EVALUATION METHODOLOGY FOR PRECAST CONCRETE DIAPHRAGM CONNECTORS BASED ON STRUCTURAL TESTING

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ABSTRACT:
Proper performance of connection details is critical for the effective design and safety of precast concrete building and bridge systems. The paper presents an experimental approach of assessing the strength and deformation capacity of embedded connections used in conventional precast concrete panel system. The approach is applied to in-plane loading on the connectors. A summary of the testing fixtures, testing procedures and data processing methods are provided. In addition, a recommendation is provided for categorizing the connector based on their deformation capability. Three in-plane deformation ranges are identified: low deformation element (LDE), moderate deformation element (MDE) and high deformation element (HDE) to categorize the connections. Lastly, a method for computing the design strength based on the test results is discussed.

KEYWORDS:
Precast concrete diaphragm connector, experimental approach, testing procedure, loading protocol, connection category

1. INTRODUCTION

Proper performance of connection details is critical for the effective design and safety of precast concrete building and bridge systems. This paper provides an approach for assessing the strength and deformation capacity of embedded connections used in conventional prefabricated concrete panel systems. In addition a series of performance levels are defined which can be used to categorize the connector based on the measured response. The methods presented in this paper provide a basis for which the adequacy of new and existing connections can be assessed through testing.

1.1. Simplified Analytical Approaches

Analytical methods have been developed and are provided in PCI design manuals. The approaches for determining the horizontal shear and horizontal tension capacity of rebar based connections are commonly used in design of precast connections.

Current formulation for in-plane strength determination of connection details is based on a general design criteria presented in the PCI design handbook (6th edition) Section 3.8.1.1. The assumption is made that the connection resists in-plane shear and tension through a “truss” mechanism. The connectors with splayed legs are designed to reach yield in the anchor leg in accordance with using Figure 1. The following relationships are used for determining the nominal capacity of the connector, where Cn is the normal compression force, Tn is the normal tension force, the nominal horizontal shear capacity of the connector is Vn_h, and the nominal horizontal tension capacity of the connector is Fn_h.

$$C_n = T_n = A_s f_y \tag{1.1}$$

$$V_{n\_h} = (C_n + T_n)\cos\theta° \tag{1.2}$$

$$F_{n\_h} = 2T_n \sin\theta \tag{1.3}$$

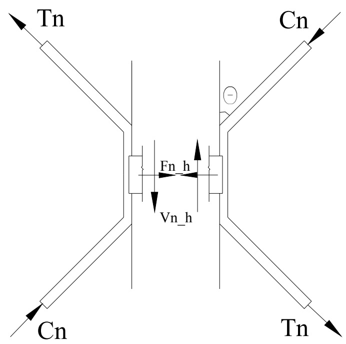

Figure 1 Truss model of double-tee connection

While the majority of connections are configured similar to the splayed connector discussed, the actual strength is dependent on the details of the connector, embedment, and welding techniques used to provide integrity between connectors. To properly assess the strength of a connection new analysis models can be developed for each connection. To validate these models an experimental verification is necessary. For these applications experimental evaluation criteria presented in this paper can be applied to determine the appropriate capacity of the connection.

1.2. Desired Ductile Connection Design

A typical diaphragm connection consists of anchorage bars, faceplate, slug, and slug weld components. To ensure that ductile modes of failure occur, a general rule can be followed. Design the connection to develop a predictable yield mechanism in the anchorage while protecting the other components through over-strength factors against premature failure, and the desired ductile mechanism cannot be formed unless each component of the connection is designed to maintain the load path without premature failure.

2. TEST MODULES

To evaluate the performance of precast connections experimentally, a minimum of one test module shall be used for each strength characteristic of interest. At a minimum one in-plane shear test module, and one in-plane tension test module shall be evaluated.

Modules shall have a scale large enough to fully represent the complexities and behavior of the real materials and of the load transfer mechanisms in a full-scale system. Since the test module represents only a small portion of a precast panel, confining effects provided by the whole panel is lost and the panel may be subjected to premature cracking. Additional reinforcement may be used to prevent premature failure of the test module. The additional reinforcement shall not be placed in a way that would alter the performance of the connector. Example reinforcing strategies for 4ft square panels are illustrated in Figure 2.

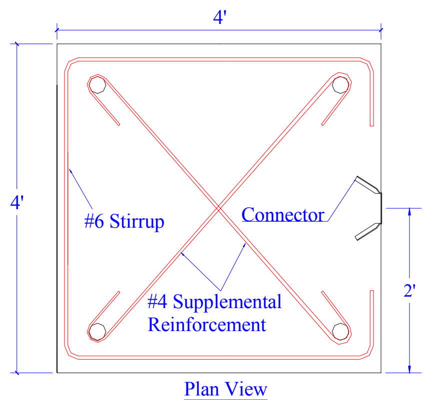

Figure 2 Supplemental reinforcement layout and construction details

3. TEST PROCEDURES

In this section, the test fixtures and loading protocols of in-plane tests are presented.

3.1. In-Plane Test Setup

A multi-directional test fixture shall be used to allow for the simultaneous control of shear, axial, and bending deformations at the panel joint. The fixture shall utilize up to three actuators, two in axial displacement and one in shear displacement (Figure 3).

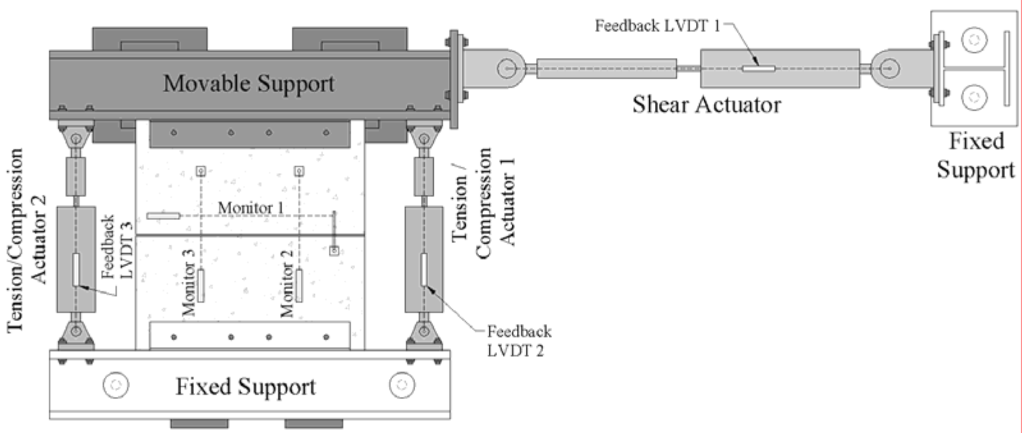

Figure 3 Multi-directional test fixture plane view

Demand shall be applied through independent displacement control of each of the three hydraulic actuators. The test specimen shall be connected to a restraint beam on either end of the panel. One beam shall be fastened to the lab floor, providing a fixed end, while the other beam rests on a pair of low friction (i.e., Teflon coated) steel plates, providing mobility with minimal frictional forces.

Independent control of the three actuators allows for application of shear, axial and bending deformations. Vertical movement of the panel shall be restricted by Teflon coated bearing pads under the center of each panel. This eliminates sag of the test specimen due to self-weight, while still allowing for free, near frictionless travel in the horizontal plane of motion.

Joint deformation shall be measured directly on the precast panel using a series of displacement transducers. Shear deformation shall be determined from measurements taken at the location of the connection. Axial deformation shall be averaged from two transducers on either side of the connection. A possible arrangement of displacement transducers is illustrated in Figure 3.

3.2. Reference Deformation

To properly represent typical hysteretic response of seismic demands connections shall be evaluated under cyclically increasing demands. The cyclic demand shall be applied relative to the yield of the connection to ensure that an appropriate number of elastic and inelastic cycles are applied. To accomplish this, a reference deformation relative to the yield of the connector shall be determined. The reference deformation shall be determined experimentally or analytically.

Experimental determination of the reference deformation shall be based on a monotonic test of the connection test module. The reference deformation represents the effective yield deformation of the connector. It shall be computed by taking the intercept of a horizontal line at the max load and a secant stiffness line at 75% of the max load (Figure 4).

Analytical determination of the reference deformation is allowed for connections where the yield deformation can be computed based on well established engineering concepts.

3.3. Displacement loading Protocols

The panels may be evaluated under in-plane pure shear, pure tension, and combinations of shear with tension. Tests shall be conducted under displacement control at quasi-static rates (< 0.05in/sec) or through force control. Unless noted, all panels shall be tested until the specimen capacity approaches zero.

Under earthquake demands a floor diaphragm system is subjected to a spectrum of relative motions. Five displacement protocols shall be used to assess the performance of connectors subjected to these possible motions. They include:

1. Monotonic In-plane Shear
2. Cyclic In-plane Shear
3. Monotonic In-plane Tension
4. Cyclic In-plane Tension and Compression
5. Monotonic In-plane Shear with Proportional Tension

Monotonic shear and tesnion loading protocols both consist of three cycles to 0.01-in. to estimate initial stiffness and verify equipment operation. Afterwards, the specimens shall be loaded monotonically to failure. As illustrated in Figure 4 and Figure 5 separately, the cyclic shear and tension/compression loading protocols both are in accordance with PRESSS program recommendations [Priestley 1992]. Three preliminary cycles to 0.01-in. shall be conducted to evaluate control and acquisition accuracy. The remaining protocol consists of groups of three symmetric cycles at increasing deformation levels. Each level is based on a percentage of a reference deformation computed from the corresponding monotonic tests.

3.4. Testing Observations and Acquisition of Data

Data shall be recorded from the test such that a quantitative, as opposed to qualitative, interpretation can be made of the performance of the test module. A continuous record shall be made of the force versus deformation. For in-plane tests the axial and shear force and deformations should be recorded. For static testing data should be recorded at a minimum rate of 1.0 cycle/second. Photographs shall be taken to illustrate the condition of the test module at the initiation and completion of testing as well as points through the testing history. Ideally photos should be taken at the end of each group of cycles. Photos taken at points of interest, such as cracking, yield, ultimate load and post-test, are adequate for most evaluations.

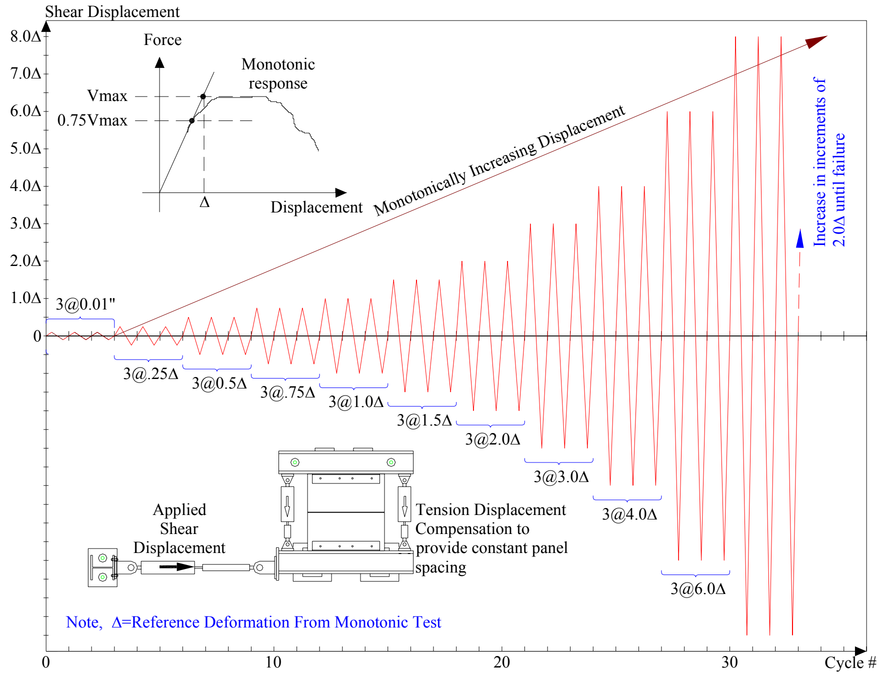

Figure 4 Shear loading protocol

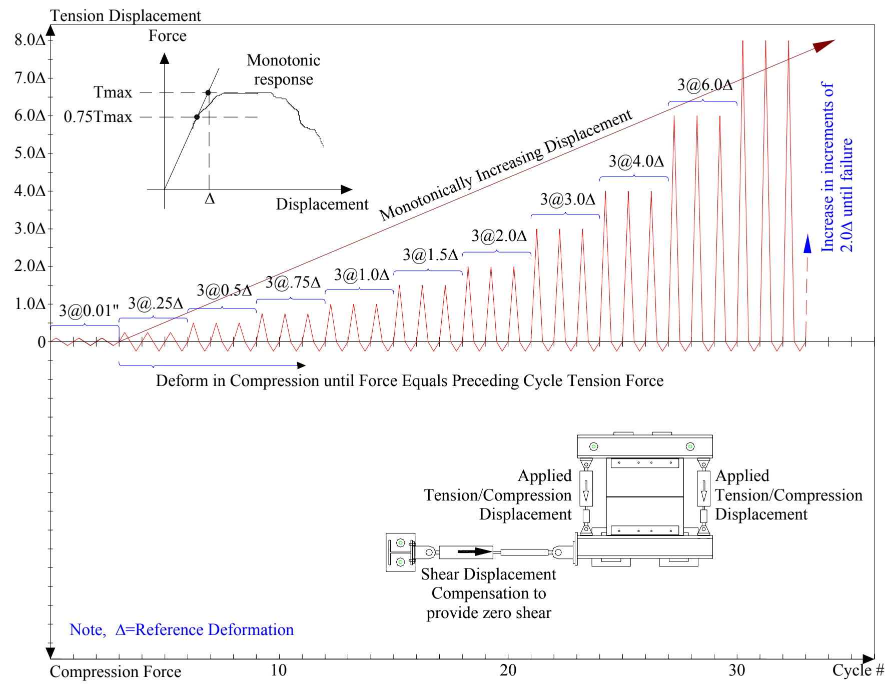

Figure 5 Tension/Compression protocol

4. BACKBONE APPROXIMATION

The experimentally measured performance shall be categorized in accordance with the procedures outlined in ASCE/SEI 41-06 Seismic Rehabilitation of Existing Buildings. Each connection shall be classified as deformation-controlled (ductile) or force-controlled (non-ductile). This assessment shall be determined based on the backbone curve of the response. For all the experimental data, a smooth "backbone" curve shall be drawn through each point of peak displacement during the first cycle of each increment of loading (or deformation) as indicated in ASCE/SEI41-06. This method provides a higher estimate of load than the previously used method outlined in FEMA356, in which the "backbone" curve is defined by drawing through the intersection of the first cycle curve for all the (i)th deformation step with the second cycle curve of (i-1)th deformation step. The difference between the two methods is illustrated in Figure 6.

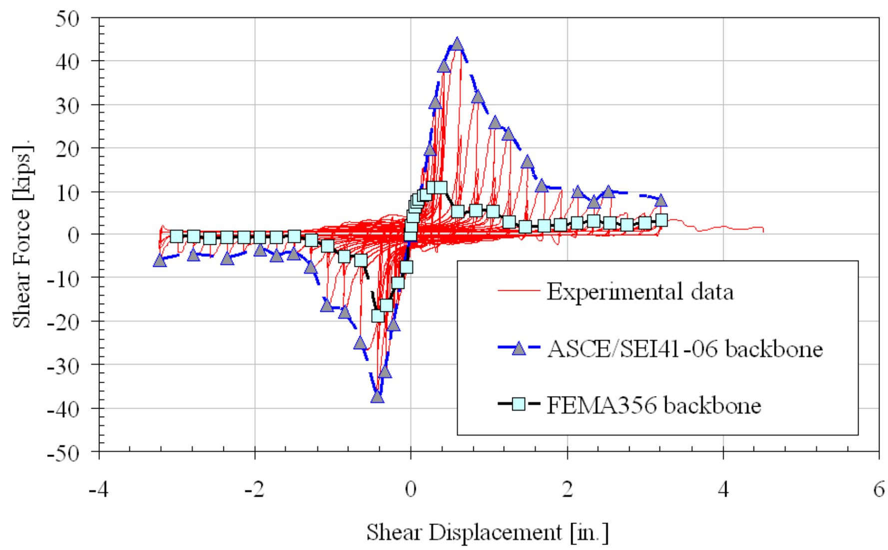

Figure 6 Backbone curve

The backbone shall be approximated by a series of linear segments drawn to form a multi-segmented curve. The curve shall be simplified to conform to one of the types indicated in Figure 7. As depicted in Figure 7, the type 1 and type 2 curve are representative of ductile behavior where there is an elastic range (point 0 to point 1) followed by a plastic range (point 1 to point 3 on the curve). The type 3 curve is representative of a brittle or non-ductile behavior where there is an elastic range (point 0 to point 1) followed by loss of strength. Deformation controlled elements shall conform to Type 1 or Type 2 response with e > 2g. All other responses shall be classified as force-controlled.

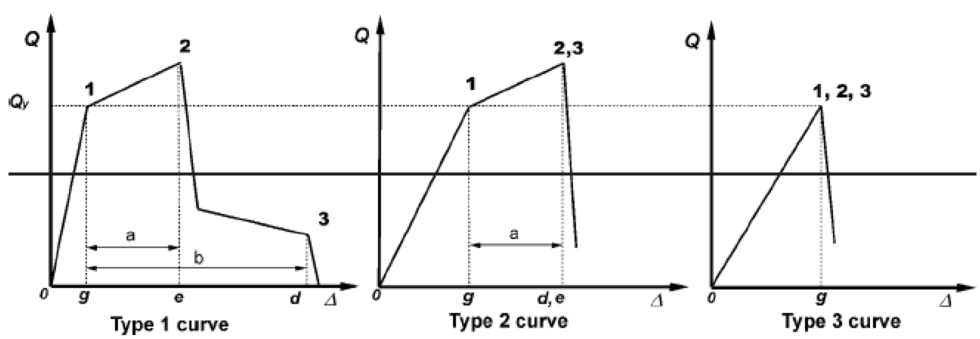

Figure 7 Component Force versus Deformation Curves [ASCE/SEI41-06]

5. TEST RESULTS ANALYSIS

The deformation capacity and the load carrying capacity of the tested connectors shall be determined in accordance with the procedures outlined in this section.

5.1. Deformation Capacity

The yield and peak values shall be determined for each test. The yield shall correspond to point 1 as indicated in Figure 7. The peak load and deformation shall correspond to point 2 as indicated in Figure 7. If the connector is deformation-controlled (i.e., e > 2g), then the mean deformation and force values shall be used. If the connector is force-controlled then the yield and peak values shall be based on the mean value minus one standard deviation.

The connectors shall be classified as a Low Deformability Element (LDE), a Moderate Deformability Element (MDE), or a High Deformability Element (HDE) based on their deformation capacity in tension and shear. The peak deformation (measured at point 2 of Figure 7) shall be used to classify the deformability category of the connector. The categorization is based on the critical values indicated in Table 1. The category ranges were determined from finite element analysis of a database of diaphragm systems under a range of earthquake demands.

Table 1 Deformation category range

Deformability Category	Tension deformation, ΔT [in]	Shear deformation, ΔV [in]
LDE	$0.00 < \Delta T \le 0.15$	$0.00 < \Delta V \le 0.30$
MDE	$0.15 < \Delta T \le 0.50$	$0.30 < \Delta V \le 0.70$
HDE	$\Delta T > 0.50$	$\Delta V > 0.70$

5.2. Force Capacity

To provide the design force for the typical connector used in the precast concrete diaphragm system, three methods can be followed:

- Three tests of each type are required with none of the results varying more than 10 percent from the average of the three, unless the lowest test value is used.
- The average result based on a minimum of six tests may be used regardless of the variations.
- The results of two tests may be used when the higher value does not exceed the lower value by more than 5 percent and the lower value is used with the required factors of safety.

Note: Where tests are not conducted to failure, the highest load achieved for each test shall be assumed as ultimate.

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