An evaluation method for precast concrete diaphragm connectors based on structural testing

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- This paper presents the results of a comprehensive research project on the development of a seismic design methodology for precast concrete diaphragms.
- For performance-based design, it is critical that the connector properties be determined in a consistent manner.
- This paper proposes a standard experimental approach for assessing the stiffness, strength, and deformation capacity of embedded connections used in conventional precast concrete diaphragm systems, along with deformation limits for categorizing their performance.
- The use of connections with limited deformation capacity could result in higher required design forces, while ductile connections could allow for lower design forces.

Precast concrete floor diaphragms are a popular form of construction in the United States for parking structures and residential and commercial facilities. The floor diaphragms comprise large precast concrete panels connected through discrete embedded connections. These connections act to transfer vertical and in-plane forces between panels. Vertical forces are limited to 3 kip (13.3 kN) in accordance with ASCE 7.[1] Assurance of connector vertical capacity can be achieved through standard strength testing. During seismic events the floor system is subject to in-plane inertial forces that subject the connections to combinations of in-plane shear, tension, and compression.[2]

In traditional diaphragm design, adequate in-plane force capacity is required for each connection to safely withstand the expected earthquake loads. Simplified diaphragm modeling methods are provided in the *PCI Design Handbook: Precast and Prestressed Concrete*[3] to determine the required shear and tension capacity in each connection. Force-based connection design approaches, such as those outlined in the *PCI Connection Manual for Precast and Prestressed Concrete Construction*[4], can be followed to size the connection required.

For enhanced safety and economy, a new performance-based formulation for precast concrete diaphragms has been outlined by the Building Seismic Safety Council Committee TS4.[5] This method relies not only on the

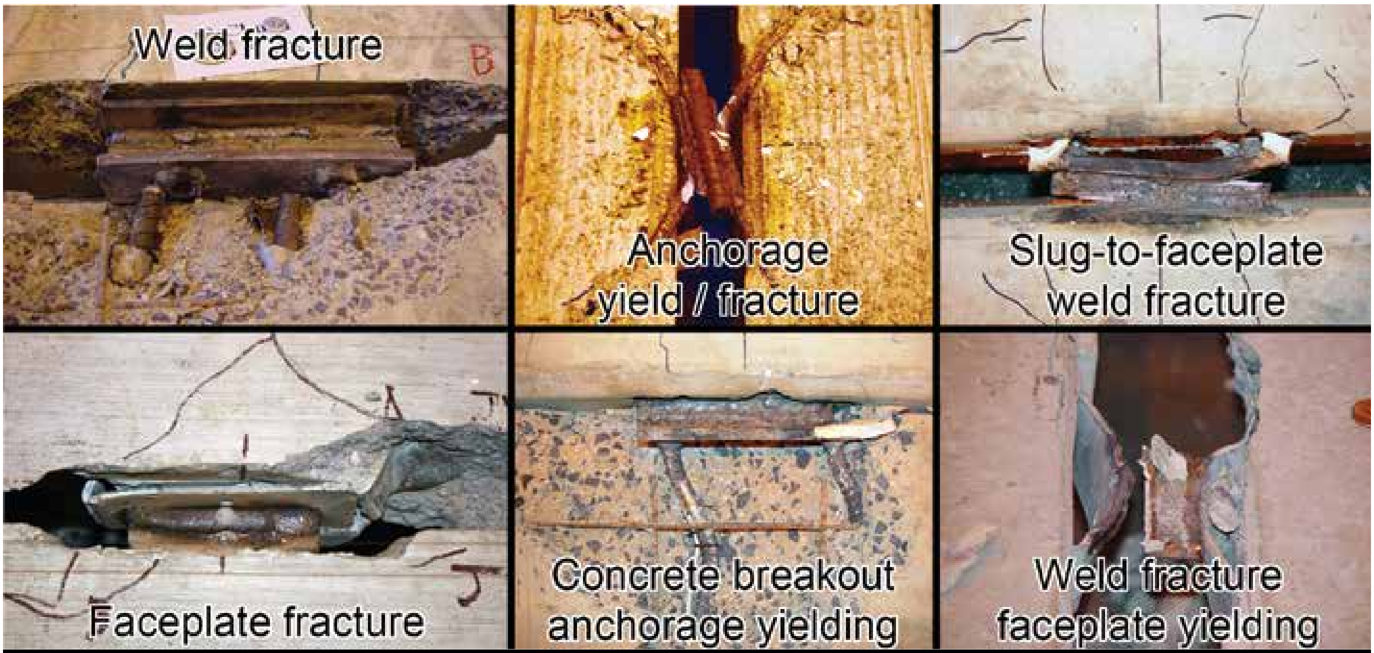

Figure 1. Potential in-plane failure modes in diaphragm connections.

strength of the connections but also on their stiffness and deformation capacities. Under the proposed design methodology the choice of connection type is tied to the flexure and shear overstrength factors needed by the diaphragm to achieve the required seismic performance. Although the methodology is complex, in essence the use of connections with limited deformation capacity could result in higher required design forces while ductile connections could allow for lower design forces. To choose the appropriate overstrength factor therefore requires knowledge of the deformation capacity of each connection type used in the diaphragm.

Due to the variety of connections in use, analytical determination of the expected deformability is not trivial. Connection deformation capacity under in-plane tension and shear is contingent on a series of inelastic failure modes. These include concrete breakout, yield of the anchorage bars, flexure or torsion of the faceplate, yield of the slug or jumper plate, fracture of the welds, or fracture of the faceplate or anchorage (**Fig. 1**). Such failures are difficult to predict even with finite element methods. Furthermore, each connection type exhibits variations in mode of failure. Consequently, proper determination of the deformation capacity of connections is best determined experimentally.

Initial experiments on shear mechanical connectors were conducted in 1968 when Venuti[6] examined 68 reinforcing bar connections. Since then, many studies have been conducted to qualify the performance of flange-to-flange connectors.[7–13] Connections were evaluated under in-plane shear loading, in-plane tension loading, and combinations of in-plane shear and tension. Studies were conducted using monotonic and cyclic loading. Most test fixtures from 1970 to 1980 were developed to examine the connector performance in monotonic in-plane shear under force control. This approach cannot capture post-peak behavior and deformation capacity. In addition, most studies used half the connection to ease installation and reduce cost. Axial restraint significantly affects the measured shear capacity.[14] These systems were connected to a stiff loading beam to restrain the connector; unfortunately in most cases the axial restraint provided by the loading beam was not measured.

To meet the requirements of performance-based diaphragm design methodologies, a consistent experimental procedure must be followed. A consistent procedure helps achieve repeatability within a laboratory and promotes reproducibility among laboratories. This paper proposes a standard experimental approach for assessing the stiffness, strength, and deformation capacity of embedded connections used in conventional precast concrete diaphragm systems. In addition, deformation limits are proposed for use in categorizing the performance of precast concrete diaphragm connections.

Proposed experimental methodology

The proposed experimental methodology assesses the in-plane strength, stiffness, and deformation capacity of precast concrete diaphragm connections. It was developed specifically for diaphragm flange-to-flange connections.

Scope

This recommendation is intended to meet American Concrete Institute's *Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary (ACI 318R-08)*

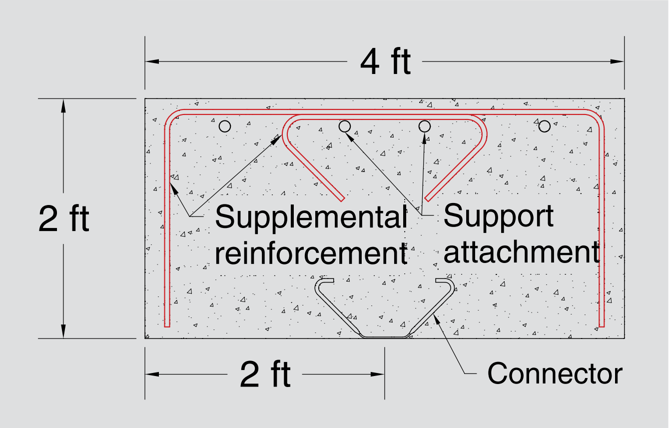

Figure 2. Test module plan view of half specimen. Note: 1 ft = 0.305 m.

for precast concrete connections.[15] As defined in section 16.6.1.1, "the adequacy of connections to transfer forces between members shall be determined by analysis or by test." This recommendation provides test procedures for assessing both strength and deformation capacity.

Under seismic loading, connections between adjacent concrete diaphragm elements are subject to combinations of shear, tension, and compression. The relative combinations of these deformation or force components depend on the location within the diaphragm and the presence of discontinuities. The test method independently determines the shear and tension performance of connections. Alternative procedures are also proposed for determining the performance under combinations of shear and tension.

Test modules

To evaluate the performance of a precast concrete connection, a test module representing the connection and the precast concrete element in which it is embedded is fabricated and tested. A separate test module is used for each characteristic of interest. At a minimum, one in-plane shear test module and one in-plane tension test module are evaluated. It is strongly recommended that multiple tests be conducted to assess repeatability.

Modules should be fabricated at full scale unless reduced-scale connectors are available. For reduced-scale specimens, the maximum aggregate size should be reduced appropriately and the laws of similitude should be followed. Full-scale modules should include a tributary concrete surface of at least 2 ft (0.6 m) from the connector. Because the test module represents only a small portion of a precast concrete panel, confinement effects are minimal, and the module may be subjected to premature cracking where the prototype would not. Additional reinforcement is necessary to prevent premature failure of the test module. The additional reinforcement should not be placed in a way that would alter the performance of the connector. **Figure** 2 illustrates example reinforcing strategies for the 2 × 4 ft (600 × 1200 mm) half module. The connections should be installed and welded in the test module in accordance with the guidelines provided by the connector supplier.

Test setup

For each connection test, a multidirectional test fixture permits the simultaneous control of shear, axial, and

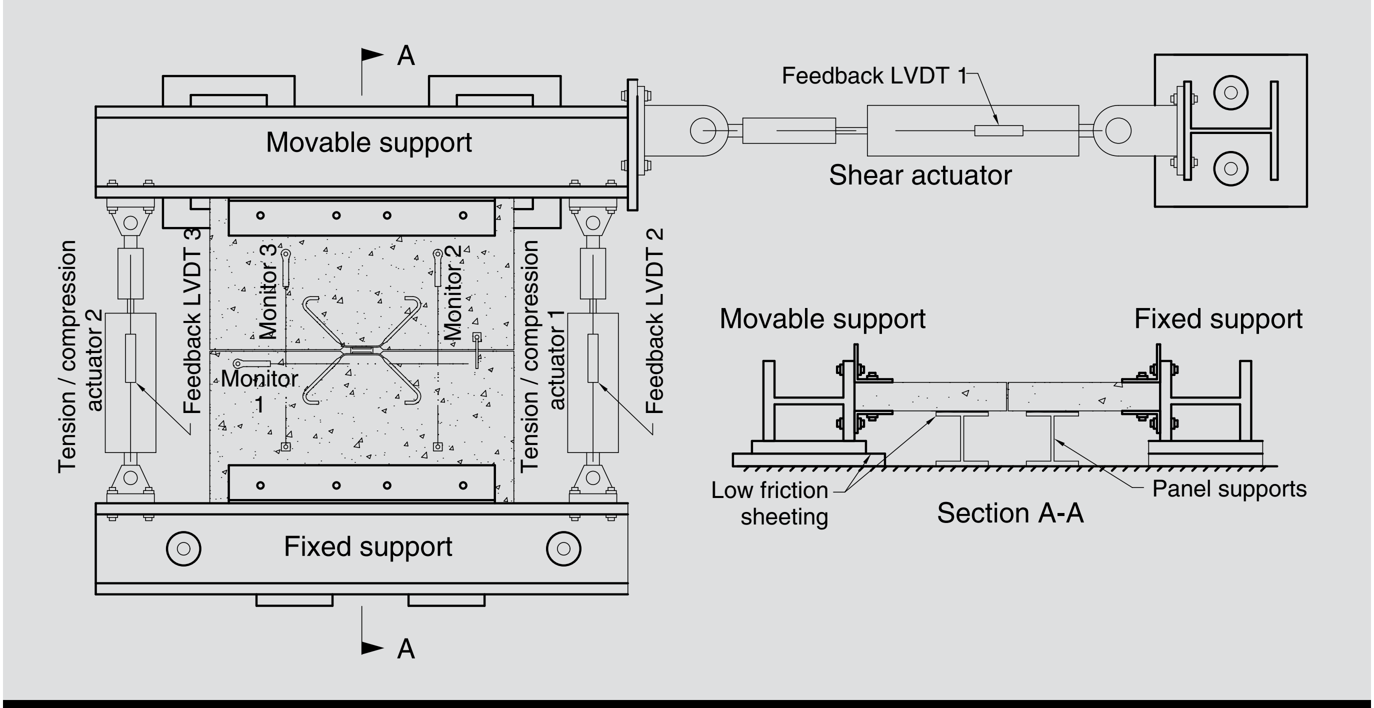

Figure 3. Multidirectional test fixture. Note: LVDT = linear variable differential transducer.

potential bending deformations at the panel joint. **Figure** 3 illustrates a possible setup. The fixture comprises three independent actuators, two providing axial displacement and one providing shear displacement to the connection. Loads are applied through displacement control of each actuator. The test specimen is connected to restraint beams on either end; slip between the test module and beams must be minimized. One support beam is fixed to the laboratory floor, while the other beam rests on a low-friction movable support. Vertical movement of the panel is restricted by supporting the center.

Instrumentation

At a minimum, instrumentation consists of displacement and force transducers. Shear and axial forces are measured in line with each actuator. Feedback transducers are incorporated into each actuator for displacement control. Connection deformation is measured directly on the test module; actuator transducers are not recommended because of potential slip in the test fixture. A minimum of two axial transducers is necessary to determine the average axial opening and closing at the connection. Shear deformation is measured at the connection. Transducers on the test module must be far enough away from the connection to minimize damage to the transducer supports during the test. Figure 3 illustrates a possible arrangement of transducers.

Loading protocols

The connections are evaluated for in-plane shear, tension, and combinations of shear with tension. Tests are conducted under displacement control using quasi-static rates less than 0.05 in./s (1.25 mm/s) or under mixed displacement and force control. All test modules are tested until the specimen capacity approaches zero.

Under seismic loading, a floor diaphragm system is subjected to a spectrum of relative motions. Analytical studies on the precast concrete diaphragm response to seismic loading[16] have shown that the connection displacement history depends on its location within the diaphragm. Connections located at midspan are subjected primarily to flexure, while connections at the edges are subjected primarily to shear with minimal tensile opening. Connections in intermediate regions are subjected to combined shear and tension with a typical shear-to-tension deformation ratio of 2.0. To encompass these possible motions, six displacement protocols are proposed to assess the performance of diaphragm connectors subjected to seismic loading. They include:

- Monotonic shear: for determination of connection shear yield and associated reference deformation for use in the cyclic loading protocol. In lieu of monotonic tests, connection yield deformation may be estimated.

- Cyclic shear: for determination of connector shear stiffness, strength, deformation limits, and modes of failure.

- Monotonic tension: for determination of connection tension yield and associated reference deformation for use in the cyclic loading protocol. In lieu of monotonic tests, connection yield deformation may be estimated.

- Cyclic tension and compression: for determination of connector tension stiffness, strength, deformation limits, and modes of failure.

- Monotonic shear with proportional tension: alternate protocol to assess performance in combined tension and shear.

- Cyclic shear with axial force control: alternate protocol to assess influence of axial confinement on shear performance.

Monotonic testing protocols The monotonic shear and tension loading protocol consists of three preliminary cycles to 0.01 in. (0.25 mm) to verify control and instrumentation operation. Following verification of the system, the test module is loaded under a monotonically increasing displacement until failure. The monotonic test is used to determine the reference deformation of the connection if a reference is not available. The reference deformation represents the effective yield of the test module.

Experimental determination of the reference deformation Δ is based on a monotonic test of a connection test module. The reference deformation represents the effective yield deformation of the connector. It is computed by taking the intercept of a horizontal line at the maximum tension force T_{max} or shear force V_{max} and a secant stiffness line at 75% of the maximum measured load (**Fig. 4** inset). In lieu of the monotonic test, the reference deformation may be determined by analysis.

Cyclic testing protocols The performance of diaphragm connections for use in seismic applications is evaluated under cyclically increasing loads. The cyclic load is applied relative to the reference deformation of the connection so that an appropriate number of elastic and inelastic cycles are applied.

Cyclic loading protocols in accordance with the PRESSS (Precast Seismic Structural Systems) program are recommended.[17] Three preliminary cycles to 0.01 in. (0.25 mm) are imposed to evaluate control and data acquisition accuracy. The remaining procedure consists of groups of three symmetric cycles at progressively increasing deformations based on a percentage of the reference deformation from the corresponding monotonic tests.

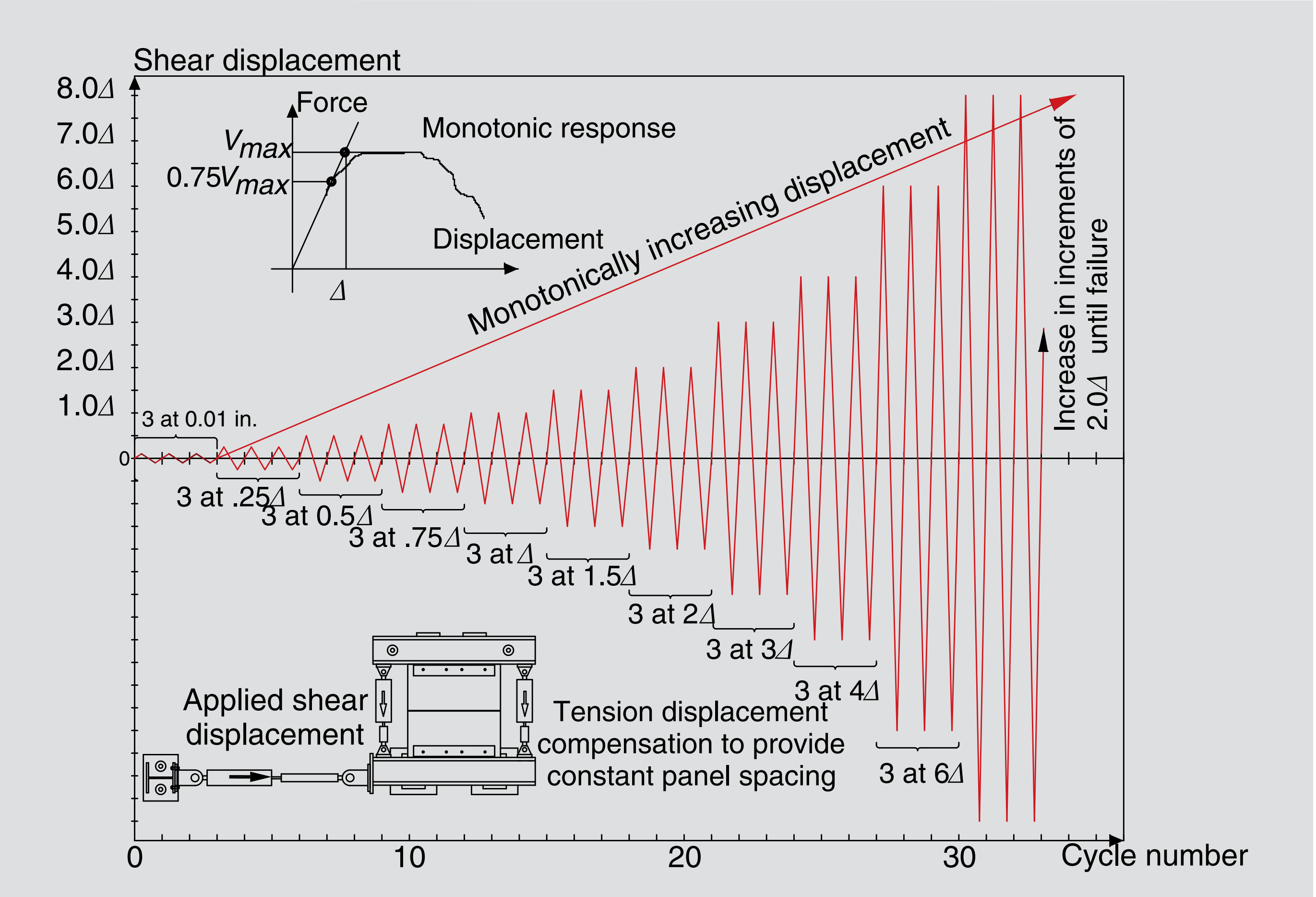

Figure 4. Shear loading protocol. Note: Δ = reference deformation from monotonic test. Note: T_{max} = force at point 3 on multisegment backbone curve; Δ = reference deformation. 1 in. = 25.4 mm.

The cyclic shear testing protocol consists of three preliminary cycles to a shear displacement of 0.01 in. (0.25 mm) to verify control and instrumentation operation. The test module is then loaded in sets of increasing shear deformation (Fig. 4). The tension deformation across the joint should be maintained constant during the shear history through adjustment of tension/compression actuators 1 and 2. The axial deformation is maintained at zero or at a tension opening of 0.1 in. (2.5 mm).

The cyclic tension/compression testing protocol consists of three preliminary cycles to a tension displacement of 0.01 in. (0.25 mm) to verify control and instrumentation operation. The test module is then loaded in progressively increasing tension deformation in sets of three replicate cycles (**Fig. 5**). Due to the high compression stiffness of connections, the compression portion of each compression half cycle consists of an increasing compression deformation until a force limit is reached. The force for each cycle is limited to the maximum force of the preceding tension half cycle. The shear deformation is maintained at zero through adjustment of the shear actuator. Alternatively, the shear actuator may be disconnected from the setup so that the shear force is zero during the cyclic tension/compression history. If the connection fails symmetrically in tension, then the results of both methods will be the same. If the connection fails in an asymmetric manner, the results will differ. The use of a shear actuator may result in a buildup of shear force as the connection deforms asymmetrically. Without a shear actuator, the panel may generate shear deformation as the connector deforms, which may result in a lower strength for the connector.

Alternative protocols For cases in which additional information on connector performance is needed, two alternative loading protocols can be used.

Connections at certain locations in the diaphragm may be subject to combinations of shear and tension. A shear-to-tensile deformation ratio of 2.0 is recommended for web connections in shear-dominated regions of the diaphragm. A ratio of 0.5 is recommended for chord connections in tension-dominated regions. The monotonic shear-with-tension test consists of three cycles of 0.01 in. (0.25 mm) shear deformation and a proportional tension/compression deformation (**Fig. 6**). The shear and tension deformations are increased proportionally using the chosen constant shear-to-tension deformation ratio. The test is paused at intervals of 0.1 in. (2.5 mm) of shear deformation for observations.

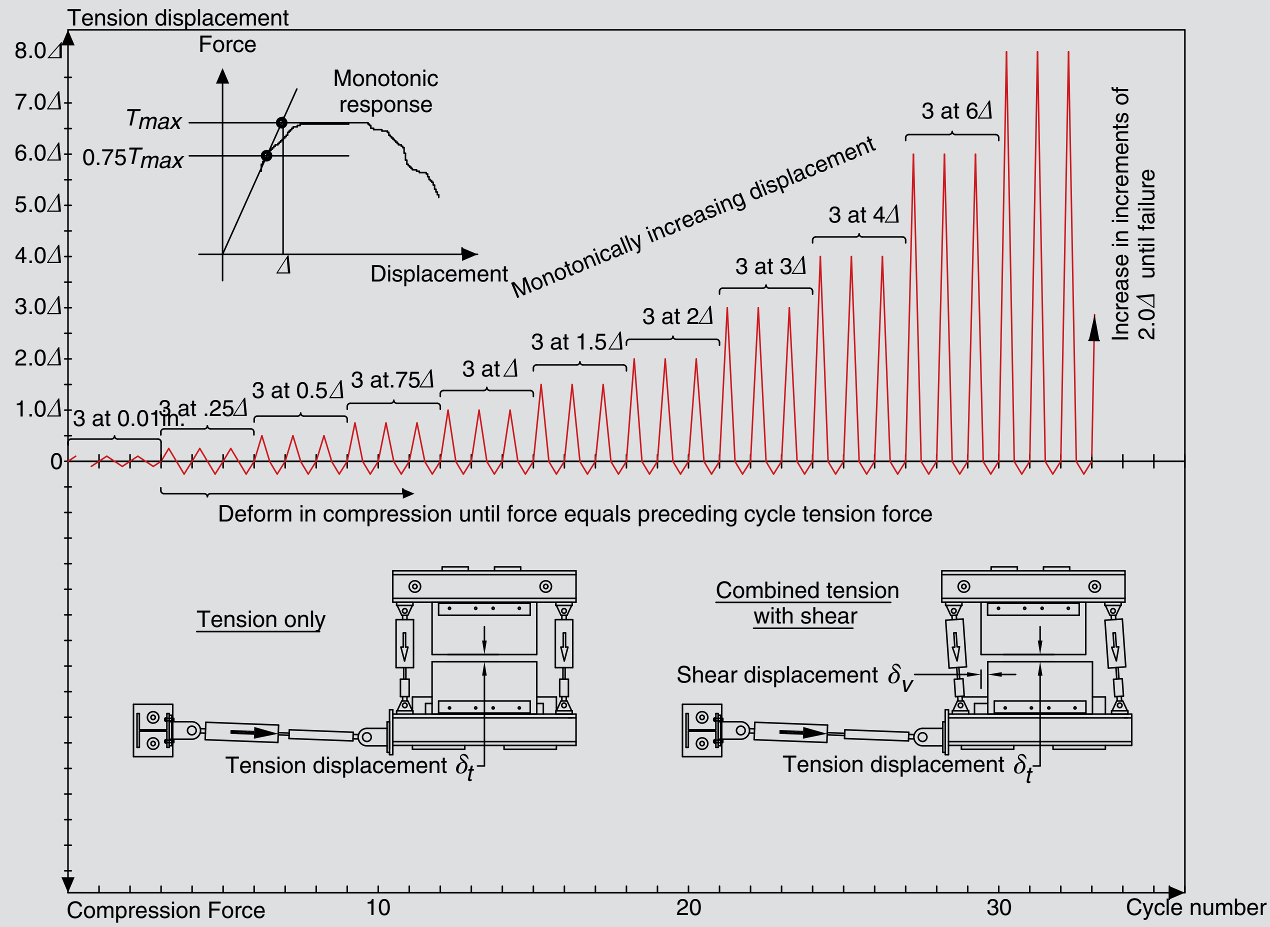

Figure 5. Tension/compression loading protocol. Note: Δ = reference deformation from monotonic test. Note: T_{max} = force at point 3 on multisegment backbone curve; Δ = reference deformation. 1 in. = 25.4 mm.

Enhanced displacement-based control testing may be used to evaluate the connections under in-plane shear. Standard shear-displacement-based tests hold the joint opening fixed, which may result in large axial forces. The enhanced protocols examine the shear performance of connections under fixed axial load. These protocols provide information that can be used to model the shear resistance of connections at various locations in the floor diaphragm, whether regions of high compression, high tension, or zero axial load.

All tests are conducted at quasi-static rates under mixed displacement and force control using inner and outer control loops. The outer loop conforms to the deformation-based shear protocols in Fig. 4. Each displacement step is divided into substeps of approximately 0.001 in. (0.025 mm) applied in the inner control loop. The inner loop is controlled in a mixed load and displacement manner. After the application of each inner loop shear sub-step, the force in the axial actuators is measured. If the sum of the forces differs from the target axial load, the actuators are adjusted accordingly to within a tolerance of 500 to 1000 lb (2.2 to 4.5 kN). This process continues until the full outer shear step is applied. The next shear step is then applied and the process repeated.

The algorithm of applying shear deformation with zero axial load is as follows:

1. Apply the shear deformation step to the shear actuator.
2. Read the force in compression/tension actuators 1 and 2, F_1 and F_2.
3. Compute the total force $F_t = F_1 + F_2$.
   a. If, $F_t > 0$, Extend actuators 1 and 2 until $F_t = 0$
   b. If, $F_t < 0$, Retract actuators 1 and 2 until $F_t = 0$
4. Repeat from step 1 until the target shear displacement is reached.

Tension tests

A monotonic tension test is conducted to determine the initial reference deformation for use in the cyclic tension tests. Alternatively, the reference deformation may be

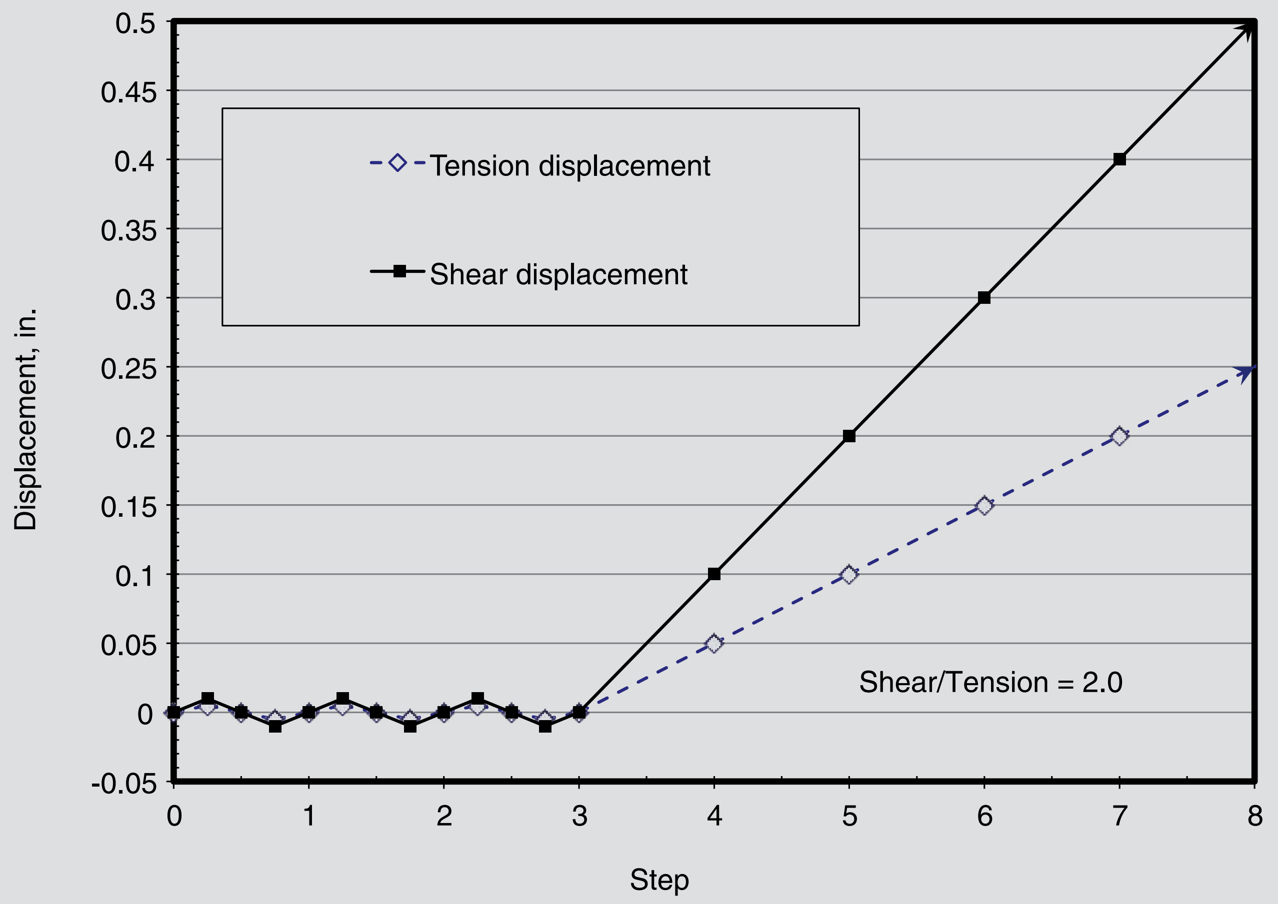

Figure 6. Monotonic shear with proportional tension (ratio of 2.0 shown). Note: 1 in. = 25.4 mm.

based on an analytical estimate of the yield deformation of the connection or on a desired deformation capacity for the connection. In this case, the deformation category of the connection may be used as the reference deformation.

In-plane cyclic tension tests are conducted to failure to determine stiffness, strength, and deformation capacity of connections under tension. The measured tension deformation capacity is used to establish the performance category of the connection.

Shear tests

A monotonic shear test is used to determine the initial reference deformation for the cyclic shear tests. Alternatively, the reference deformation may be based on an analytical estimate of the shear yield deformation of the connection or on a desired deformation capacity for the connection.

In-plane cyclic shear tests (with a constant 0.1 in. [2.5 mm] axial opening) are conducted to failure to determine the stiffness and strength of a connection in shear.

In-plane monotonic shear with proportional tension tests may also be conducted for connections in intermediate diaphragm regions. In-plane cyclic shear with target axial load tests can be conducted if needed.

Test observations and acquisition of data

Data are continuously recorded to support a quantitative interpretation of the performance of the test module. For in-plane tests, the axial and shear force and deformations should be recorded at a minimum rate of 1.0 Hz. Photographs are taken to illustrate the condition of the test module before and after testing and at intervals during testing. Ideally, photos should be taken at the end of each group of cycles. However, photos taken at points of interest, such as cracking, yield, ultimate load, and post-test, are adequate for most evaluations.

Backbone approximation The measured cyclic response is processed in accordance with ASCE/SEI 41-06.[18] Connections are classified as deformation-controlled (ductile) or force-controlled (nonductile) based on the backbone curve of the response.

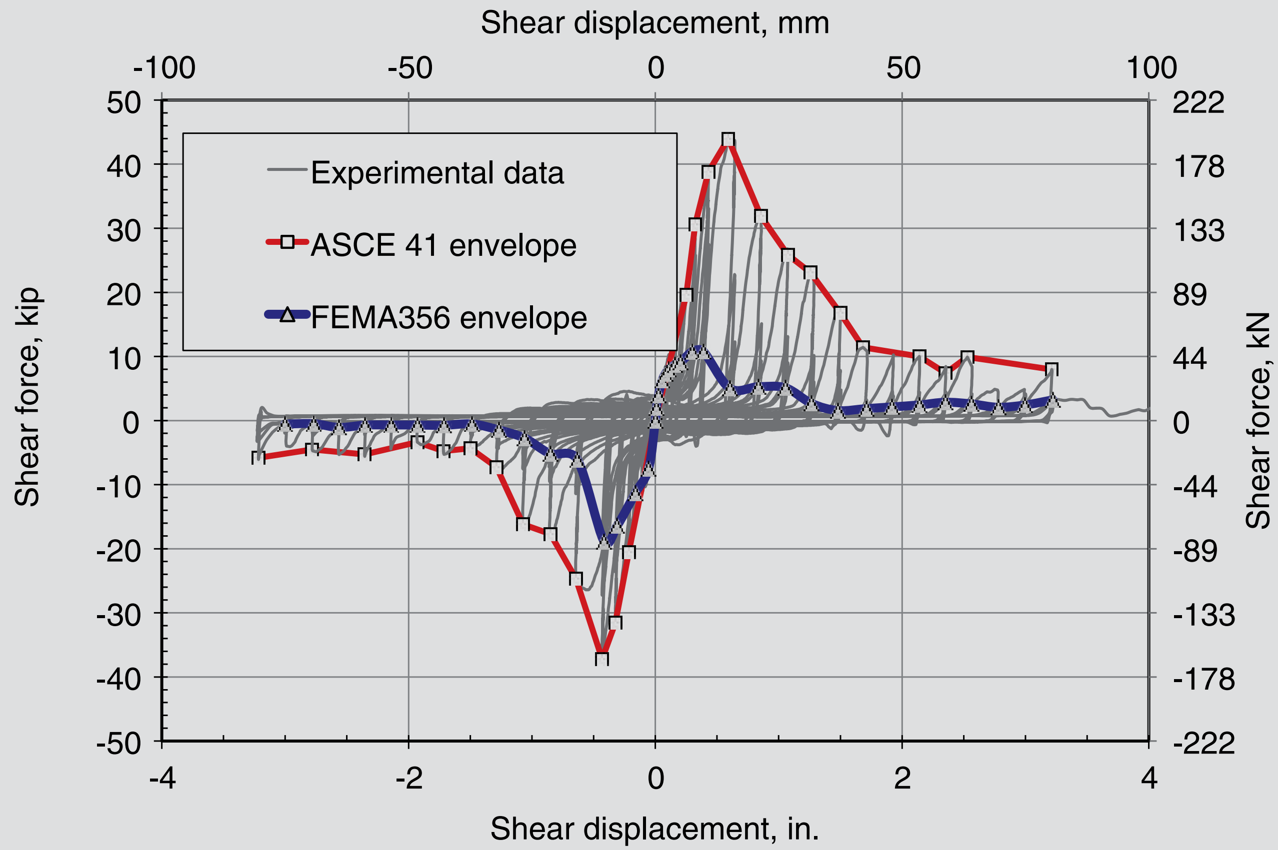

Figure 7. Cyclic envelope determination.

An envelope of the cyclic force deformation response is constructed from the points making up the peak displacement applied during the first cycle of each increment of loading (or deformation), as indicated in ASCE/SEI 41-06. This method provides a higher estimate of strength than FEMA 356,[19] in which the envelope is defined by the intersection of the first cycle curve for the i^{th} deformation step with the second cycle curve of the $(i-1)^{th}$ deformation step. **Figure 7** shows the difference between the two methods for a ladder connection.[20]

The cyclic envelope is further simplified to a multisegment backbone curve consisting of a four-point multilinear curve (**Fig. 8**). The backbone curve is a simplistic approximation of the load-deformation response of the connection. The points are defined in terms of the resistance force P_a, P_1, P_b, P_2, P_{2a}, and P_3 and the displacements Δ_a, Δ_1, Δ_b, Δ_2, Δ_{2a}, and Δ_3. The initial elastic stiffness K_e is the secant at point a. The procedure of determination of these points is as follows:

1. Determine the force at point 2 $P_2 = P_{max}$ (where P_{max} is the force at yield point).

2. Determine the force at point a $P_a = 15\% \times P_{max}$.

   Determine the deformation Δ_a at point a from original data.

3. Determine the initial elastic stiffness $K_e = \dfrac{P_a}{\Delta_a}$.

4. Determine the deformation at point b $\Delta_b = \dfrac{P_2}{K_e}$.

   Determine the force P_b at point b from the original data.

5. Determine the deformation Δ_1 and force P_1 at point 1 using:

$$\Delta_1 = \frac{(P_b \Delta_2 - P_2 \Delta_b)}{K_e(\Delta_2 - \Delta_b) - (P_2 - P_b)}.$$

6. Determine the force at point 3 $P_3 = 15\% \times P_{max}$.

   The deformation Δ_3 can be found from original data.

7. Determine the deformation at point 2a $\Delta_{2a} = \dfrac{\Delta_2 + \Delta_3}{2}$.

   Determine the force P_{2a} at point 2a from the original data.

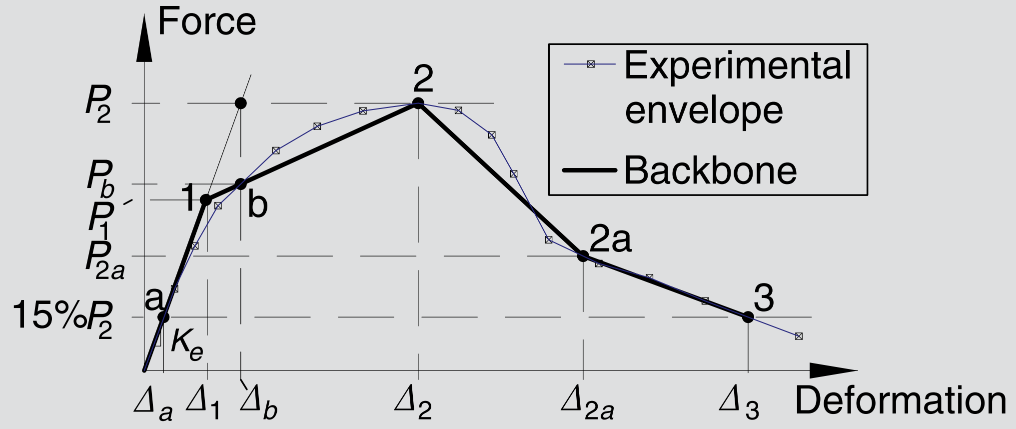

Figure 8. Simplified backbone curve. Note: K_e = initial elastic stiffness of the multisegment backbone curve; P_1 = force at point 1 on multisegment backbone curve; P_2 = force at point 2 on multisegment backbone curve; P_{2a} = force at point 2a on multisegment backbone curve; P_b = force at point b on the multisegment backbone curve; Δ_1 = deformation at point 1 on the multisegment backbone curve; Δ_2 = deformation at point 2 on the multisegment backbone curve; Δ_{2a} = deformation at point 2a on the multisegment backbone curve; Δ_3 = deformation at point 3 on the multisegment backbone curve; Δ_a = deformation at point a on the multisegment backbone curve; Δ_b = deformation at point b on the multisegment backbone curve.

Figure 9 classifies the backbone curve. The type 1 curve represents ductile behavior, with an elastic range from point 0 to point 1 on the curve and an inelastic range from point 1 to point 3, followed by loss of force-resisting capacity. The type 2 curve represents ductile behavior with an elastic range and an inelastic range followed by substantial loss of force-resisting capacity. Some connections may exhibit low peak strength with limited ductility. For these cases, the type 2 curve is recommended. The type 3 curve represents brittle or nonductile behavior with an elastic range from point 0 to point 1 followed by loss of strength. Deformation-controlled elements should exhibit a type 1 or type 2 response with Δ_2 greater than or equal to $2\Delta_1$. All other responses are classified as force controlled.

Data reduction The performance characteristics of the connector are quantified from the backbone response. The initial elastic stiffness of the connection is determined from the secant to yield point 1 using the equation for K_e.

The yield deformation is defined at Δ_1, the maximum deformation at Δ_2, and the residual deformation at Δ_3. For deformation-controlled connections, the deformation capacity corresponds to Δ_2. For force-controlled connections, it corresponds to Δ_1. When multiple tests are conducted, the deformation capacity for each connection test is determined separately. The connection deformation capacity is the mean test deformation capacity for deformation-controlled connections and the mean minus one standard deviation for force-controlled connections.

The connection is classified as a low-, moderate-, or high-deformability element based on its deformation capacity in tension (**Table 1**). The category ranges were determined

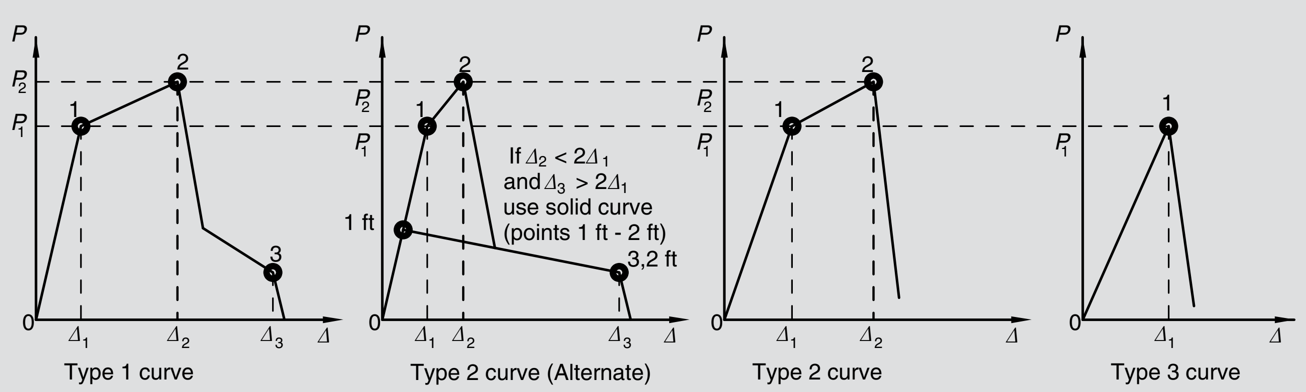

Figure 9. Deformation curve types. Note: P = force; P_1 = force at point 1 on multisegment backbone curve; P_2 = force at point 2 on multisegment backbone curve; Δ = reference deformation; Δ_1 = deformation at point 1 on the multisegment backbone curve; Δ_2 = deformation at point 2 on the multisegment backbone curve; Δ_3 = deformation at point 3 on the multisegment backbone curve.

Table 1. Deformation category ranges

Connection deformability category	Tension deformation limits *DT*, in.
Low deformability element	$0.00 < DT \leq 0.15$
Medium deformability element	$0.15 < DT \leq 0.50$
High deformability element	$DT > 0.50$
Note: 1 in. = 25.4 mm	

from finite element analysis of a database of diaphragm systems under a range of seismic loading.[5] Alternative deformation limits can be used if supporting data are provided.

The tension force capacity of the connection is defined as the maximum force P_2 for deformation-controlled connections and as P_1 for force-controlled connections.

The intention is for the diaphragm system to remain elastic in shear. Thus inelastic shear force capacity of connections is neglected. Shear force capacity is taken as P_1 for all connections. Limits are placed on the allowable deformation at which the force capacity can be determined:

- If the shear deformation Δ_1 is less than 0.25 in. (6.4 mm), the shear force capacity is taken as the yield force P_1.
- If the shear deformation Δ_1 is greater than 0.25 in. (6.4 mm), the shear force capacity is taken as the force at 0.25 in. This shear force capacity can be computed as the stiffness K_e multiplied by 0.25 in.

Multiple tests Multiple tests for shear and tension are recommended. The performance rating of the connector should be based on the five percent fractile, which provides a 90% confidence that there is a 95% probability that the actual performance will exceed the value. The determination of the five percent fractile value depends on the sample size, sample mean, and sample standard deviation. [15]

Test report

The test report should be sufficiently complete for a qualified expert to be satisfied that the tests have been designed and conducted in accordance with the criteria previously described and that the results satisfy the intent of these provisions. As a minimum, all of the following information should be provided:

- Details of test module design and construction, including engineering drawings.
- Description of test setup, including diagrams and photographs.
- Description of instrumentation, location, and purpose.
- Description and graphical presentation of applied loading procedure.
- Compressive strength of the concrete measured in accordance with ASTM C39.[21] (Note: the mean of at least three replicate cylinder strengths should be used. These tests should be conducted within 7 days of the connection tests or interpolated from compressive strength tests conducted before and after the connection test series.)
- Material properties of the connector, slug, and weld metal based on material testing or mill certification. (Note: as a minimum, the yield stress, tensile stress, and ultimate strain should be reported.)
- Description of observed performance, including photographs, of test module condition at key loading cycles.
- Graphical presentation of force versus deformation response.
- The envelope and backbone of the load-deformation response.
- Yield strength, peak strength, deformation capacity, and connection category.
- Test data, report data, name of testing agency, report author(s), supervising professional engineer, and test sponsor.

All connections should be installed and welded in accordance with the manufacturer's published installation instructions. The results of the data generated are limited to connections built to the specified requirements.

Summary

An evaluation method for precast concrete diaphragm connectors based on structural testing is provided. The recommendation provides a detailed procedure for determination of stiffness, deformation capacity, and force capacity. Details on developing a test module, loading setup, load histories, instrumentation, data reduction, reporting, and performance categorization are given. Adherence to the test method allows connection properties to be determined in a consistent manner so that existing and new connections can be quantified and used effectively in the diaphragm system.

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Notation

F_1 = axial force read from actuator 1

F_2 = axial force read from actuator 2

F_t = axial force resisted by connections

K_e = initial elastic stiffness of multisegment backbone curve

P = force

P_1 = force at point 1 on multisegment backbone curve

P_2 = force at point 2 on multisegment backbone curve

P_{2a} = force at point 2a on multisegment backbone curve

P_3 = force at point 3 on multisegment backbone curve

P_a = force at point a on multisegment backbone curve

P_b = force at point b on multisegment backbone curve

P_{max} = force at yield point on multisegment backbone curve

T_{max} = force at point 3 on multisegment backbone curve

V_{max} = maximum shear force

δ_t = tension displacement

δ_v = shear displacement

Δ = reference deformation

Δ_1 = deformation at point 1 on multisegment backbone curve

Δ_2 = deformation at point 2 on multisegment backbone curve

Δ_{2a} = deformation at point 2a on multisegment backbone curve

Δ_3 = deformation at point 3 on multisegment backbone curve

Δ_a = deformation at point a on multisegment backbone curve

Δ_b = deformation at point b on multisegment backbone curve

ΔT = tension deformation measured across connector

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Abstract

This paper describes an experimental approach for assessing the stiffness, strength, and deformation capacity of embedded connections in conventional precast concrete floor systems. It summarizes the test fixtures and equipment, testing procedures, and data processing. Connectors are categorized by their deformation capacity using three in-plane deformation ranges: low-deformation element, moderate-deformation element, and high-deformation element. The paper also discusses a method for computing the design strength based on the test results.

Keywords

Acceptance criteria, connection category, experimental approach, precast concrete diaphragm connector, test method.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

Reader comments

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