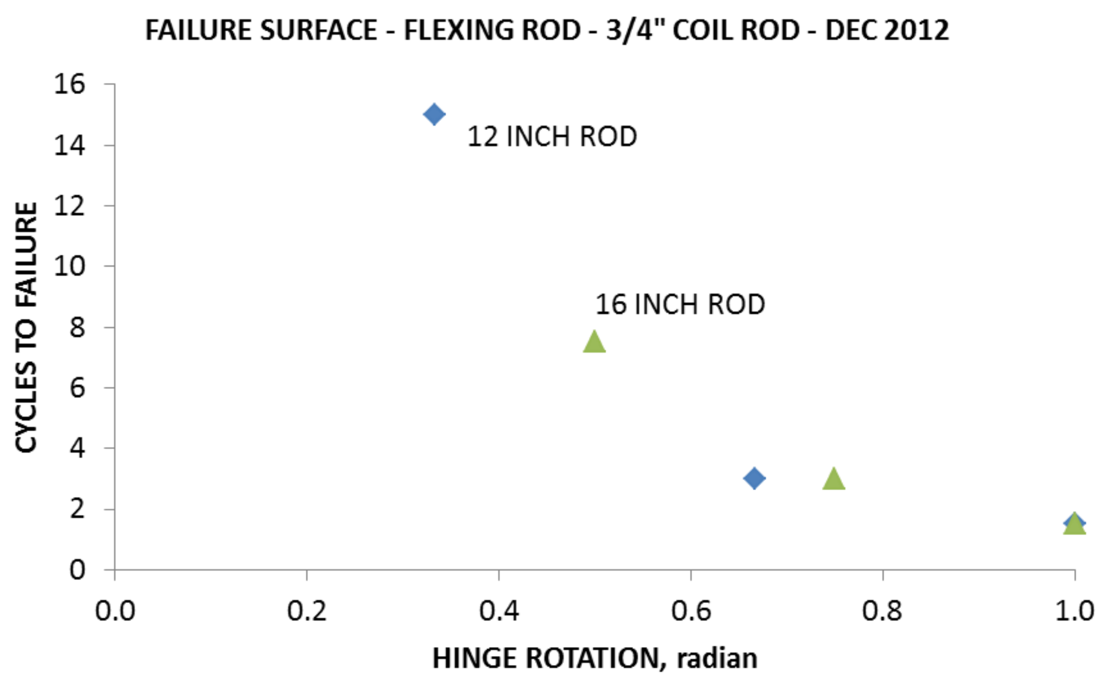


Figure 8. Prediction of Cycles of Failure based on Peak Hinge Rotation

Hinge rotation shows promise of predicting maximum cycles before fracture. Figure 8 shows the results of two series of experiments tested with ¾-inch diameter rods of 12 inch and 16 inch lengths. Loading was applied as a series of constant amplitude displacements (LP2 in Table 2) and the number of cycles prior to fracture was recorded.

Using the relationship for rotation from Figure 7, the rods were plotted in Figure 8. The resulting function approximates a hyperbolic function with rather consistent results regardless of the rod length. Several cycles were resisted while the rotation was limited to approximately 0.3 (lateral displacement of approximately 0.15 of the rod length). When lateral displacement neared half the length of the rod, fracture occurred before completing two complete cycles.

WORK FORTHCOMING

In the following months, work will focus primarily on four areas: expanded testing, data reduction, computer modeling, and research dissemination. Additional testing of 3/4 inch rods will be conducted to strengthen the reliability of the curve observed in Figure 8. Additional testing of 1-inch coil rods will also be conducted to see if comparable results are observed in larger diameter rods.

Data reduction will continue for the current and future experiments. Data to be evaluated includes energy dissipation during testing. Energy dissipated is intended to show that energy can be used to compare random loading configurations (such as those observed during seismic loading) and the constant displacement loadings of LP2. In addition, a shear strength model will be investigated related to Figure 8. Geometric standards for coil rods vary depending upon the manufacturer and the size of the original steel rod prior to rolling of the threads. In addition, the mechanical properties of cold-worked steel are expected to be significantly different than the original steel prior to cold-working.

Nonlinear modeling is critical to allow for practicing engineers to correlate experimental testing to the wide variety of cladding panel designs in use today. Using modern software, such as SAP 2000, structural models are being developed for the individual coil rod connections and then attached to linear shell elements models for the concrete panels. Nonlinear links using gap, hook and multilinear plastic elements are being assembled for each coil rod. In addition, experimental testing of panel assemblies show that cracking and nonlinear behavior of panels may occur if rods are relatively stiff (see Figure 1). Expanding the software models from elastic shell elements to nonlinear behavior will be challenging.

As experimental data is processed and combined with analytical studies, dissemination of research findings is continual. The outcome of the testing is contribution to a design procedure to be distributed to precast fabricator engineering staff. This design procedure will allow engineers guidance on the intentional use of inelastic behavior of coil rods to accommodate high interstory drifts expected in significant earthquakes.

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