Connection Materials and Testing Procedures

<course title>

<professor name>

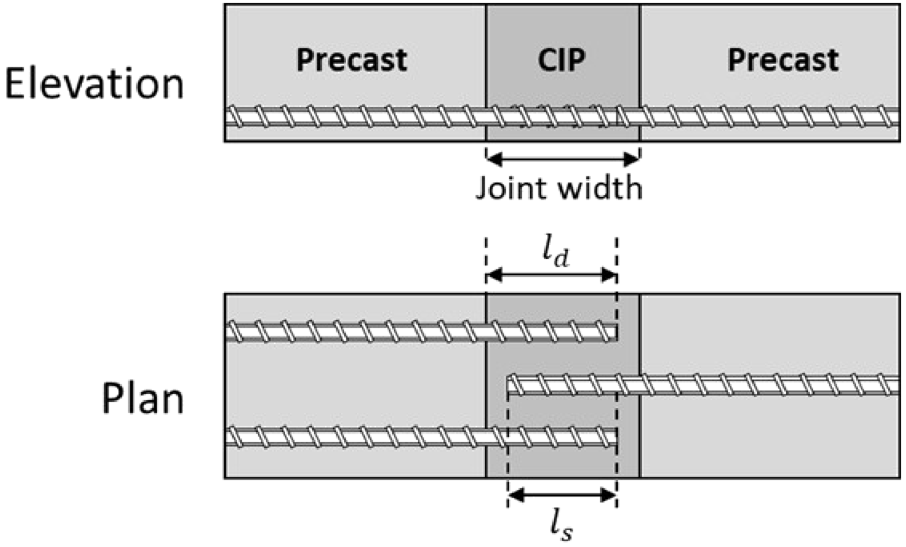
Learning Objectives

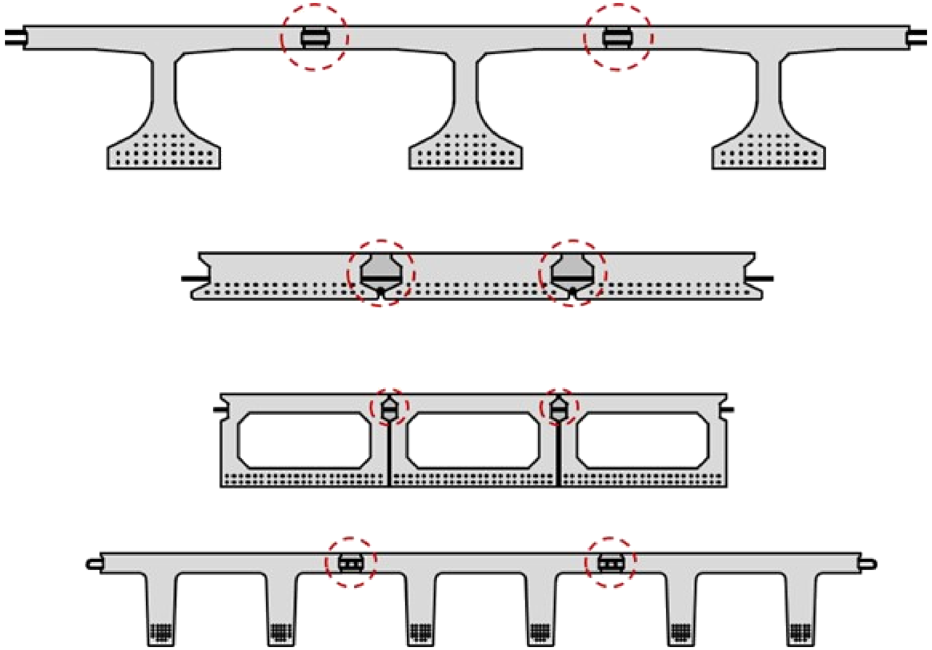
- *Describe* desirable material characteristics for joints and connections between precast elements
- *List* the typical materials used in joints and *identify* key properties for each
- *Explain* significant material tests used to measure the important characteristics for joint materials

Desirable Materials Characteristics (1)

There are several different materials that are commonly used in joints. Some of the generally desirable characteristics for these cast-in-place (CIP) connection materials include:

- **Decreased development/splice length (high tensile strength)**: Reinforcement typically extends from one or both adjacent precast elements. Materials are used to fill in a closure pour region or joint to splice reinforcement together. A high tensile strength in the material will typically result in shorter development/splice lengths, which allows for smaller closure pour regions and less CIP material required.



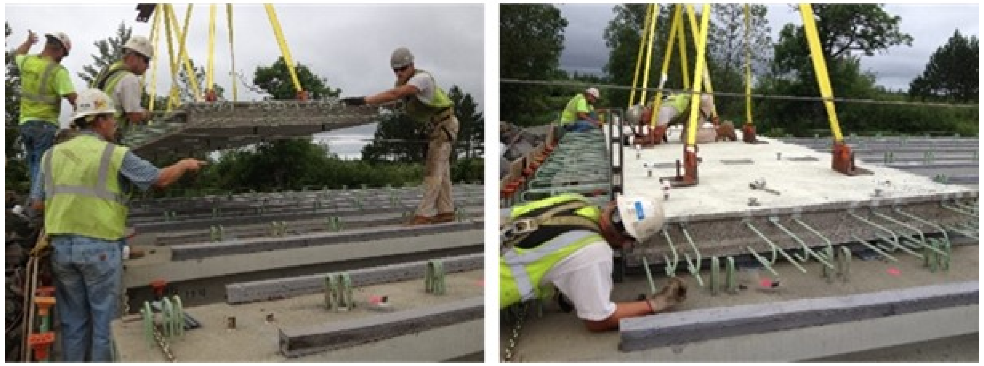


Desirable Materials Characteristics (2)

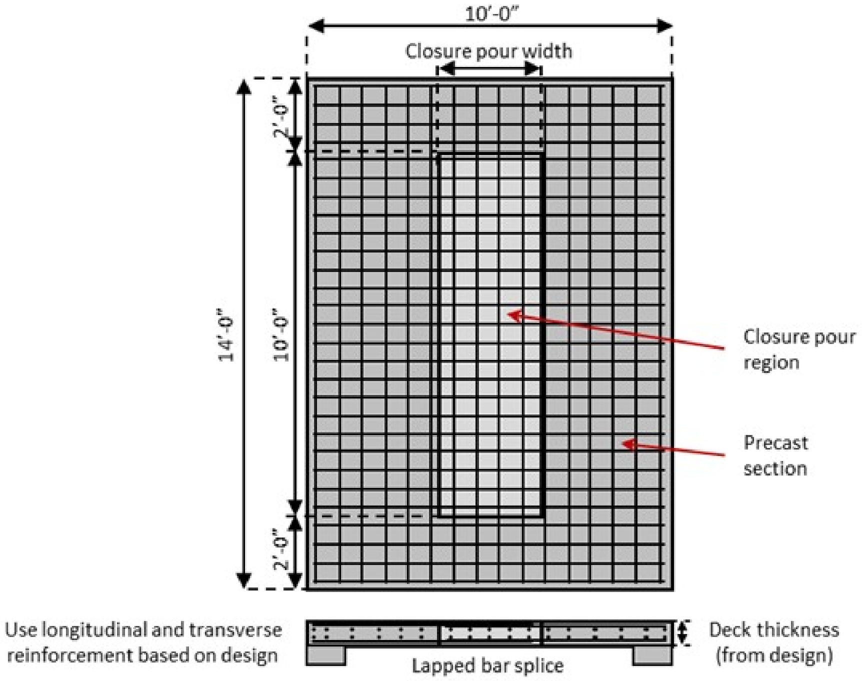
(list continued from last slide)

- **Smaller amount of shrinkage**: Precast elements are typically cast months before construction in the field. CIP materials should have less shrinkage than typical materials to prevent shrinkage cracks from developing in the closure pour regions. Proper curing of CIP materials is also essential to help prevent/limit shrinkage cracking.

FDPC deck panels



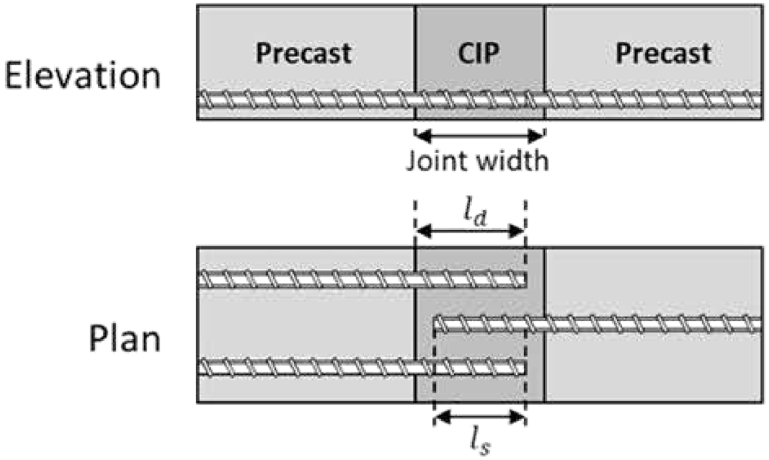
TH 53 Bridge over Paleface River (2012, Minnesota)



Desirable Materials Characteristics (3)

(list continued from last slide)

- **High adhesive bonding / bond strength**: CIP materials are cast against the already dried precast element. CIP materials should have high adhesive bonding to prevent cracks from developing at the cold joint between the CIP material and precast element. The surface of the precast element can be intentionally roughened to improve this bond.



Graybeal (2017), "Bond of Field-Cast Grouts to Precast Concrete Elements."

Some have suggested lower stiffness may be beneficial as well, since a lower stiffness would help to ensure that less stress is attracted by the joints. However, the other properties listed above are considered to be more important.

Typical Materials (1)

Some materials that are commonly used for CIP connections include:

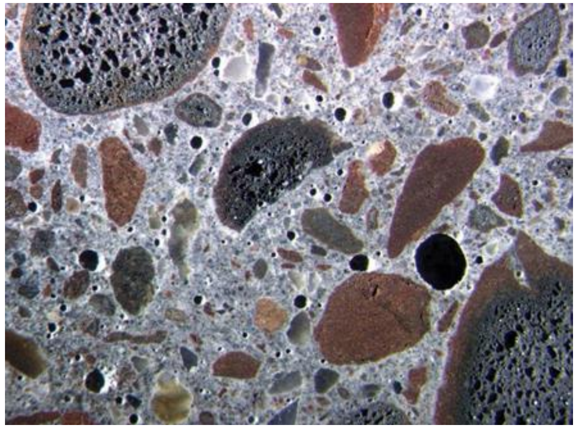
- Cementitious or epoxy grouts,
- Conventional concrete,
- Self-consolidating concrete,
- Lightweight concrete,
- Ultra-high performance concrete, and
- Polymer concrete

Cementitious Grout

Graybeal (2017), "Bond of Field-Cast Grouts to Precast Concrete Elements."

Epoxy Grout

http://e-chem.net/products/



Lightweight Concrete

https://www.structuremag.org/?p=1163

Self-Consolidating Concrete

https://www.selfconsolidatingconcrete.org/testing.html

Polymer Concrete

https://www.capitalconcretecuttinginc.com/understanding-polymer-concrete

Typical Materials (2)

Some of the important material properties for these materials are summarized in the following table:

Property	Cementitious Grout	Epoxy Grout	Conventional Concrete	UHPC	Polymer Concrete
Compressive Strength (ksi)	6 – 9	14	4 – 10	18 – 30	8 – 9
Modulus of Elasticity (ksi)	2,400 – 3,200	3,400	4,000 – 5,500	4,000 – 8,000	1,110 – 1,200
Split Cylinder (ksi)	0.5 – 0.7	2.1	0.3 – 0.6	1.4 – 3.0	1.8 – 2.5
Bond Strength (ksi)	0.25 – 0.4	0.5	0.15 – 0.4	0.35 – 0.6	> 0.25

Typical Materials (3)

- The cost of grout, UHPC, and polymer concrete materials will be significantly higher than conventional concrete and may require specialty contractors to help with field placement
- The high cost of these materials makes smaller joints between elements necessary to use the material most effectively
- Many states prefer conventional concrete connections due to the lower cost of conventional concrete and the familiarity of contractors working with conventional concrete
- More details on these materials can be found in the following references:
  - ABC-UTC Guide for Full-Depth Precast Concrete (FDPC) Deck Panels
  - Graybeal. (2013). “Material Characterization of Field-Cast Connection Grouts.”
  - Haber, Varga, Graybeal, Nakashorji, El-Helou. (2018). Properties and Behavior of UHPC-Class Materials. FHWA-HRT-18-036.

Grout Materials

- **Cementitious Grouts:** Hardened properties are the product of the hydration reaction of cementitious materials. These are the most typical and lowest cost grout materials.
- **Epoxy Grouts:** Epoxy (resin and hardener) is used to bond aggregate powder to create desired hardened properties. These are typically the most expensive grout materials.
- Grouts using other cementitious materials, such as magnesium phosphate are available. Magnesium phosphate grout exhibits rapid setting characteristics, but is more expensive than typical cementitious grout.
- Grouts are typically prebagged materials mixed with a manufacturer specified amount of water or pre-packaged liquid component.
- Grouts used for connections are often classified as “non-shrink” grout, but shrinkage performance can vary based on specific materials and conditions, and some grouts are designed for expansion.

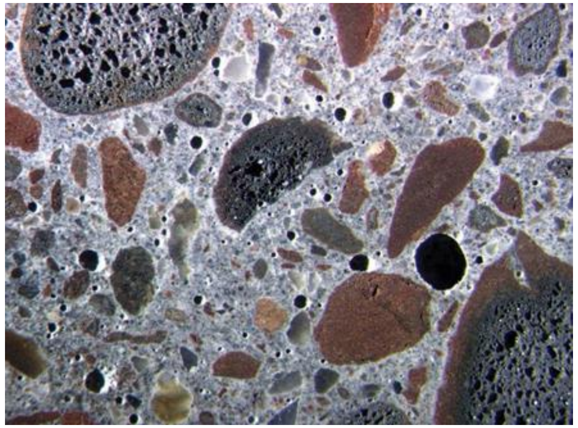
Self-Consolidating Concrete

- Self-consolidating concrete is similar to conventional concrete but has high flowability, consolidates under its own weight (no vibration needed), and has a high resistance to segregation.
- Self-consolidating concrete can be designed using a well proportioned cementitious material and aggregate matrix combined with high range water reducing admixtures, or by using high range water reducing and viscosity modifying admixtures.
- High flowability reduces time and labor required for placement, noise from concrete vibrators, and creates self-leveling behavior.

Self-Consolidating Concrete
https://www.selfconsolidatingconcrete.org/testing.html

Lightweight Concrete

- Lightweight concrete is defined by AASHTO LRFD as "concrete containing lightweight aggregate conforming to AASHTO M 195 and having an equilibrium density not exceeding 0.135 kcf, as determined by ASTM C567."
- Typical aggregates used for lightweight concrete include expanded shale, clay, or slate and should be presoaked due to high absorption capacity.
- Lightweight concrete properties are similar to conventional concrete.
  - Maximum compressive strength is typically controlled by the aggregate.
  - Modulus of elasticity is typically less than for conventional concrete.
  - A modification factor is required for many design equations.
- Internal curing from water absorbed in the lightweight aggregates has been shown to decrease concrete shrinkage and improve concrete performance.



Lightweight Concrete
https://www.structuremag.org/?p=1163

Ultra-High Performance Concrete (UHPC)

- FHWA Definition:
  - UHPC is a cementitious composite material composed of an optimized gradation of granular constituents, a water-to-cementitious materials ratio less than 0.25, and a high percentage of discontinuous internal fiber reinforcement.
  - The mechanical properties of UHPC include compressive strength greater than 21.7 ksi (150 MPa) and sustained post-cracking tensile strength greater than 0.72 ksi (5 MPa).
  - UHPC has a discontinuous pore structure that reduces liquid ingress, significantly enhancing durability compared to conventional and high performance concretes.
- Typical properties of UHPC class materials:
  - Compressive strength of 18 – 30 ksi.
  - Post-cracking tensile strength of 0.70 – 0.90 ksi.
  - High flowability and excellent durability.
  - Discontinuous fiber reinforcement, typically steel.

ABC UTC

Polymer Concrete

- Polymer concrete is a composite material utilizing a polymer binder instead of cementitious materials to bind aggregates together.
- Polymer concrete materials have high early strength, high tensile strength relative to the compressive strength, high shear strength, and high bond strength to base concrete materials and reinforcement.
- It is widely available due to frequent use as a bridge deck overlay material.

Polymer Concrete
https://www.capitalconcretecuttinginc.com/understanding-polymer-concrete

Procedures for Measuring Material Properties

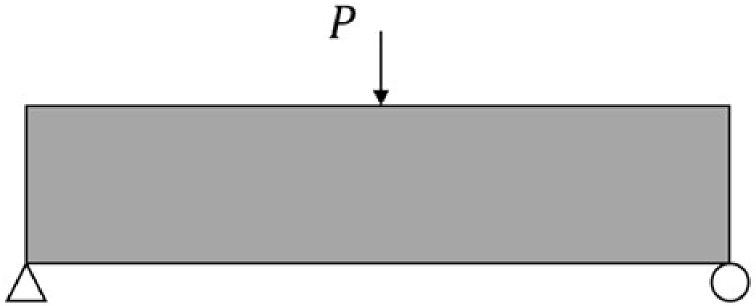
- As mentioned, the compression strength is not the most important property for CIP connection materials; high tensile strength, decreased development length, smaller amounts of shrinkage, and high adhesive bonding are all desirable characteristics

- There are several different tests that can be used to determine some of these relevant material properties

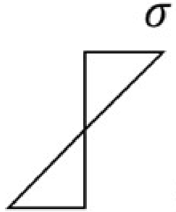
- The three primary tests for determining the tensile strength of concrete are:
    1. Modulus of rupture,
    2. Split cylinder, and
    3. Direct tension

Procedures – Modulus of Rupture

- The modulus of rupture test basically measures the tensile capacity of concrete when it is failed in flexure.
- The test is typically a 3-point (ASTM C293) or 4-point-load (ASTM C78) beam test run on 6-inch square specimens. By measuring the load applied, the rupture strength of the concrete can be calculated using simple mechanics.



$$M = \frac{PL}{4}$$

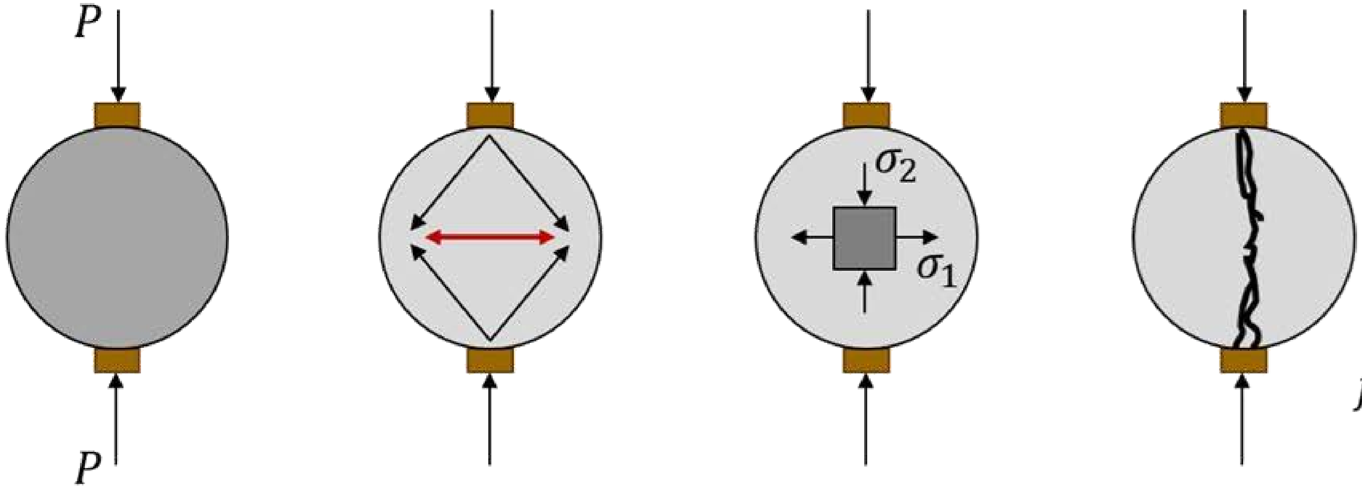


$$f_r = \frac{My}{I} = \frac{6M}{bh^2} = \frac{3PL}{2bh^2}$$

The rupture strength of concrete will typically be around $7.5\sqrt{f'_c}$

Procedures – Split Cylinder Strength

A split cylinder test is run on the same 4-inch by 8-inch cylinders used for standard compressive tests. The load is applied using two wood strips on each side of the cylinder.



$$f_{ct} = \frac{2P}{\pi l d}$$

- ASTM C496 specified procedure to determine the concrete tensile strength using a standard concrete cylinder tested on its side
- Splitting tensile strength of concrete will typically be around $6\sqrt{f'_c}$

Procedures – Modifications for UHPC

- The high strength of UHPC and fiber reinforcement requires modifications to typical testing methods which are covered by ASTM C1856.
- Compressive strength should be tested on 3 in. x 6 in. cylinders that must be ground plane. The load rate is increased to 150 psi/s.
- Flexural strength should be determined using methods of ASTM C1609 with specimen dimensions based on fiber length.

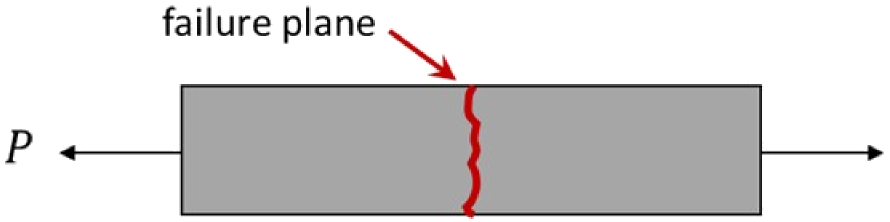
TABLE 3 Dimensions of Beams for Measuring Flexural Strength

Maximum Fiber Length (l_f)	Nominal Prism Cross Section
< 15 mm [0.60 in.]	75 mm by 75 mm [3 in. by 3 in.]
15 mm to 20 mm [0.60 in. to 0.80 in.]	100 mm by 100 mm [4 in. by 4 in.]
20 mm to 25 mm [0.80 to 1.00 in.]	150 mm by 150 mm [6 in. by 6 in]
>25 mm [1.00 in.]	200 mm by 200 mm [8 in. by 8 in.]

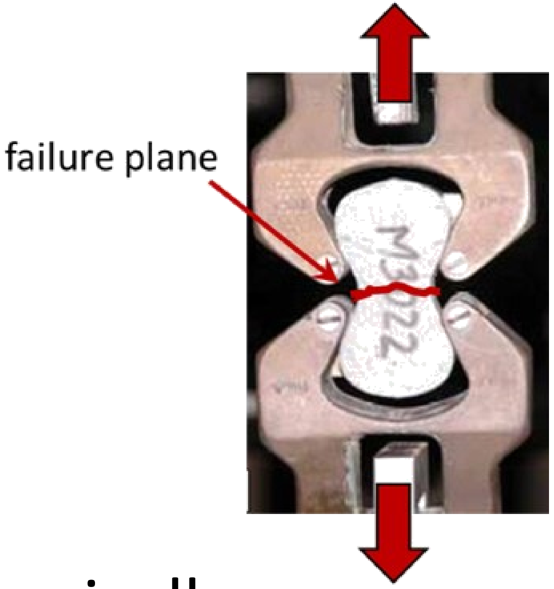
Table from ASTM C1856

Procedures – Direct Tension Test (General)

The tensile strength of concrete can be measured by applying a direct tensile force in the concrete. The direct tensile strength is typically measured on 6-inch square prisms.



$$f_t = \frac{P}{bh}$$

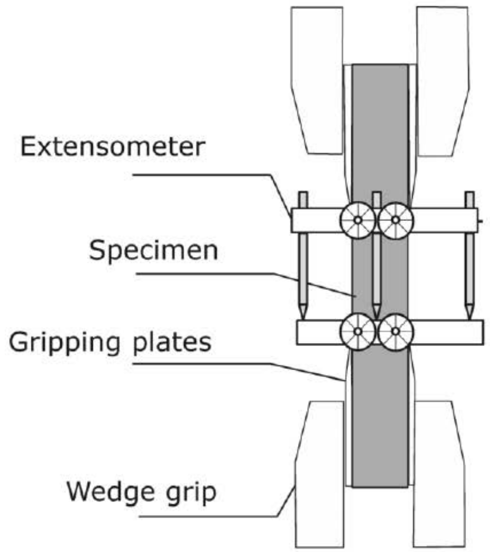


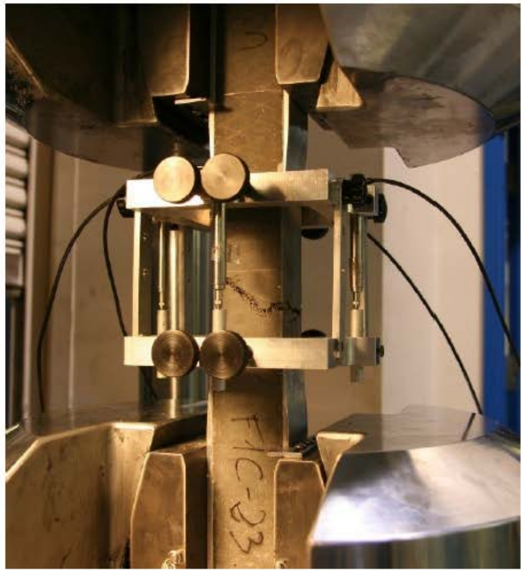
The direct tensile strength of concrete will typically be around $4\sqrt{f'_c}$

Photo from FHWA-HRT-06-103

Procedures – Direct Tension Test for UHPC (1)

- The tensile strength of ultra-high performance concrete (UHPC) is much higher than conventional materials (due to its steel fiber content and high compressive strengths).
- Direct tension tests on 2-inch by 2-inch by 17-inch prisms are typically recommended to capture the true tensile behavior of UHPC (1-inch by 1-inch prisms have also been used).

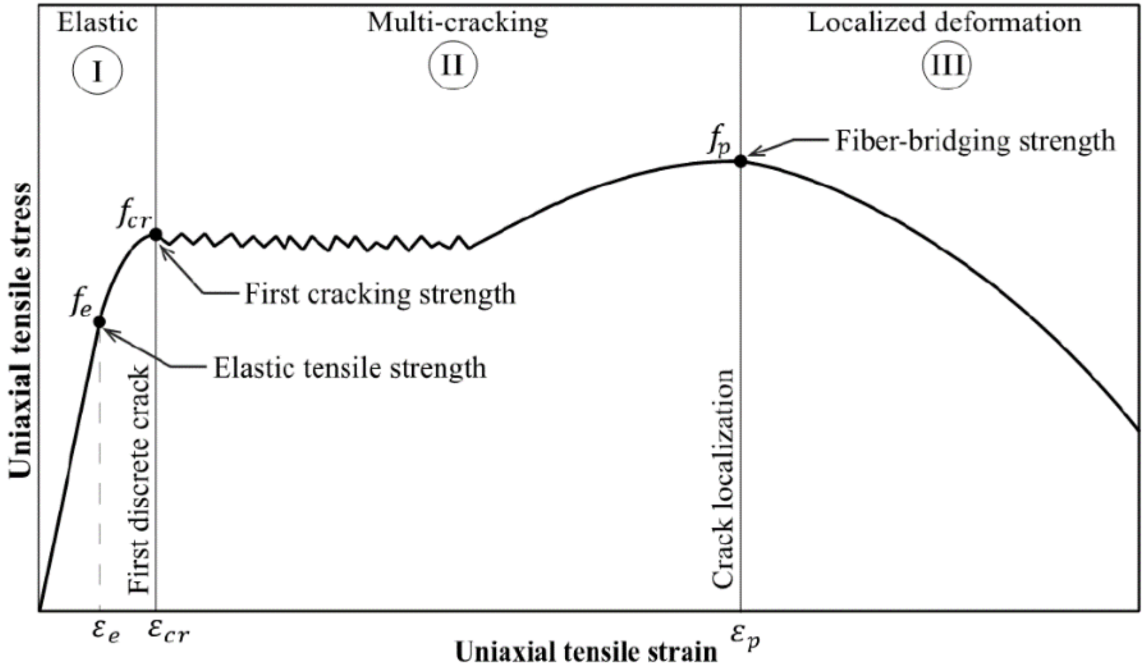




Haber, Varga, Graybeal, Nakashorji, El-Helou. (2018). Properties and Behavior of UHPC-Class Materials. FHWA-HRT-18-036

Procedures – Direct Tension Test for UHPC (2)

UHPC will typically have a post-cracking plasticity and tension hardening response (like steel); this is possible because of the steel fibers.



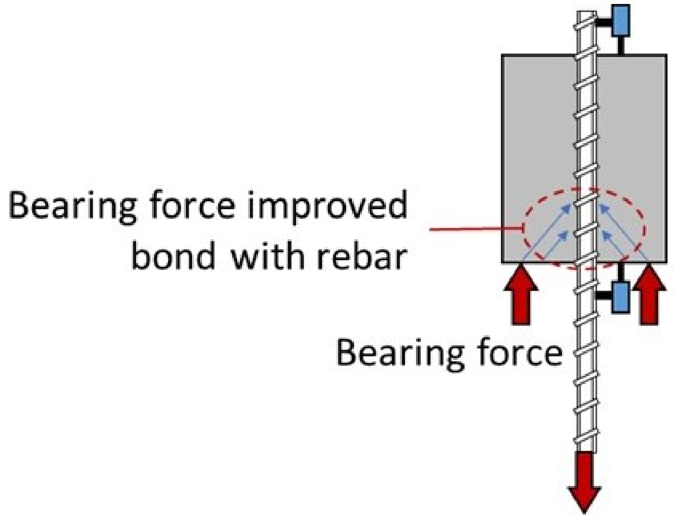
This post-cracking response is not necessarily essential for joints, but it does help to improve the ductility of joints.

Haber, Varga, Graybeal, Nakashorji, El-Helou. (2018). Properties and Behavior of UHPC-Class Materials. FHWA-HRT-18-036

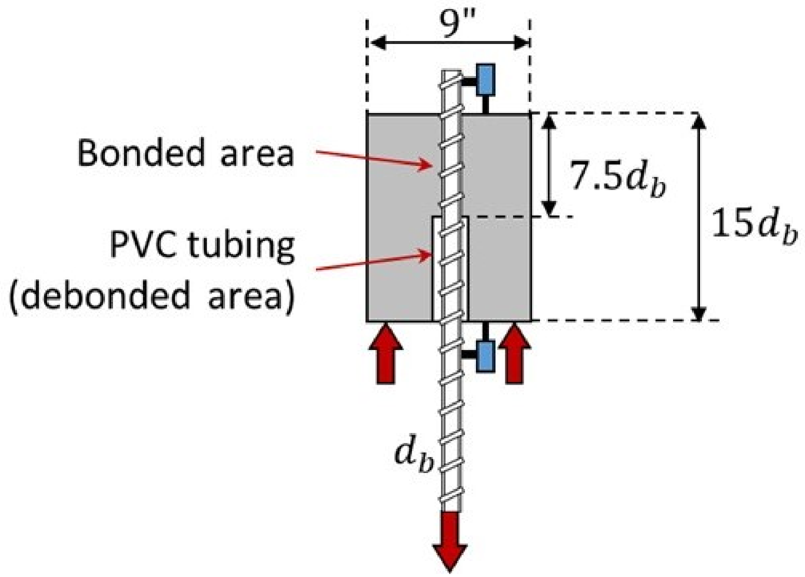
Procedures – Direct Pullout for Rebar (1)

- A direct pullout test bond test has an individual rebar embedded in a concrete cylinder or prism with a certain portion of the bar debonded on the side where the bar is being pulled out.
- Debonding of the bar helps to eliminate confinement benefits that would otherwise be experienced near where the bar is being pulled out.

Test if no debonding



Test with debonding



(test shown based on RILEM 2004 RC5)

Procedures – Direct Pullout for Rebar (2)

Many connections depend on the direct embedment of a bar extending from a precast element into a pocket or sleeve in a separate precast element. Direct pullout tests would test this type of connection.

Pocket connection between cast-in-steel-shell (CISS) piles and CIP abutment caps
(Craig Creek Bridge)

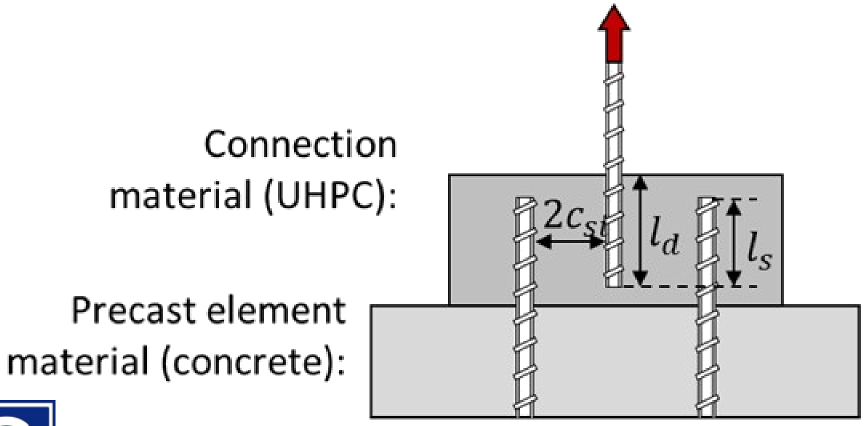
Pocket connection between precast piles and precast pile caps
(I-10 Bridge over Escambria Bay)

Photos from ABC Project Database

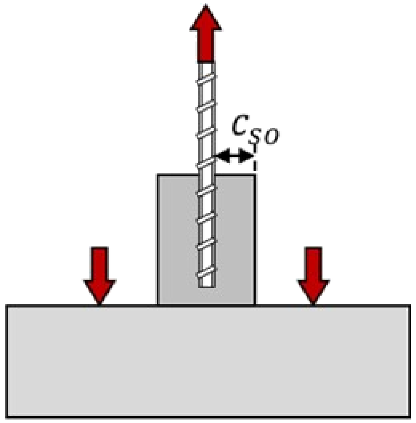
Procedures – Direct Pullout for Rebar (3)

A spliced pullout test requires:

- A series of bars extending from a concrete element (typically a slab or large concrete block) that represents one precast element.
- A strip of connection material cast on top of the slab or concrete block that splices two bars extending from the block with one bar extending from the strip of connection material.



Elevation

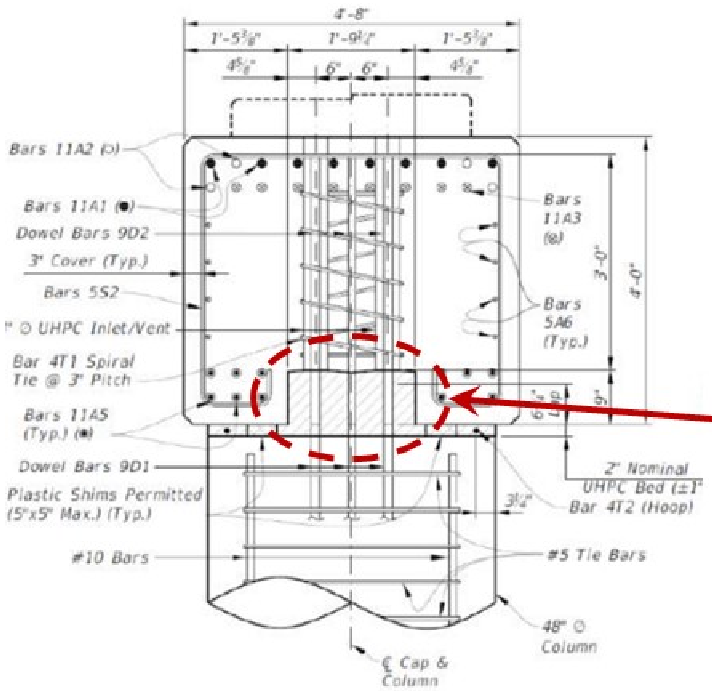


Cross Section

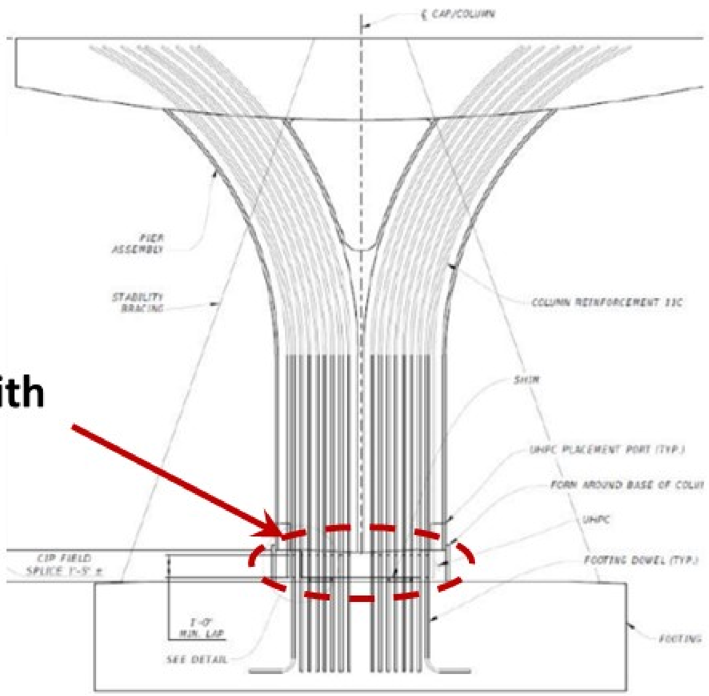
The embedment length of the spliced bar (l_d), splice length between bars (l_s), distance between spliced bars ($2c_{si}$), and side cover distance (c_{so}) can all be varied in this test to match actual connection details if needed.

Procedures – Direct Pullout for Rebar (4)

This type of behavior would typically occur when splicing together large bars extending from multiple precast substructure elements. Two examples of these are shown below:



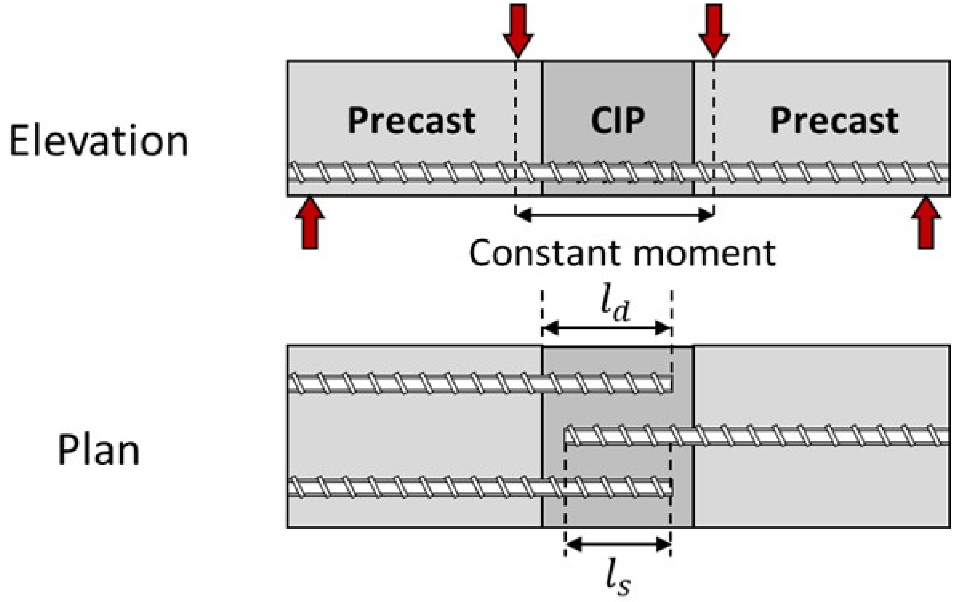
Large-bar splices with direct tension



Freeman. (2018). "Large Bars Spliced in UHPC." 2018 FDOT Structures Research Update.

Procedures – Flexure Splice Test for Rebar (1)

- A flexure splice test for connections is a beam made up of two precast portions and a cast-in-place (CIP) closure pour region.
- Sufficient development occurs if the bar ruptures before it pulls out of the concrete; sometimes tests are also considered successful if the bar develops at least its yield strength.

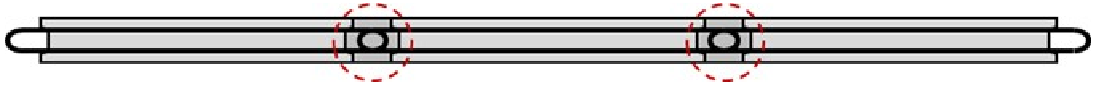


See for more details: Ramirez and Russell. (2008). Transfer, Development, and Splice Length for Strand/Reinforcement in High-Strength Concrete. NCHRP Report 603.

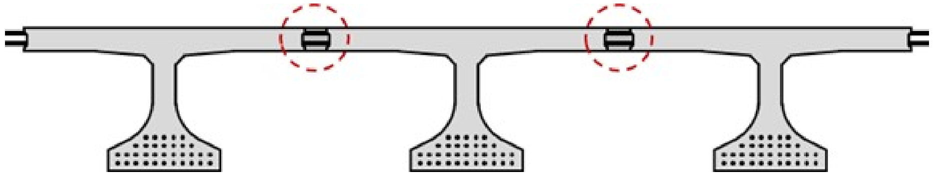
Procedures – Flexure Splice Test for Rebar (2)

This type of test would be most appropriate for determining the behavior of connections that are controlled by flexural stresses and shear stresses in the interface, e.g., superstructure elements including:

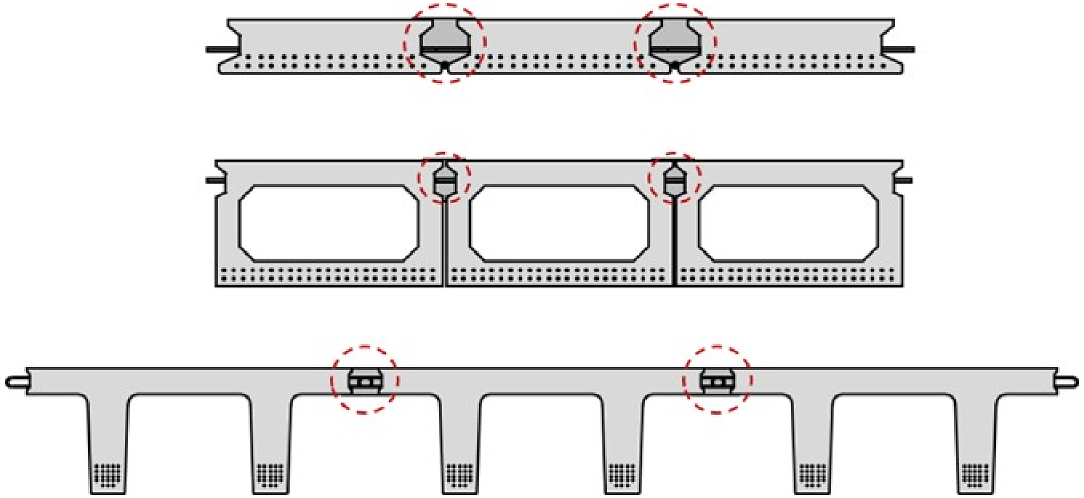
1. Between FDPC deck panels



2. Between decked beams

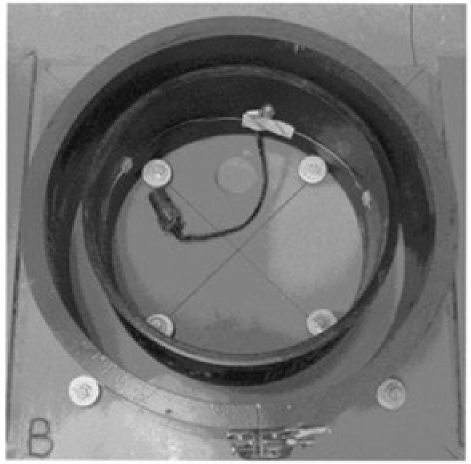


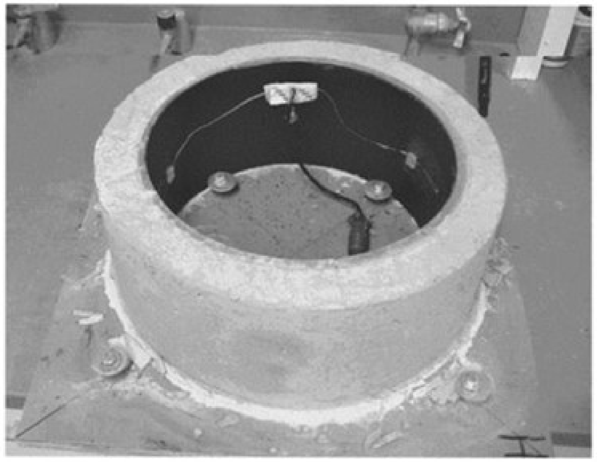
3. Between adjacent slab/box beams

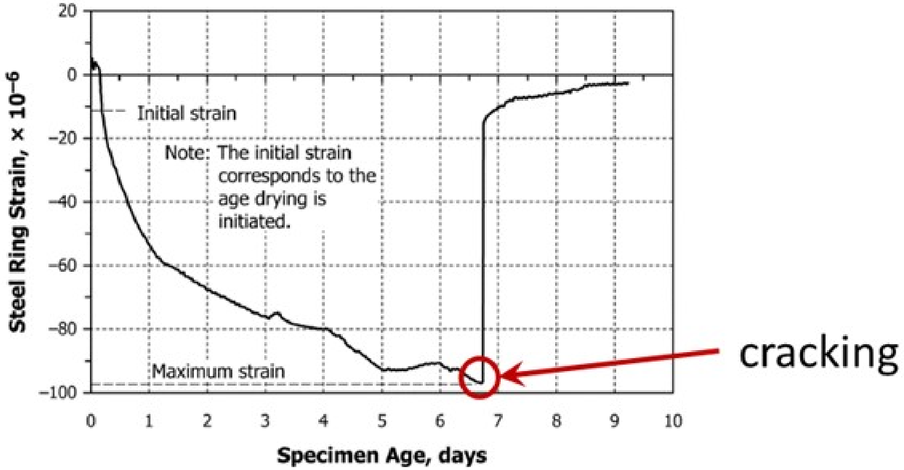


Procedures – Shrinkage/Restrained Shrinkage (1)

- In addition to the standard ASTM shrinkage test (ASTM C157), a restrained shrinkage test (ASTM C1581, AASHTO T334 or similar) can be used to determine if cracking will develop due to shrinkage of the joint material.
- Restrained shrinkage tests are recommended throughout the AASHTO Guide Specification for ABC.
- ASTM C1581 involves casting a concrete ring around a steel ring and plotting steel ring strain versus time. The AASHTO Guide Specification for ABC gives acceptance criteria for some materials, e.g., non-shrink grout shall exhibit no cracking in 4 days using the ASTM C1581 test.



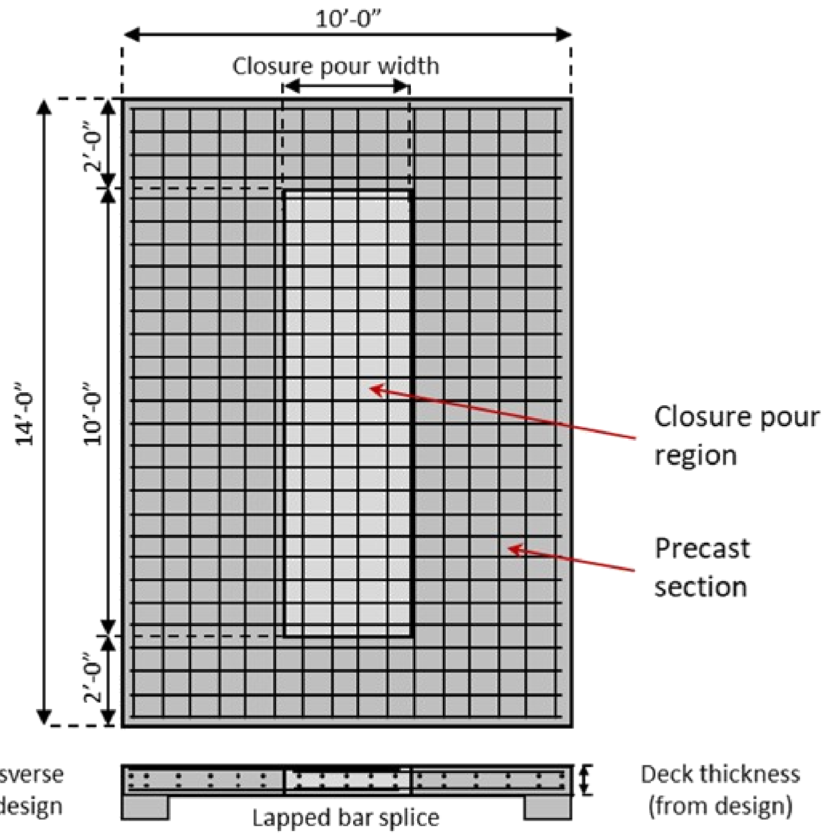




Procedures – Shrinkage/Restrained Shrinkage (2)

A full-scale restrained shrinkage test can also be conducted by creating specimen with a similar size and shape to the connection that will be cast.

Recommended shape by AASHTO LRFD Guide specification for ABC:



The precast section should be cast enough time before casting of the closure pour to allow for shrinkage to occur; the age of the precast portion at time of closure pour casting can also be selected based on the expected age of precast components at time of closure pour casting for the actual structure.

Procedures – Shrinkage/Restrained Shrinkage (3)

- The stated acceptance criteria are listed below:
  - The trial placement concrete shall not exhibit cracking or separation from the adjacent element in excess of 0.10 inches wide.
  - There shall be no more than one visible transverse crack per 10 feet of joint length. A visible crack is defined as a crack between 0.010 and 0.16 inches wide.
  - The evaluation of the trial placement shall take place 14 days after placement.
- The contractor will need to submit a corrective action plan on how to prevent the cracks and/or repair the cracks if the trial fails one of these criteria.

Procedures – Bond Strength (1)

- All bond strength tests require casting and curing of a precast portion of the test specimen before casting of the connection material.
- Two of the primary ways to test the bond strength of a CIP material against precast concrete are the flexural beam bond test based on ASTM C 78 and direct tension bond pull-off test using ASTM C1583.

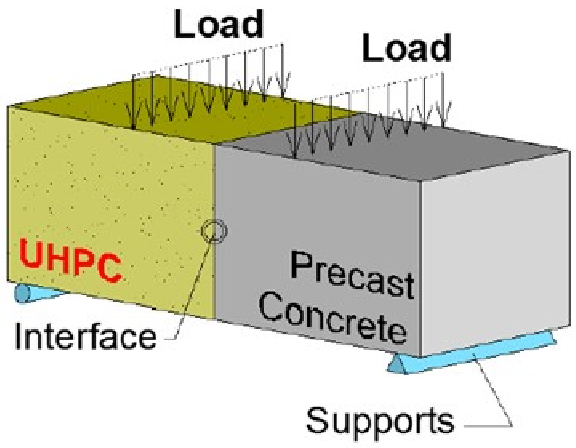


Figure 102. Illustration. Flexural beam bond test based on ASTM C78.

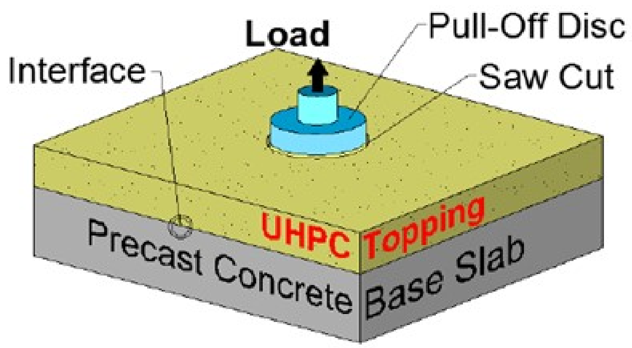
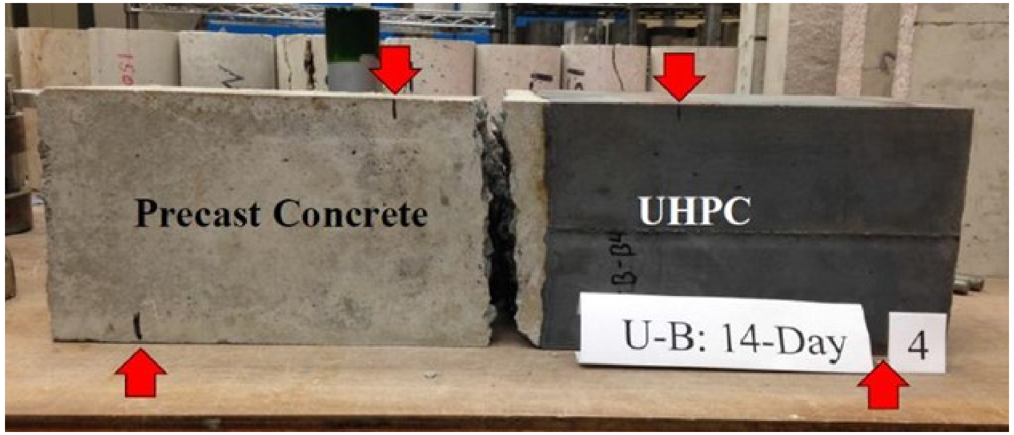


Figure 103. Illustration. Direct tension bond pull-off test based on ASTM C1583.

Haber, Varga, Graybeal, Nakashorji, El-Helou. (2018). Properties and Behavior of UHPC-Class Materials. FHWA-HRT-18-036

Procedures – Bond Strength (2)

- Failure in the flexural beam or pull-off test can be in the precast material, connection material, or at the interface.
- Failure of the flexural beam or pull-off test should be in the precast concrete material; this result would mean the bond strength of the connection material to the precast element and the tensile strength of the connection material itself are both greater than the tensile strength of the precast element.



Interface/bond failure

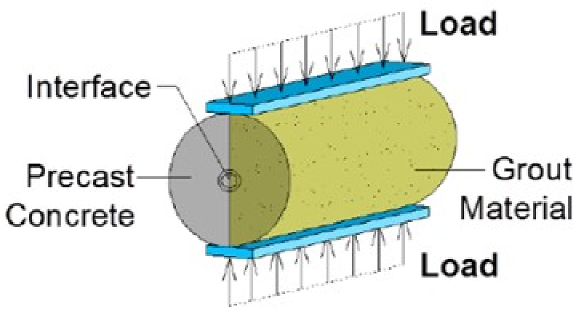
Substrate failure

Haber, Varga, Graybeal, Nakashorji, El-Helou. (2018). Properties and Behavior of UHPC-Class Materials. FHWA-HRT-18-036

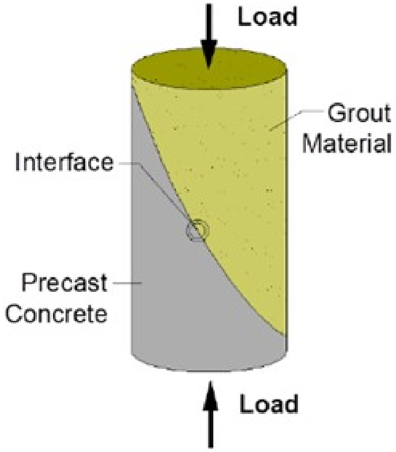
Procedures – Bond Strength (3)

- Two other tests that can be used are a modified split cylinder test and slant-shear compression test based on ASTM C882.
- Similar to flexure beam bond and direct tension bond, a good joint material will lead to failure in the precast concrete material and not at the interface or in the connection material for modified split cylinder bond and slant shear tests.
- Slant shear tests are different than the other tests described in this section because a normal force is applied across the interface.

Modified Split Cylinder



Slant Shear



Haber, Varga, Graybeal, Nakashorji, El-Helou. (2018). Properties and Behavior of UHPC-Class Materials. FHWA-HRT-18-036

Questions?

<course title>

<professor name>