# Cyclic and Strength Performance of Slab-Beam Superstructure System with UHPC Closure Pour

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# Outline

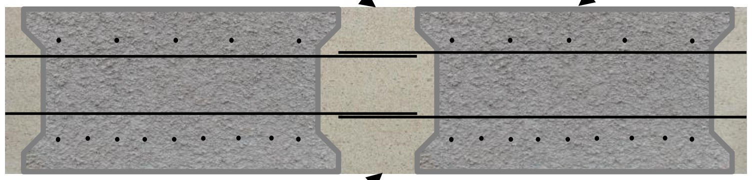
- Background
  - Slab Beams
  - Florida Slab Beam (FSB)
  - Ultra-High-Performance Concrete (UHPC)
- Research Objectives
- Joint and Section Development
- Joint Testing
- Full-Scale Beam Testing
- Implementation

# Background

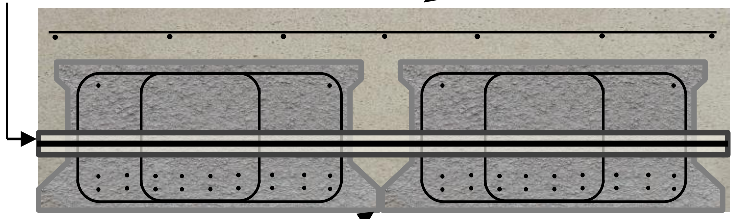
- Slab Beams

Slab beams have been used in construction since prestressing began in the US

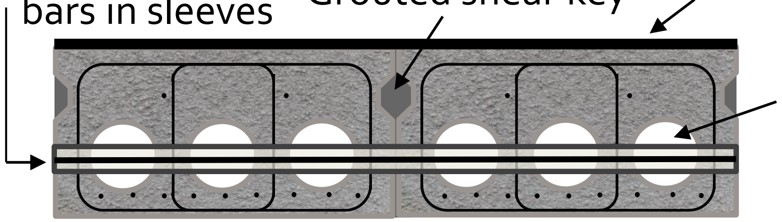
**Prestressed Rectangular Slab Units (1955)**



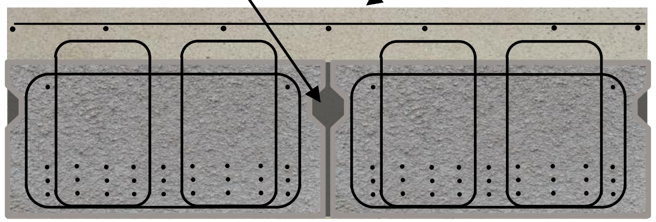

**Prestressed Keyed Slab Units (1958)**




**Prestressed Voided Slab Units – Sonovoids (1959)**



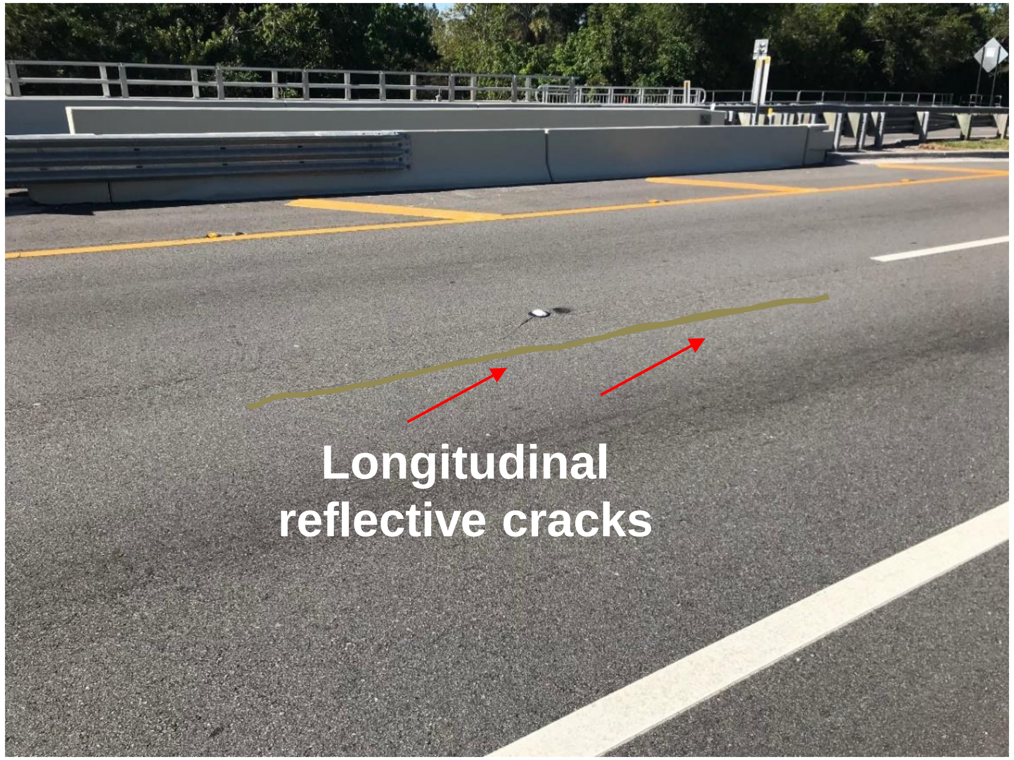

**Prestressed Slab Units – PSU (2008)**

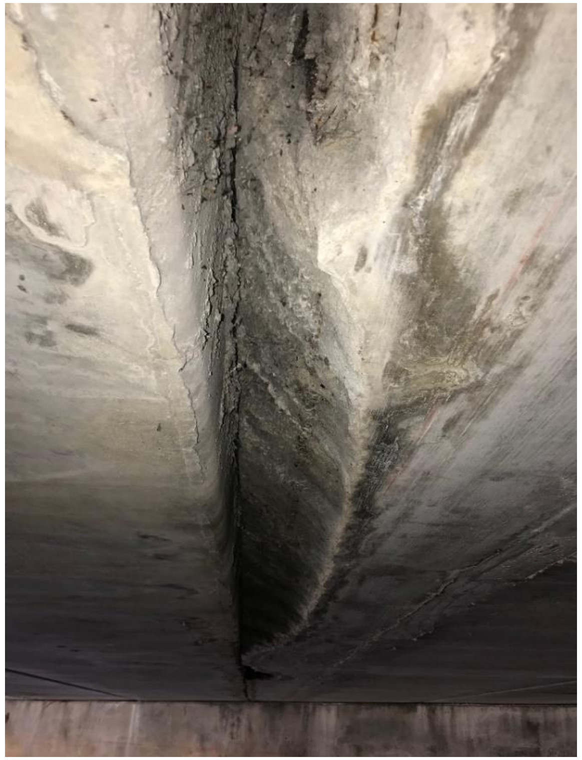


# Background

- Slab Beams – Performance

There have been some issues observed with previously used slab beams



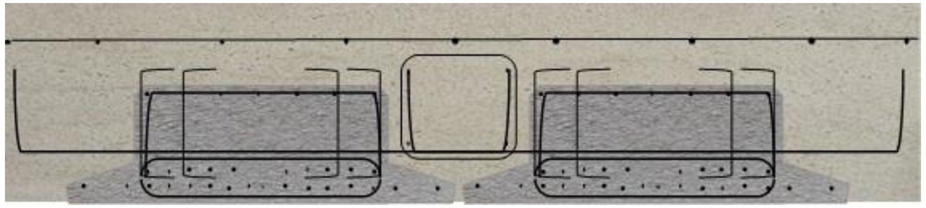
Bridge over Danforth Creek near West Palm Beach, FL (Spring 2018)

# Background

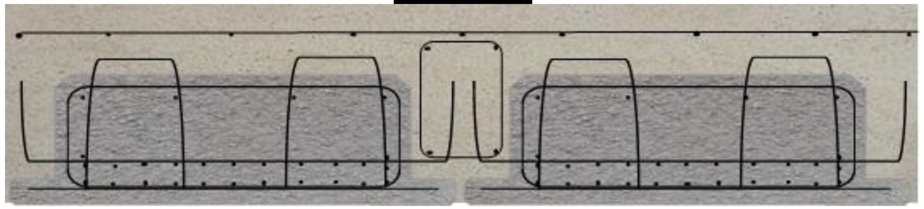
- Slab Beams

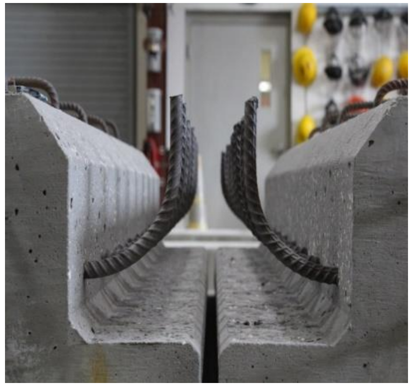
Poor performance of previous systems led to development of alternate systems

**Precast Composite Slab Span System – PCSS (2005)**



**Florida Slab Beam – FSB (2015)**





These systems require field placement of large reinforcement

# Background

- Ultra-High-Performance Concrete (UHPC)

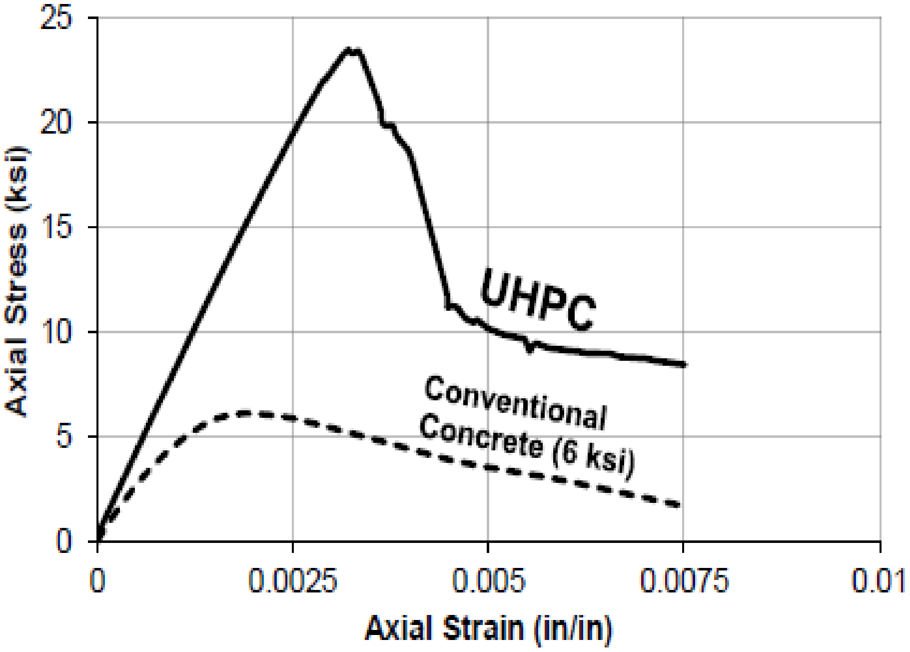
| ***Property*** | ***Range*** | |
|---|---|---|
| Compressive Strength ($f'_c$) | 20 to 30 ksi | 140 to 200 MPa |
| Tensile Cracking Strength ($f_r$) | 0.9 to 1.5 ksi | 6 to 10 MPa |
| Modulus of Elasticity ($E_c$) | 6,000 to 10,000 ksi | 40 to 70 GPa |


Source: https://www.fhwa.dot.gov/research/resources/uhpc/

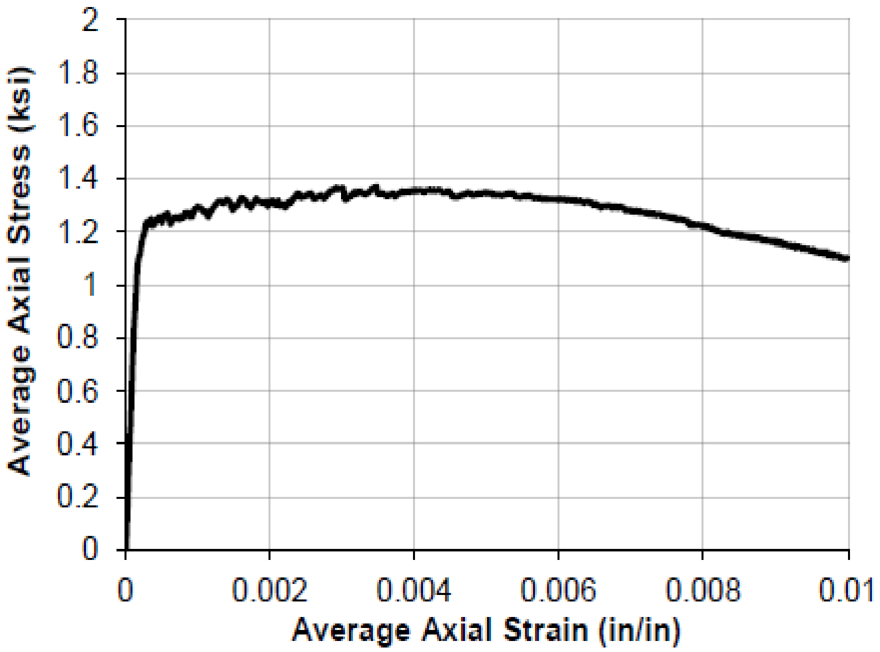
# Background

- Ultra-High-Performance Concrete (UHPC)

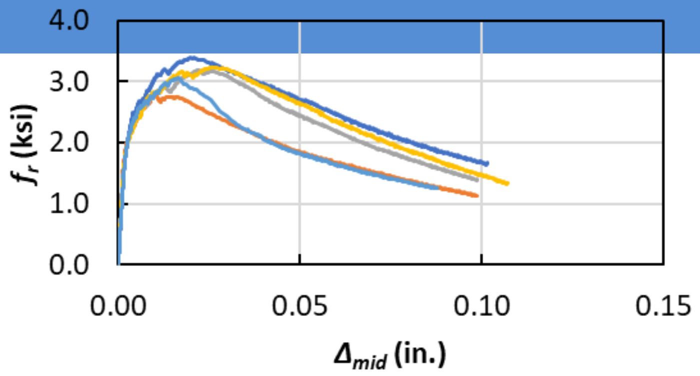
**Typical (a) Compressive and (b) Tensile UHPC Behavior (Haber, 2016)**




(a)




(b)




**Measured Compressive and Tensile UHPC Strengths (FDOT)***

| UHPC Mixes | $f'_c$ (ksi) | $f'_r$ (ksi) |
|---|---|---|
| Batch 1 | 22.52 | 3.14 |
| Batch 2 | 24.99 | 3.44 |
| Batch 3 | 23.19 | 2.92 |
| Batch 4 | 24.14 | 3.23 |
| Batch 5 | 22.47 | 3.10 |

*Based on current project UHPC mix designs for large-scale specimens

# Background

- Ultra-High-Performance Concrete (UHPC)

**UHPC Overlays (Haber, 2016)**


**Precast, prestressed girders and waffle slab systems (source: FHWA)**

Source: https://highways.dot.gov/research/structures/ultra-high-performance-concrete/ultra-high-performance-concrete

# Research Objectives

- Develop cross-section and joint region detail for short- to medium-span bridges for use with accelerated construction
- Assess strength and fatigue performance of cross-section and joint
- Recommend fabrication procedures, on-site construction practices, and erection tolerances

# Joint Testing Program

- Test Specimens with Naming Convention

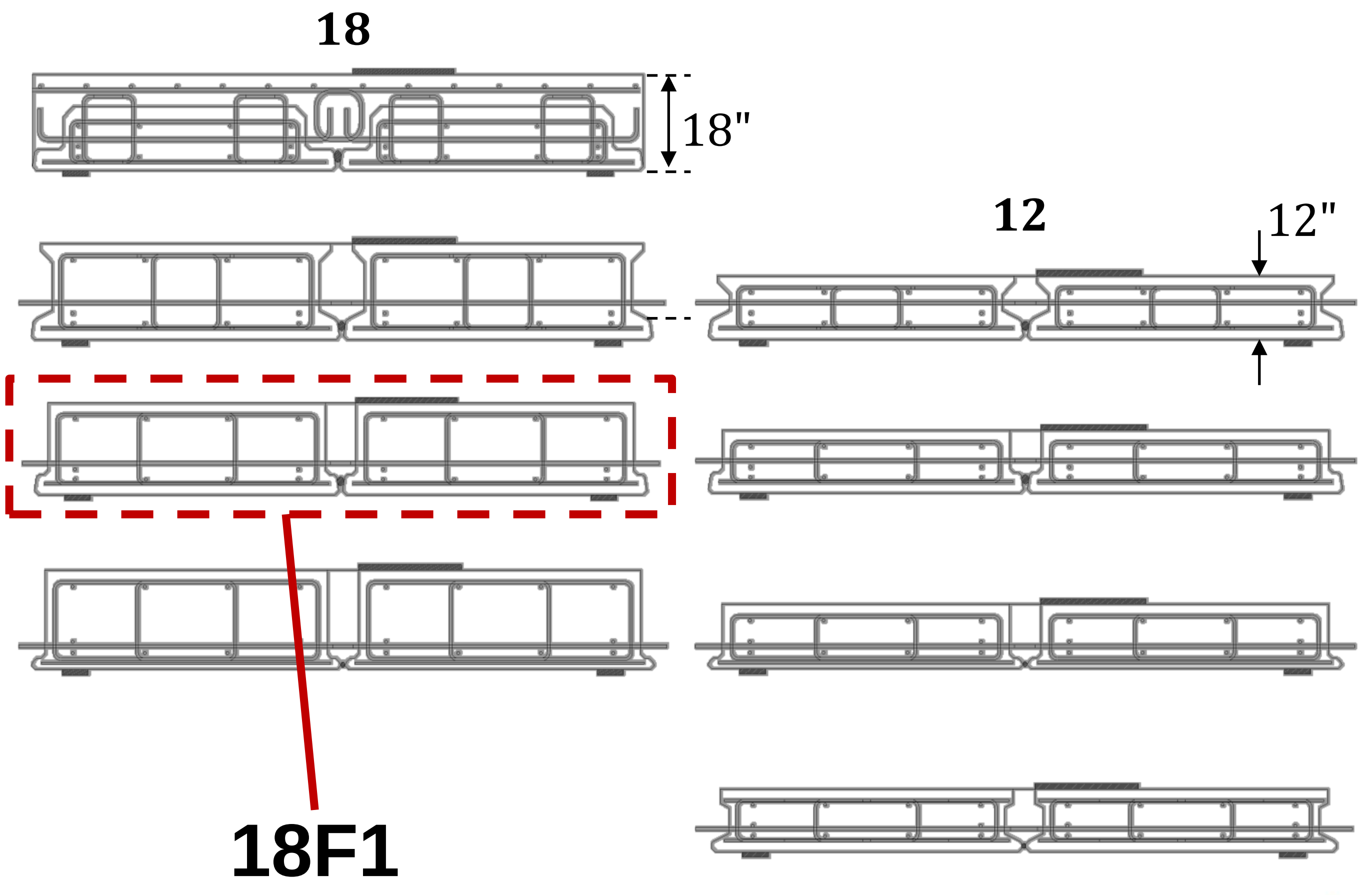
**Slab Beam w/CIP Deck:** **FSB:**

**Joint 1 – Integrated Box Beam Joint:** **A1:**

**Joint 2 – No Shear Key (4” Lip):** **F1:**

**Joint 3 – No Shear Key (2” Lip):** **F2:**

**Joint 4 – Modified Box Beam Joint:** **A2:**

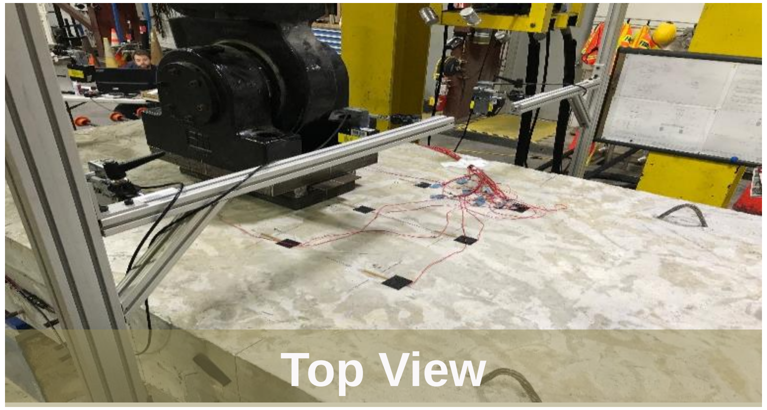


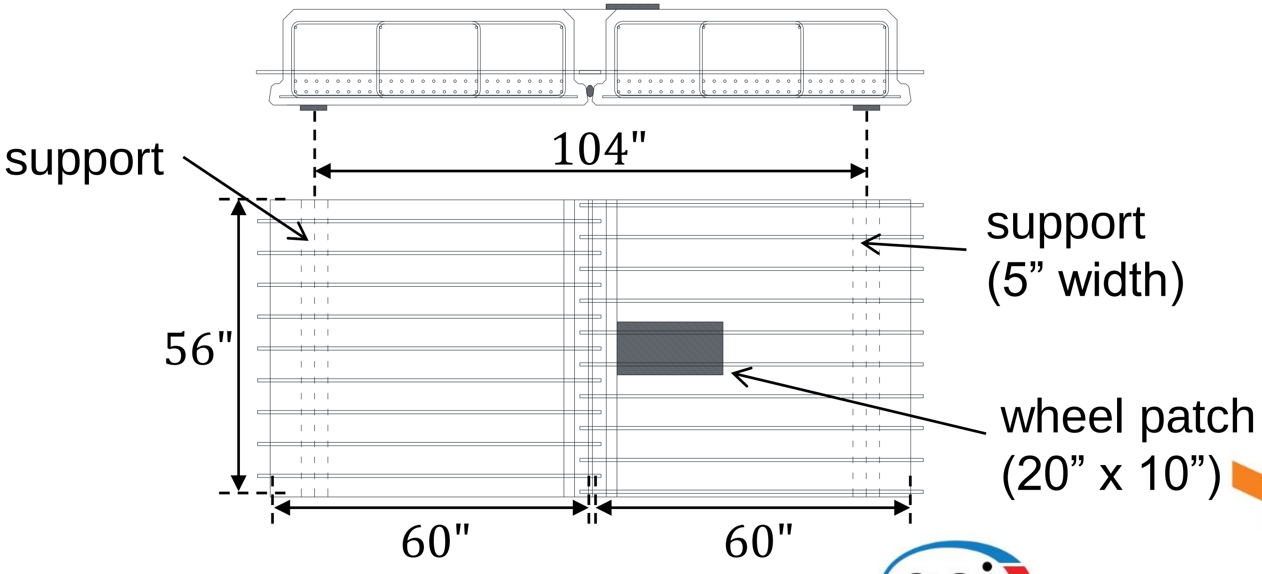

**Note**: 2 tests were performed on each specimen

# Joint Testing Program

- Test Setup

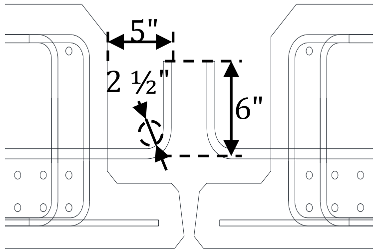


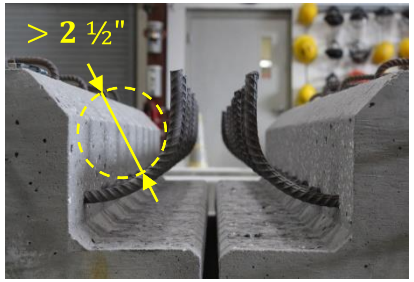


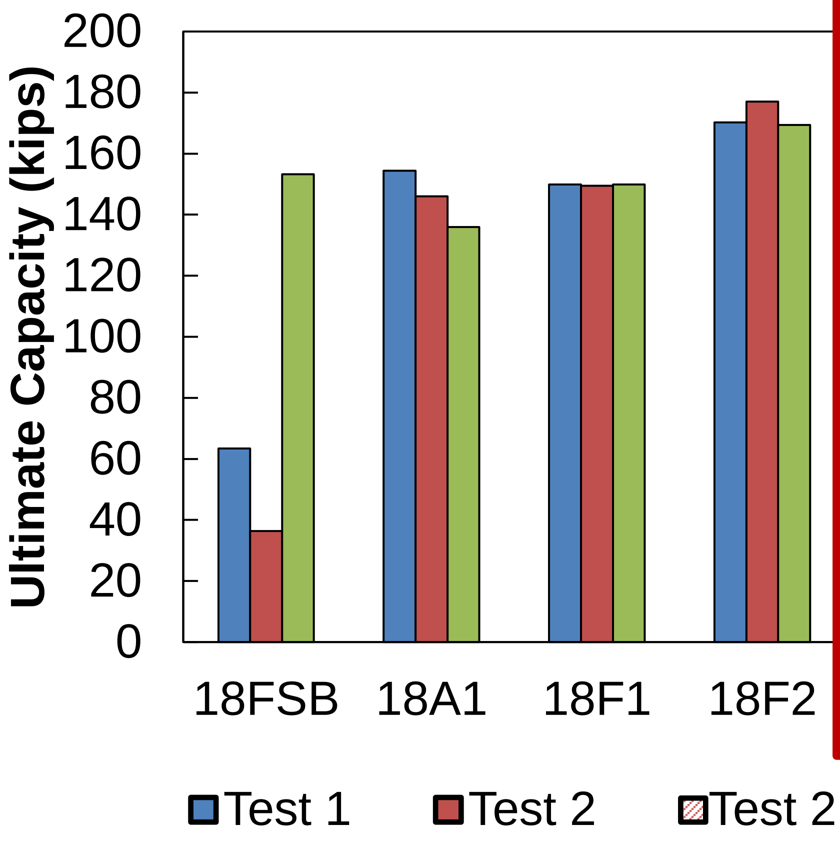



# Joint Testing Program

- Experimental Results



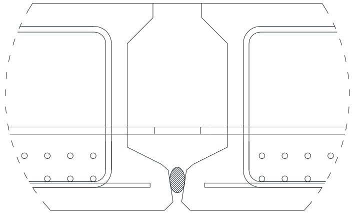




**18-inch-deep specimens**

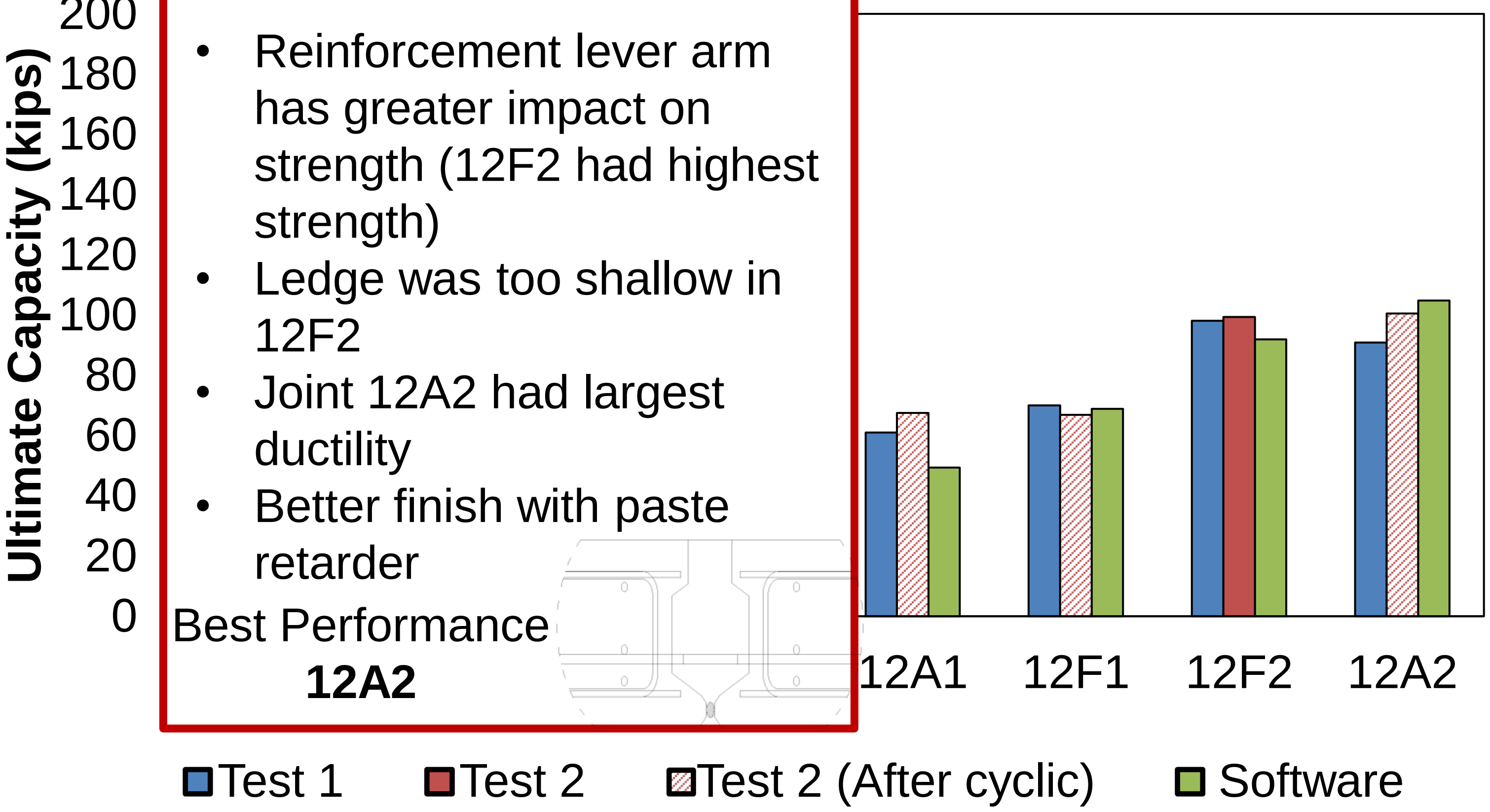
- Current FSB joint failed much lower than expected
- Modified UHPC joints had similar ultimate capacities to current FSB
- Joint 18A1 had the largest ductility among all the joints
- Sandblasted joint finish was not sufficient for achieving desired bond

Best Performance **18A1**



# Joint Testing Program

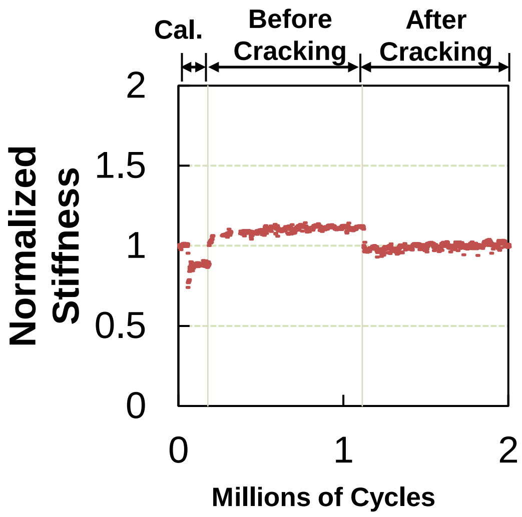
- Experimental Results



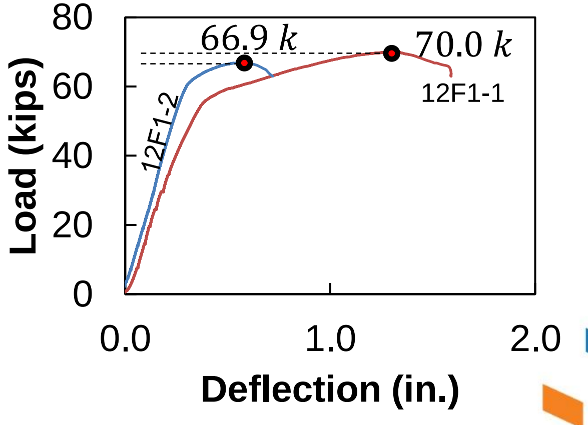

**12-inch-deep specimens**

- Reinforcement lever arm has greater impact on strength (12F2 had highest strength)
- Ledge was too shallow in 12F2
- Joint 12A2 had largest ductility
- Better finish with paste retarder

Best Performance
**12A2**



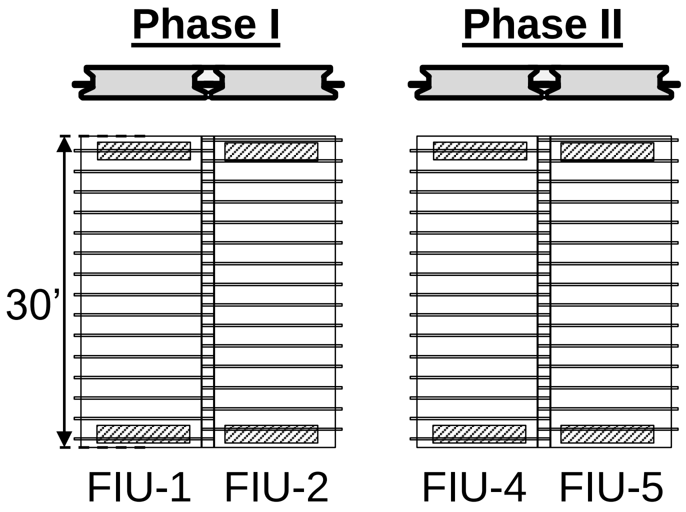

Fatigue loading did not impact the strength of the joint

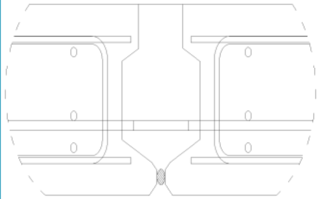


# Full-Scale Beam Testing

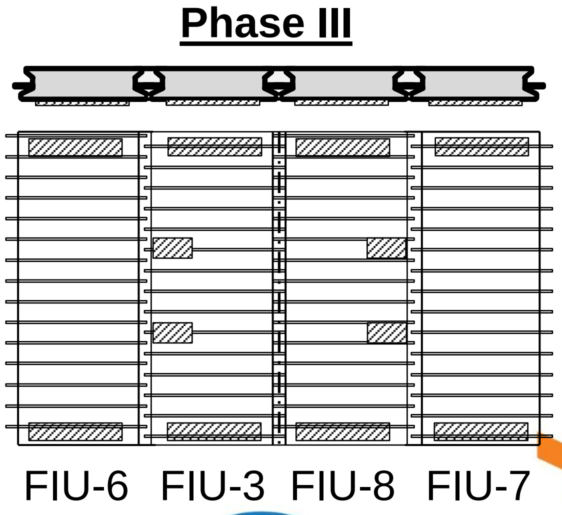
- Testing Phases

| Phase | $n_{beams}$ | Type of Loading | Boundary Conditions and Loading | Other Notes |
|---|---|---|---|---|
| **1** | 2 | service, strength | simply supported; varying loading points | |
| **2** | 2 | fatigue, service, strength | simply supported; varying fixity and loading points | moment distribution; SDCL Approach |
| **3** | 4 | fatigue, service, strength | simply supported; varying loading points | differential camber; moment distribution |



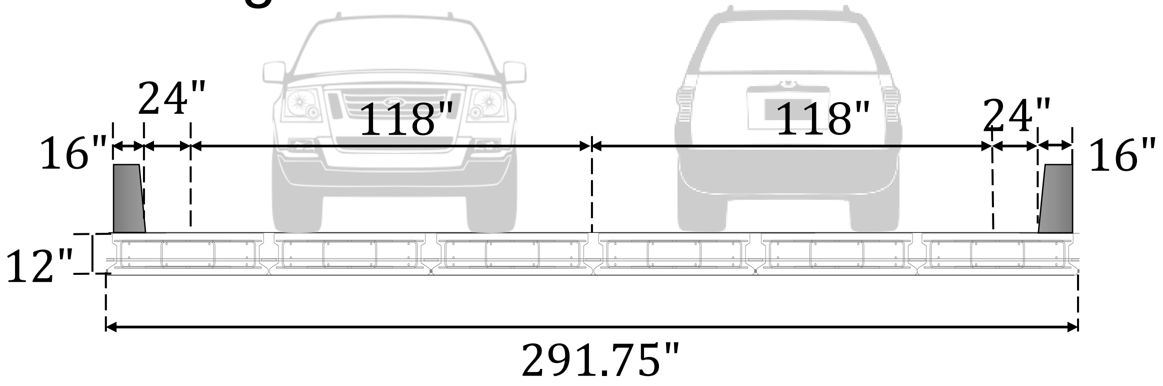

| Beam Cross Section | Joint Area (for 12-in. depth) (in²) | Approx. UHPC Cost (per foot of joint)* | Embedment Length (in) | Splice Length (in) |
|---|---|---|---|---|
| **12A2**  | 60.8 in² | $78.20 | 6.375 in. | 5 in. |

*based on $5,000 /cy for UHPC

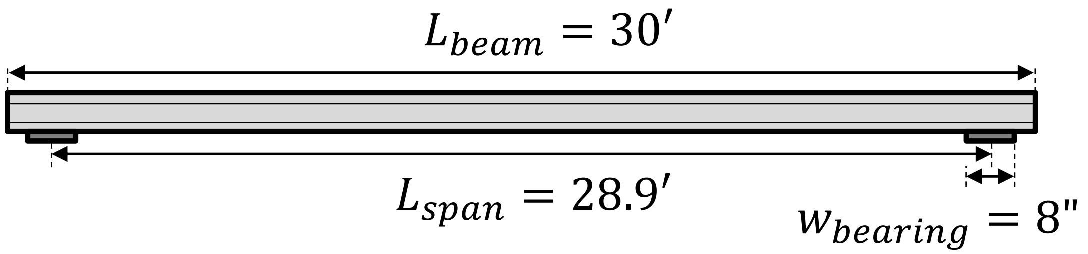


# Full-Scale Beam Testing

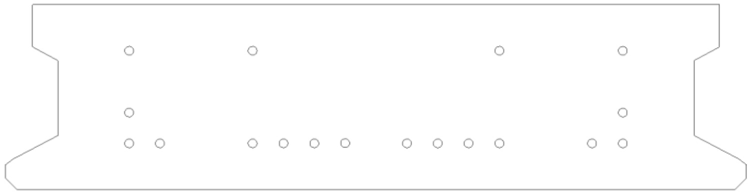
- Beam Design




Design based on 2-lane bridge with 6 slab beams and 28.9' span length




12-inch-deep FSB section with 14 - 0.6" diameter strands

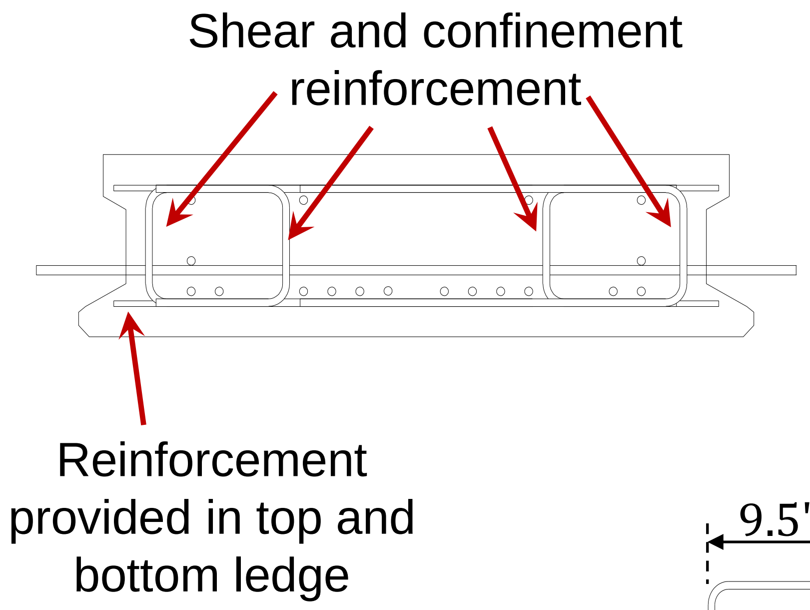


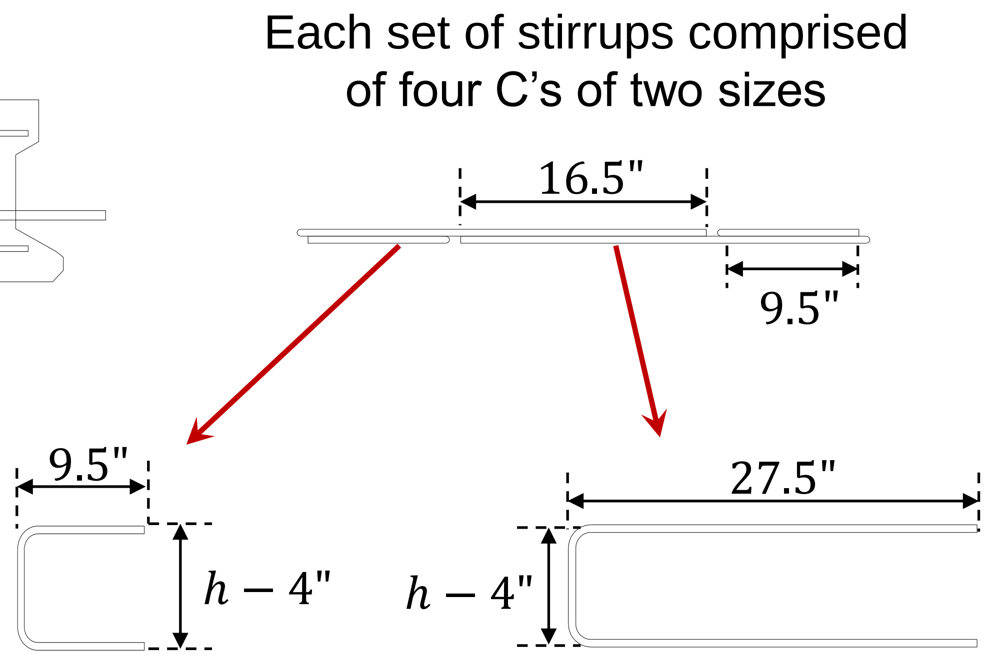
| Layer | $y_t$ | $n_{strands}$ | $F_{strand}$ |
|---|---|---|---|
| 1 | 3" | 4 | 10 k |
| 2 | 7" | 2 | 43.9 k |
| 3 | 9" | 12 | 43.9 k |

# Full-Scale Beam Testing

- Beam Design

Shear and confinement reinforcement based off of current FSB standard with slight modifications



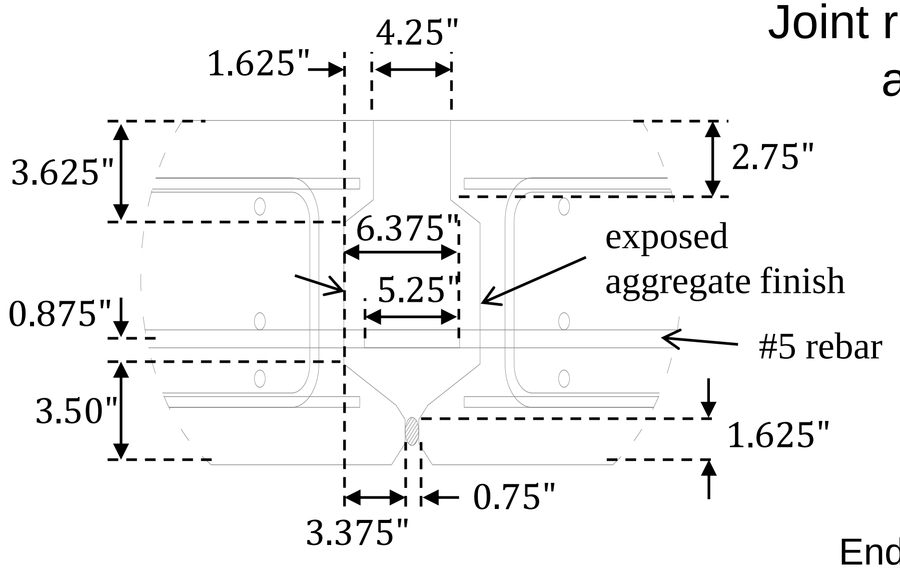



# Full-Scale Beam Testing

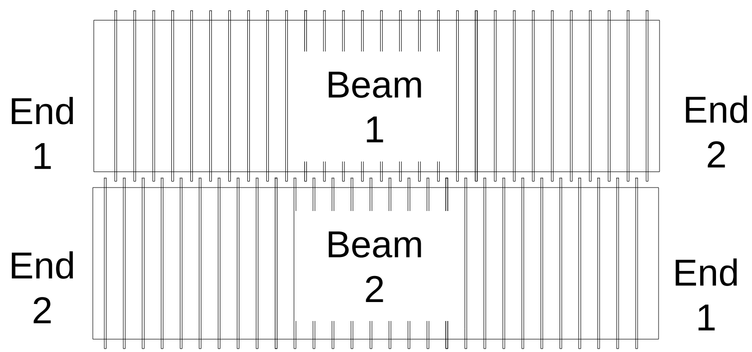
- Beam Design

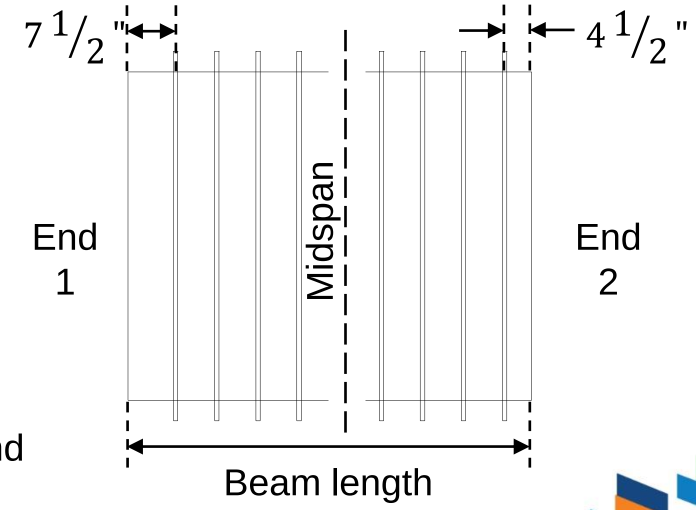
Joint reinforcement based on results from small-scale testing and FHWA “Design and Construction of Field-Cast UHPC Connections”

**Joint A2**




Joint reinforcement offset in each beam to allow for beam rotation to avoid reinforcement interference

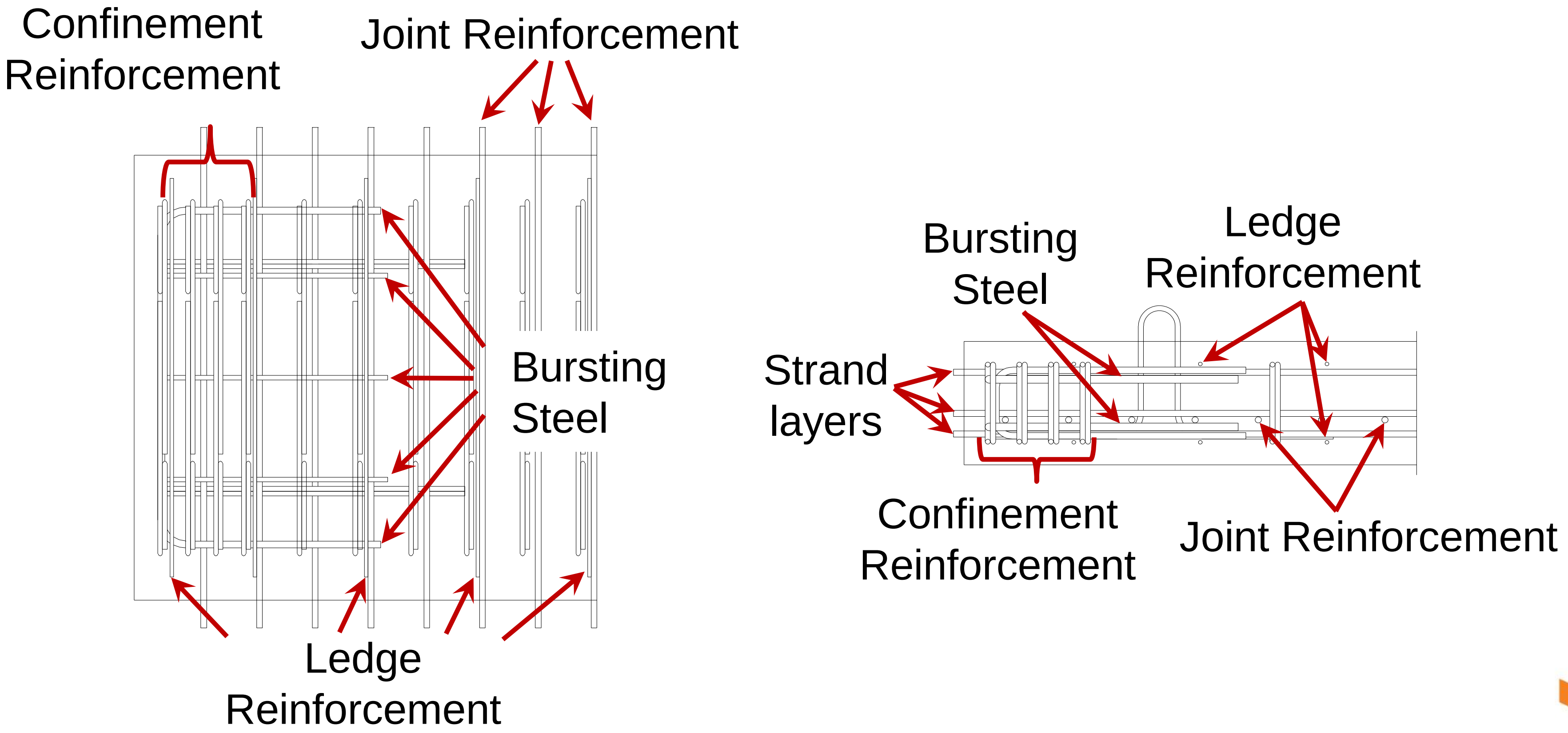


# Full-Scale Beam Testing

- Beam Design

End region was designed based on AASHTO



# Full-Scale Beam Testing

- Beam Construction

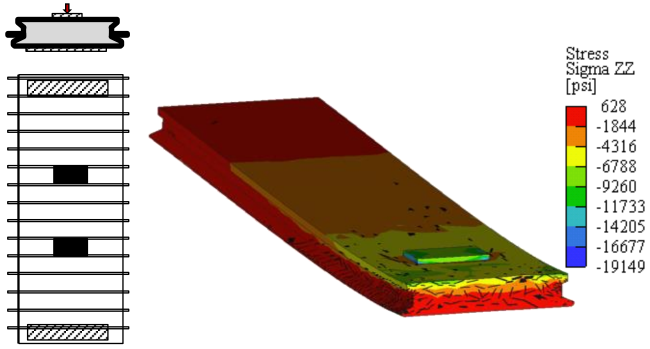
Two beams constructed for service and strength testing

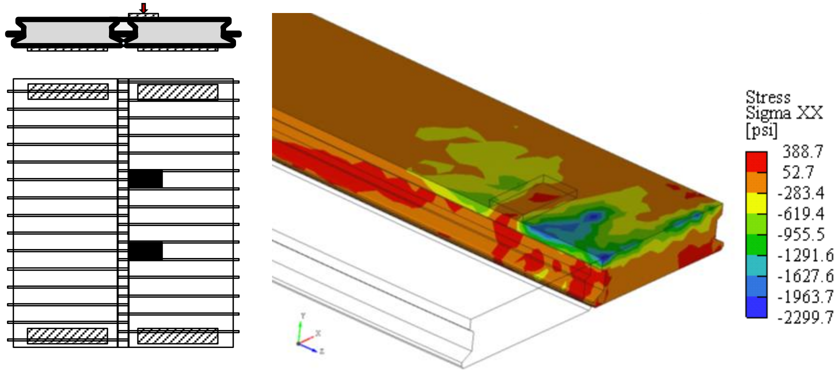
UHPC joint cast at FDOT SRC

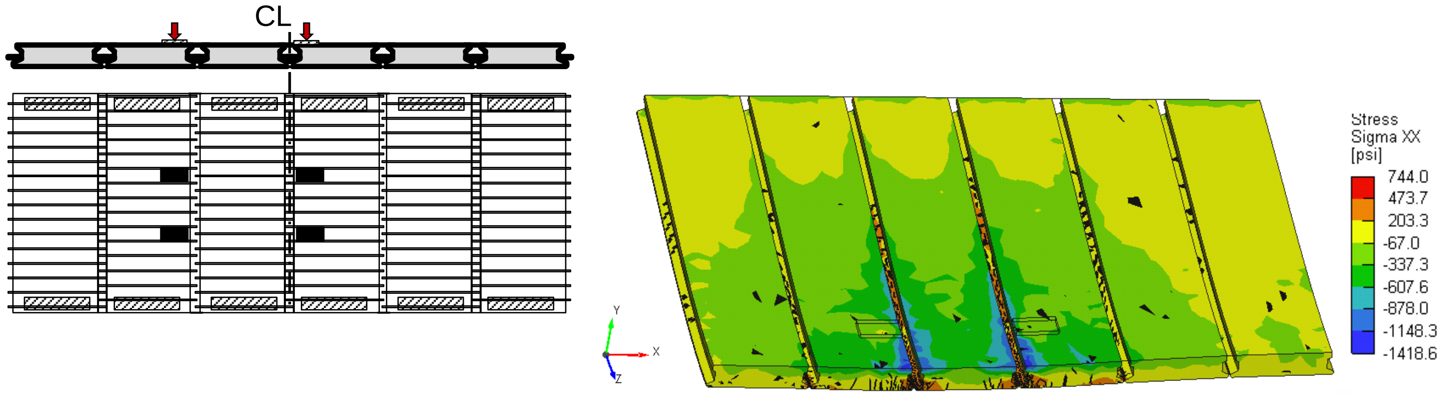
# Full-Scale Beam Testing

- FEA for Multi-Girder Configurations

Used ATENA to model different beam and load configurations to determine loading configuration



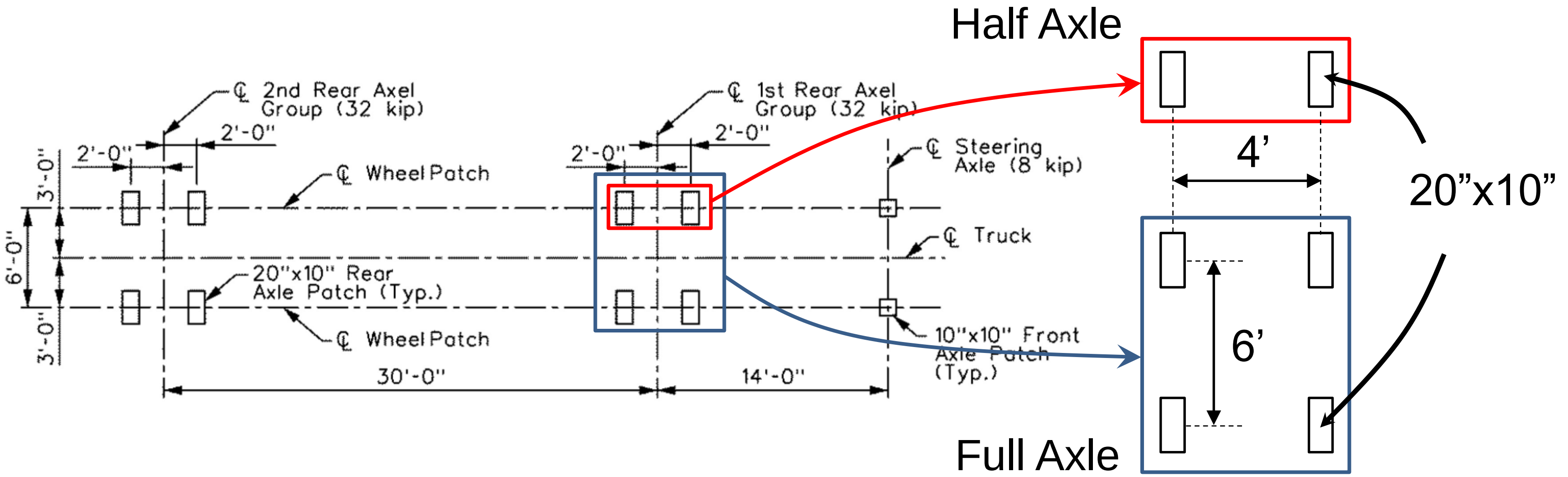



# Full-Scale Beam Testing

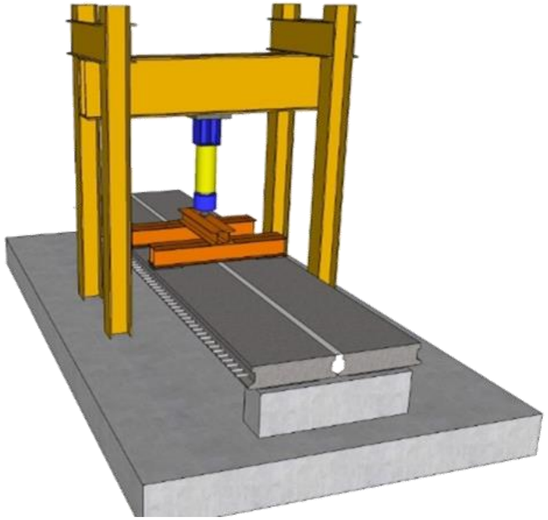
- Load Configuration

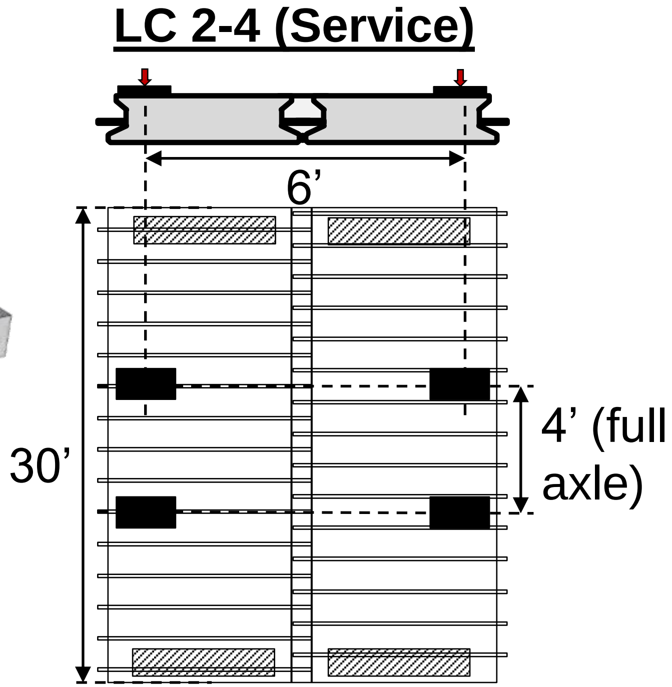
Loading based on either half or full-axle of HS-20 truck

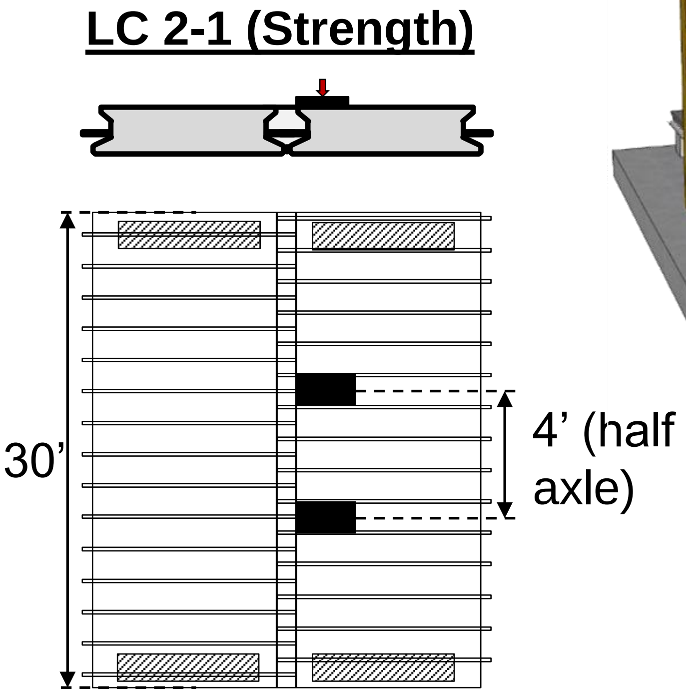


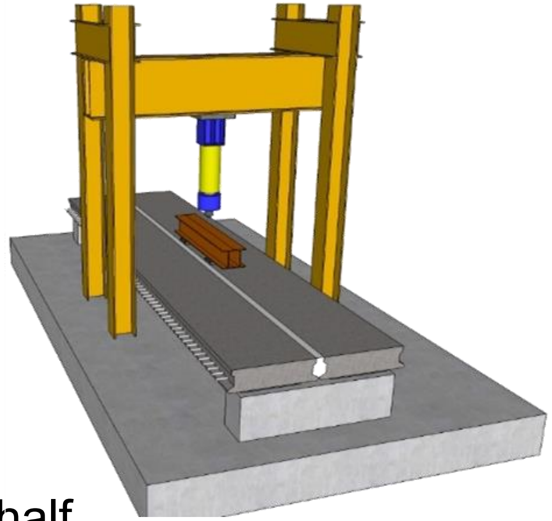
# Full-Scale Beam Testing – Two Beam Systems

- Static Load Configurations





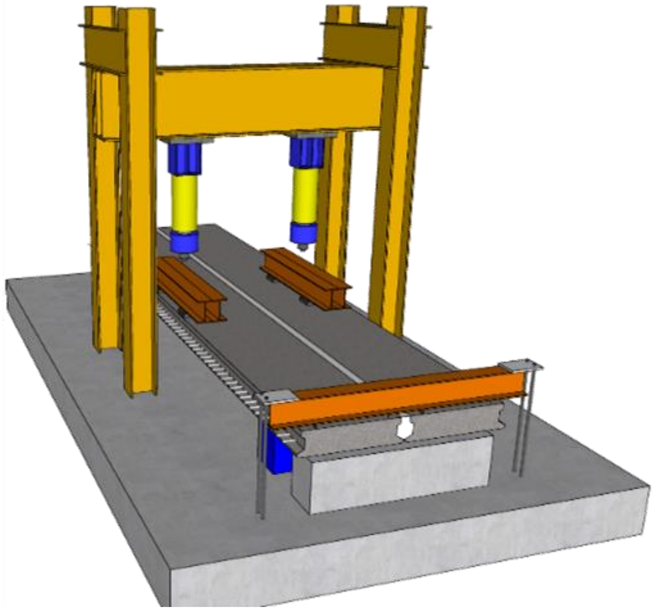



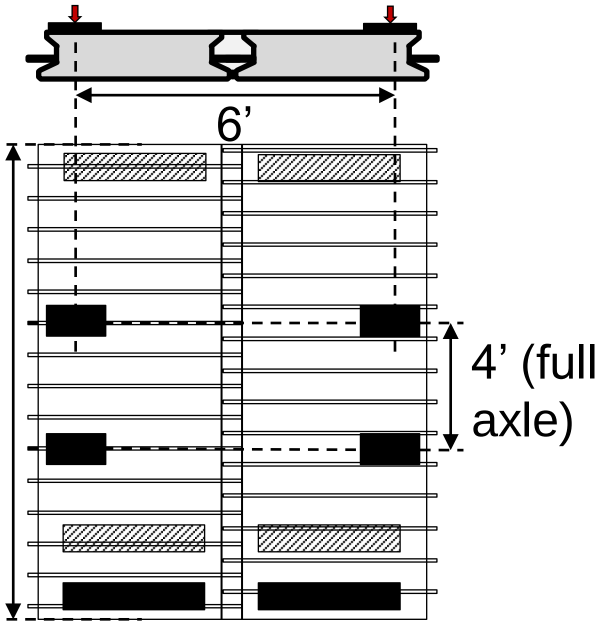
These static tests were performed on both two-beam systems (Phase I and Phase II)

# Full-Scale Beam Testing – Two Beam Systems

- Static Load Configuration - Continuous



**FC 2-7 (Service)**

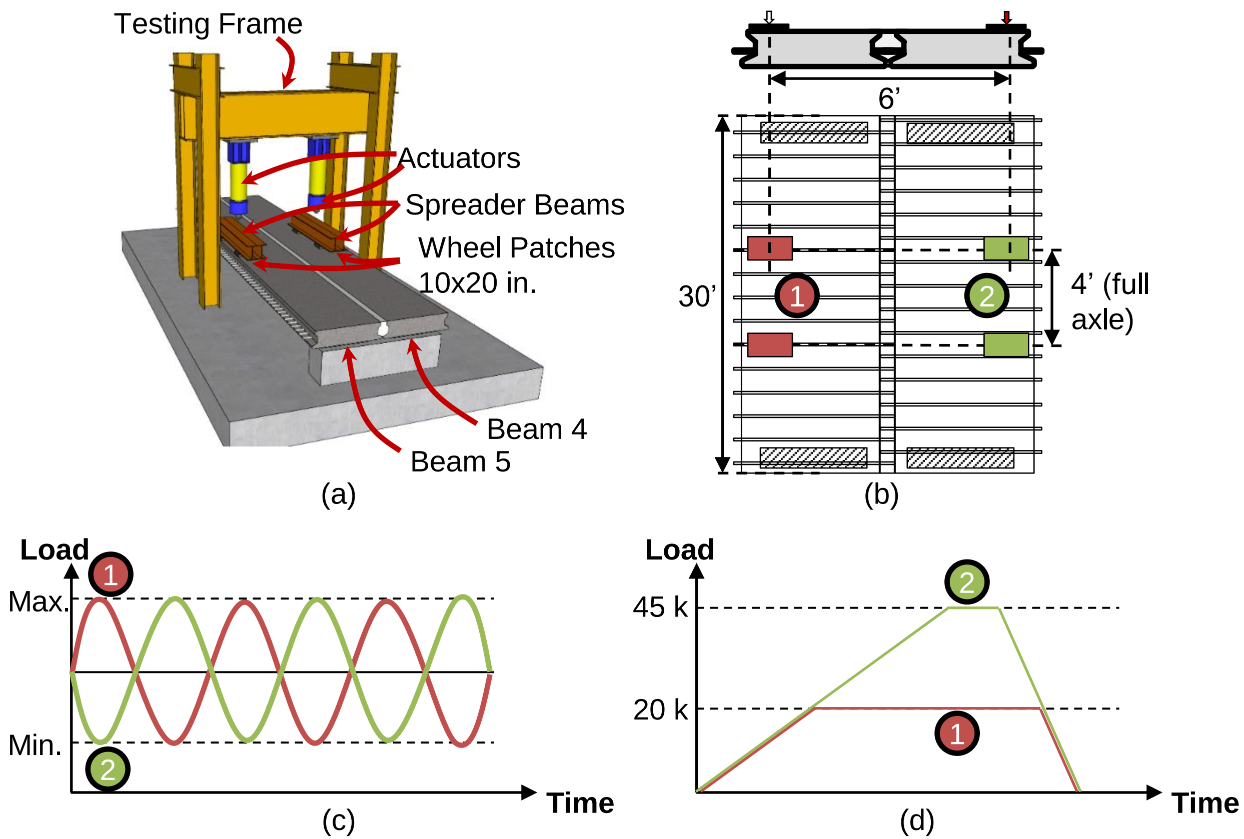



FC 2-7 was used for Phase II

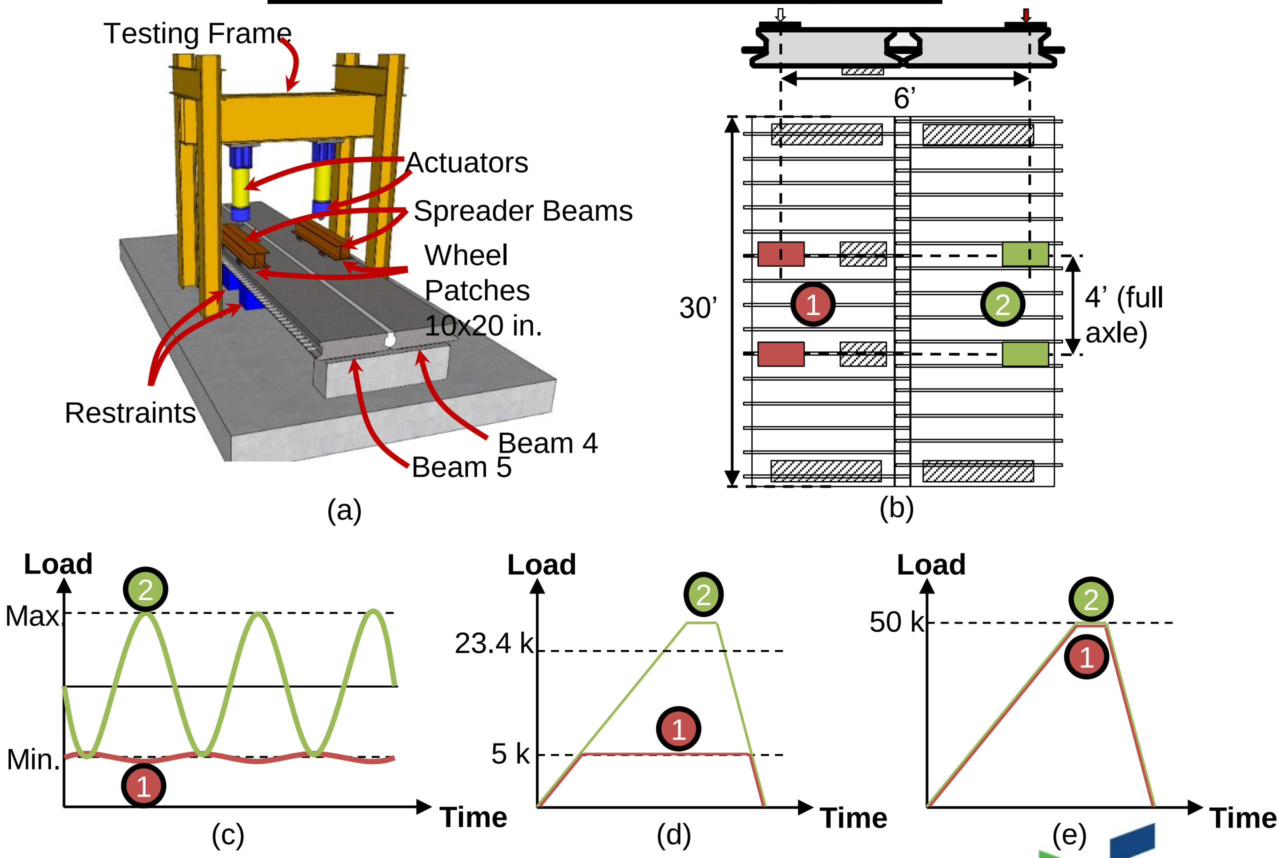
# Full-Scale Beam Testing – Two Beam Systems

- Fatigue Load Configurations

## FC 2-5 (Reverse Sinusoidal)




## FC 2-6 (Intermediate Support)

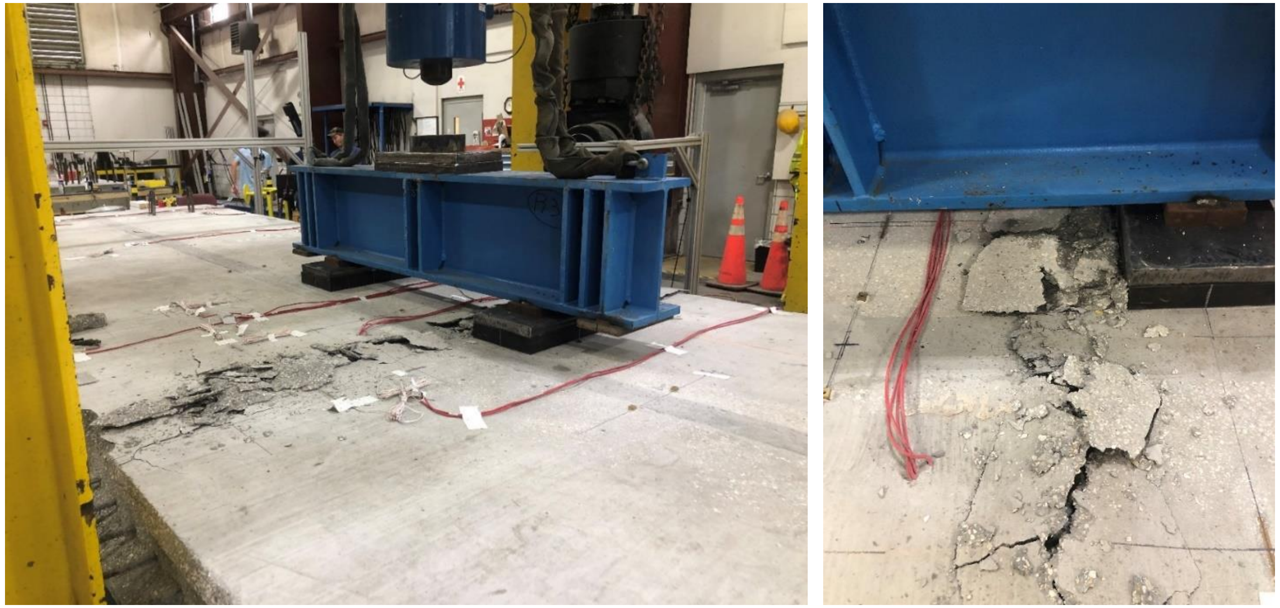



FC 2-5 and FC 2-6 were used for Phase II. Over 4.7 million load cycles were applied to the two-beam system in Phase II. An additional cracking load protocol was also used.

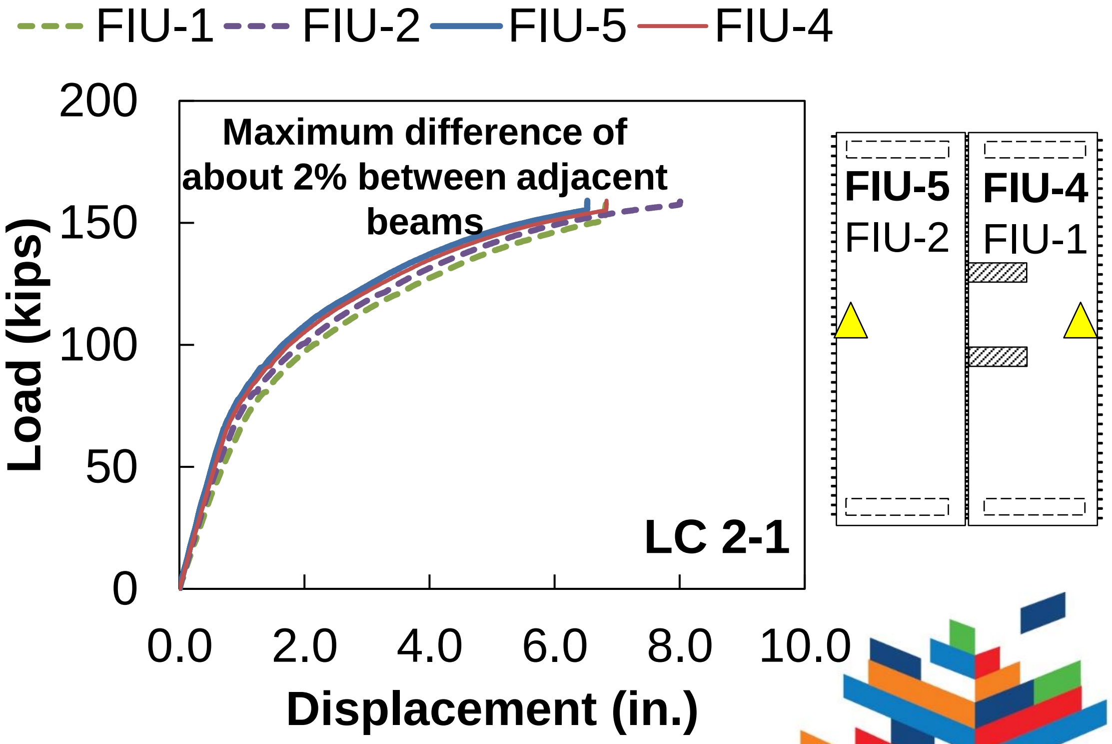
# Full-Scale Beam Testing – Two Beam Systems

- Observations

1. Joint performed well during service, fatigue, and strength testing; no joint debonding or distress was observed throughout testing of both two-beam systems; good transfer of stress between beams



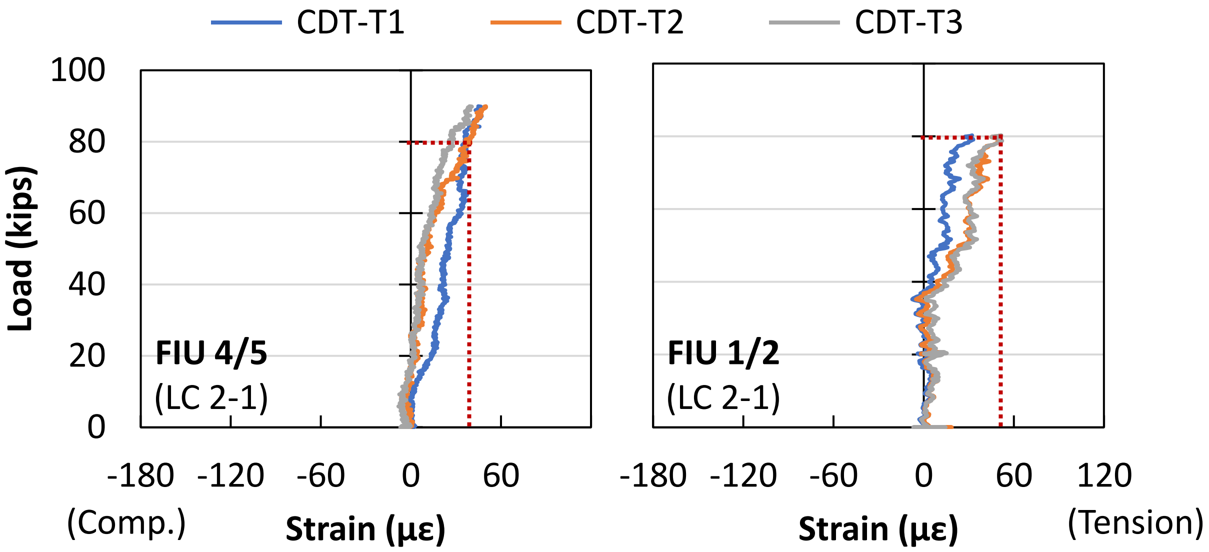
Compression block crushing across joint in FIU-1/2
(Same occurred in FIU-4/5)

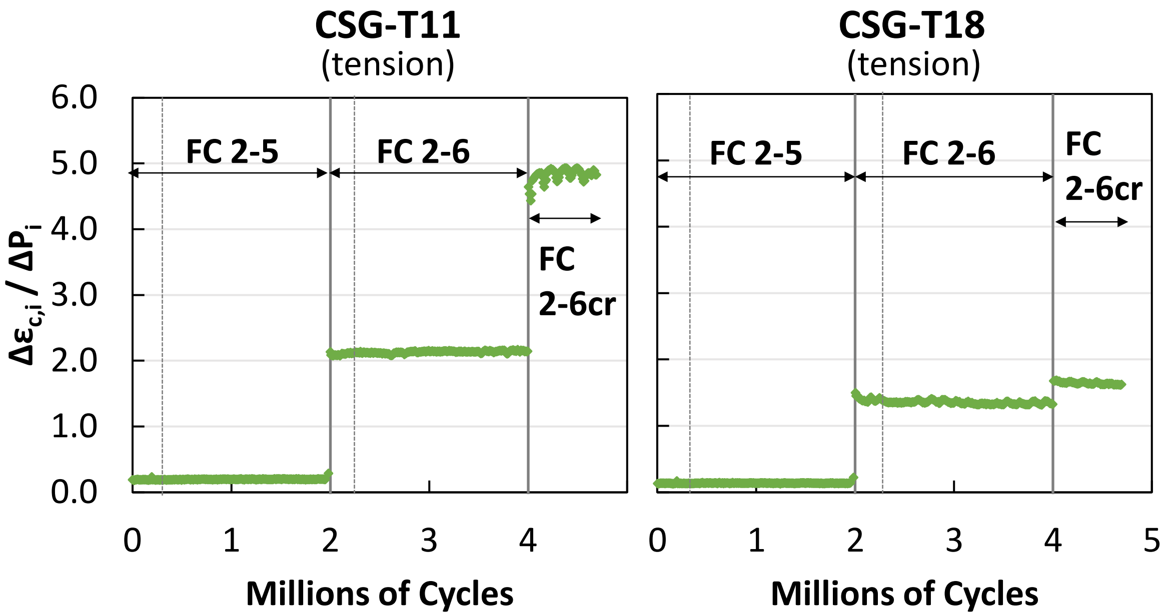


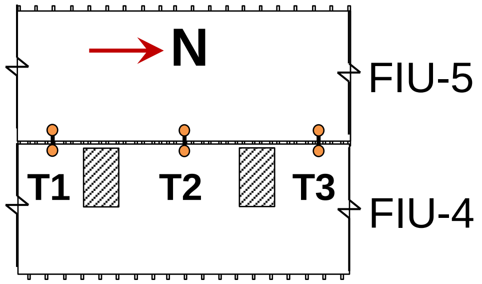
# Full-Scale Beam Testing – Two Beam Systems

- Observations

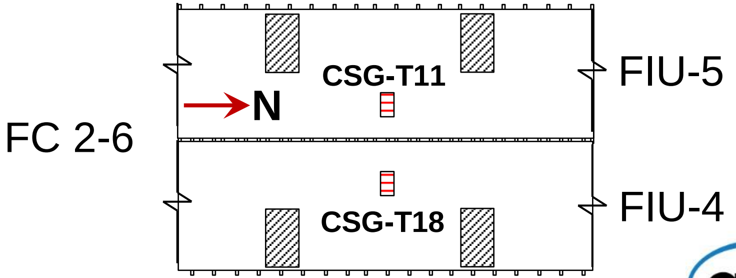
  2. FIU-4/5 had similar performance to FIU-1/2 during ultimate strength testing → 4.7 million cycles and other service load and cracking tests did not impact overall system behavior



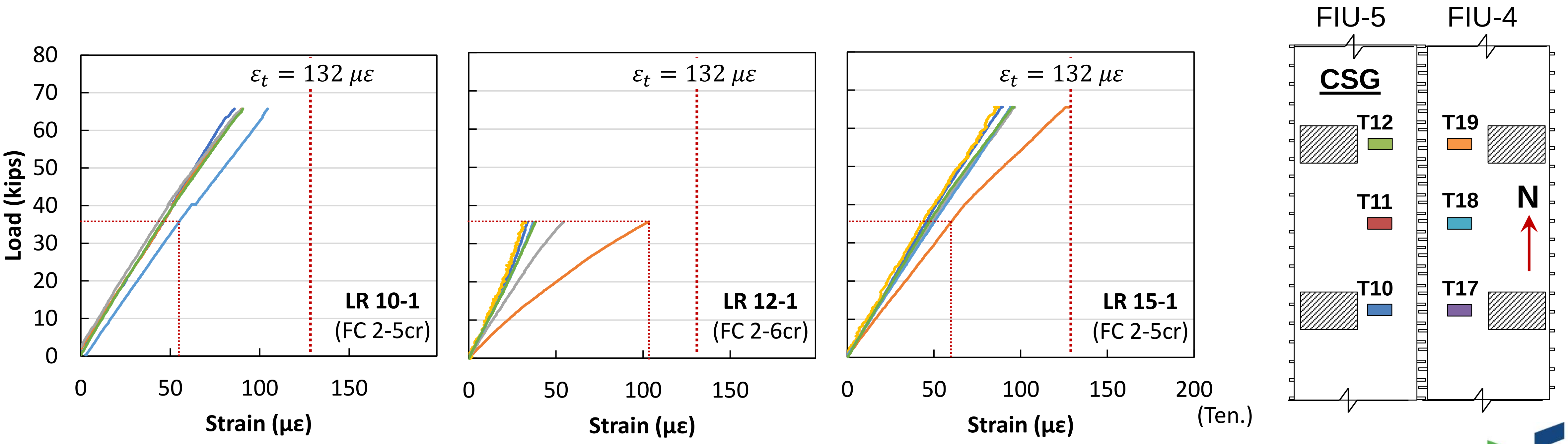

See also results on previous slide



# Full-Scale Beam Testing – Two Beam Systems

- Observations

3. Transverse tension in precast beams and across joints remained below estimate cracking strains on top and bottom of systems for all service tests

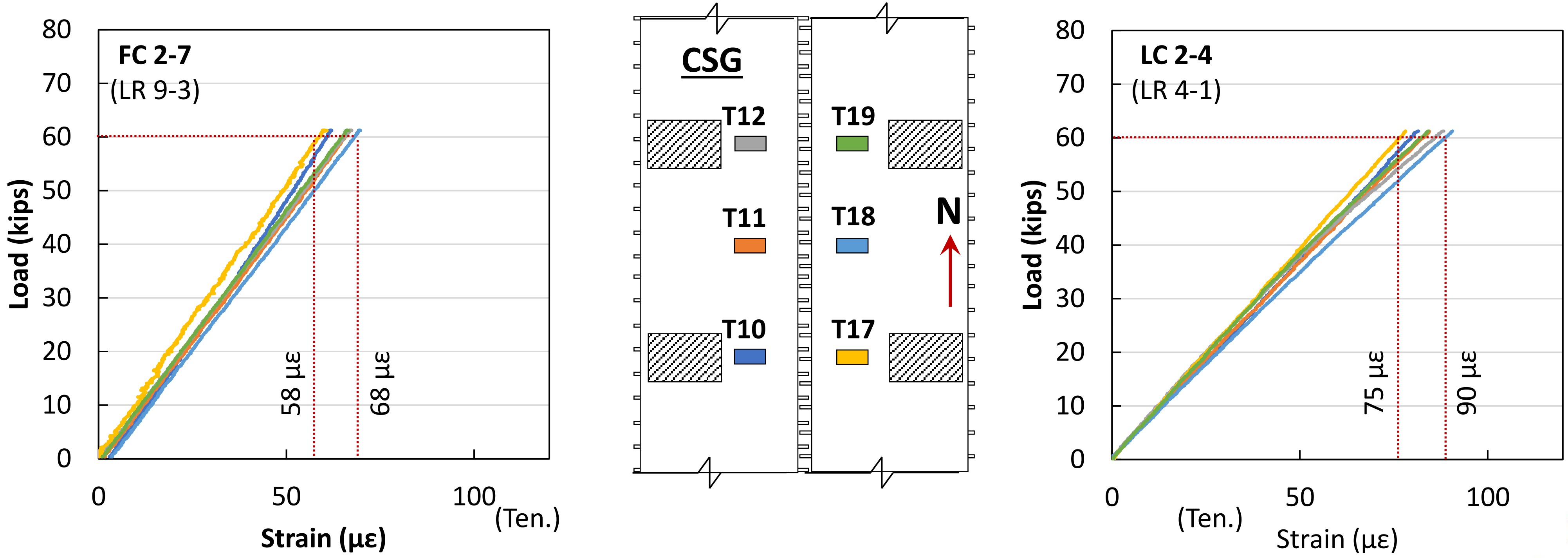



Tension strains shown from these cracking load protocols were highest observed on top of specimens and across joints

# Full-Scale Beam Testing – Two Beam Systems

- Observations

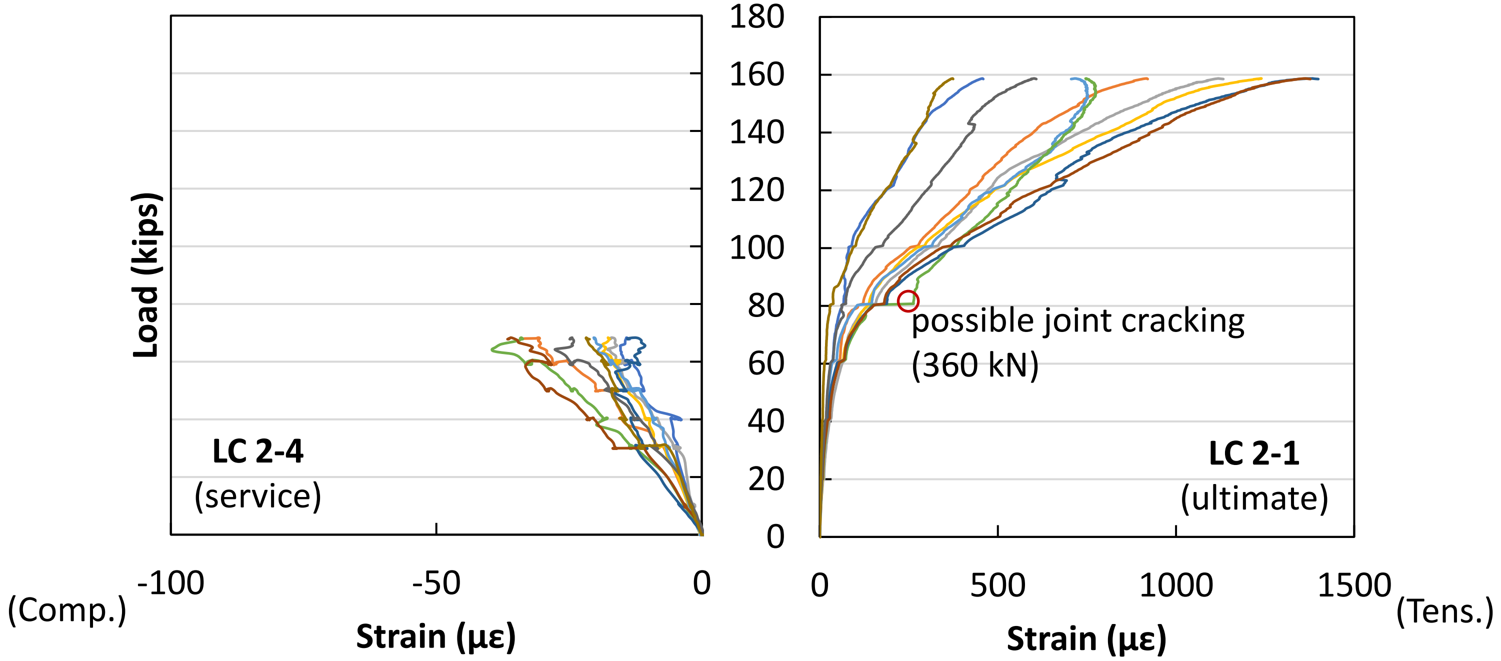
4. Joint demand (measured using transverse CSGs, CDTs across joint, and RSGs on joint reinforcement) decreased when a moment restraint was provided on one end of FIU-4/5

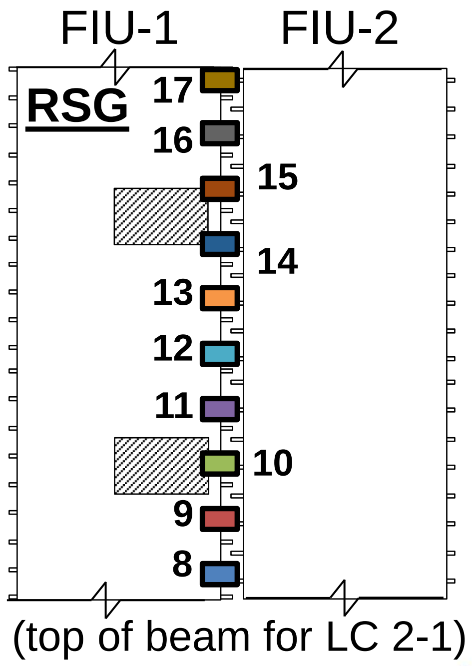


# Full-Scale Beam Testing – Two Beam Systems

- Observations

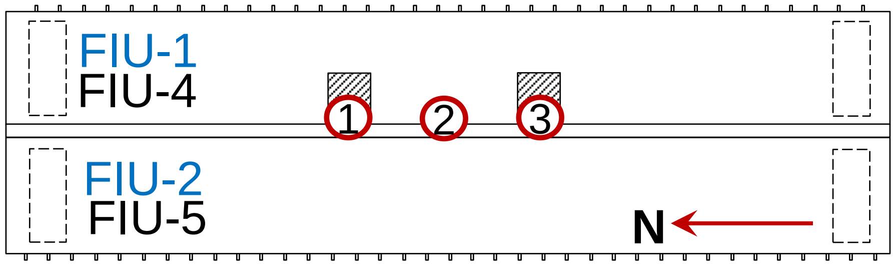
5. Small compression strains (< 50 με) were measured in service and fatigue load configurations. Larger tensile strains (> 300 με) were measured during strength testing (LC 2-1) but remained less than yield strains.

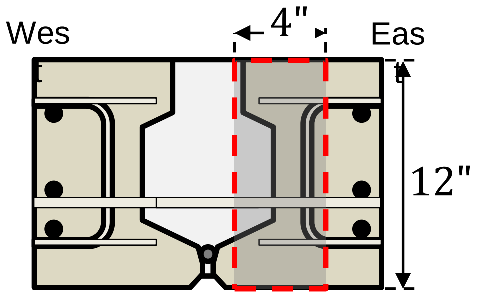


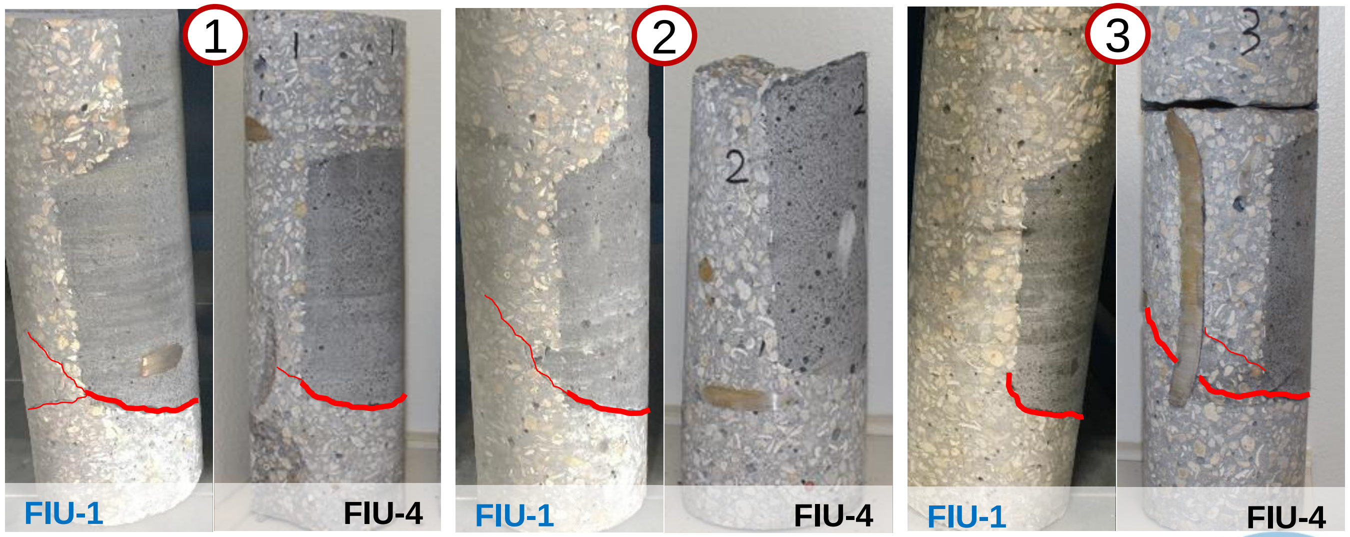



# Full-Scale Beam Testing – Two Beam Systems

- Observations
  6. No signs of bond deterioration between joint reinforcement and UHPC in joint in any fatigue service, or strength testing



# Implementation

- Observations from Construction

**Side Forms and Joint Construction of Large-Scale Specimens**


Paint side forms with paste retarder


Remove side forms 24h after casting


Pressure wash concrete cover


Finalized exposure

**Joint Reinforcement Length**


Variable joint reinf. lengths


Variable joint reinf. lengths cuts

**Retarder Finishes***


Light penetration (1/8 inch.)

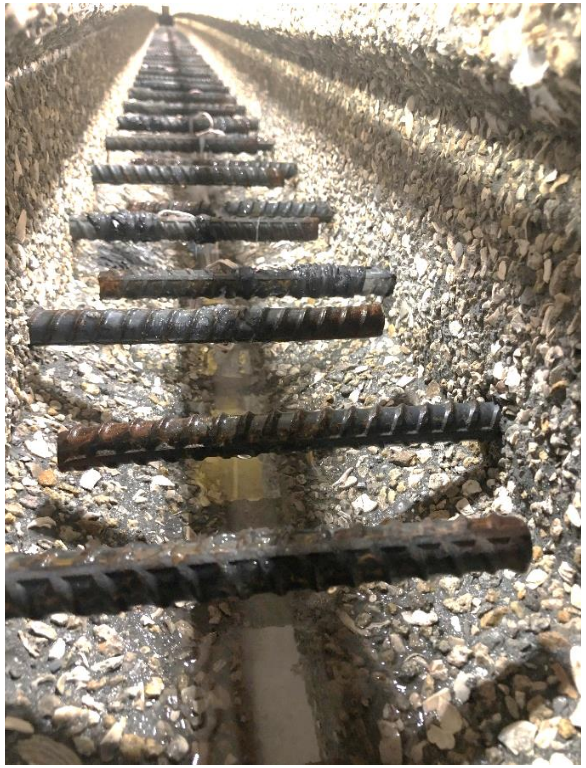

Medium light penetration (1/4 inch.)

*Based on Master Finish HV Retarder Lilac (Light) and Pink (medium light)

# Implementation

- Observations from Joint Casting

## Joint Surface Preparation



Saturated Surface Dry (SSD) condition

## Formwork Preparation and UHPC Pour

Joint Formwork preparation

UHPC Joint cast from one end

Rodding of two UHPC pour heads

## Joint Grinding Action

Joint Formwork removal after 24h

Grinding action of UHPC overpour

Final joint finish

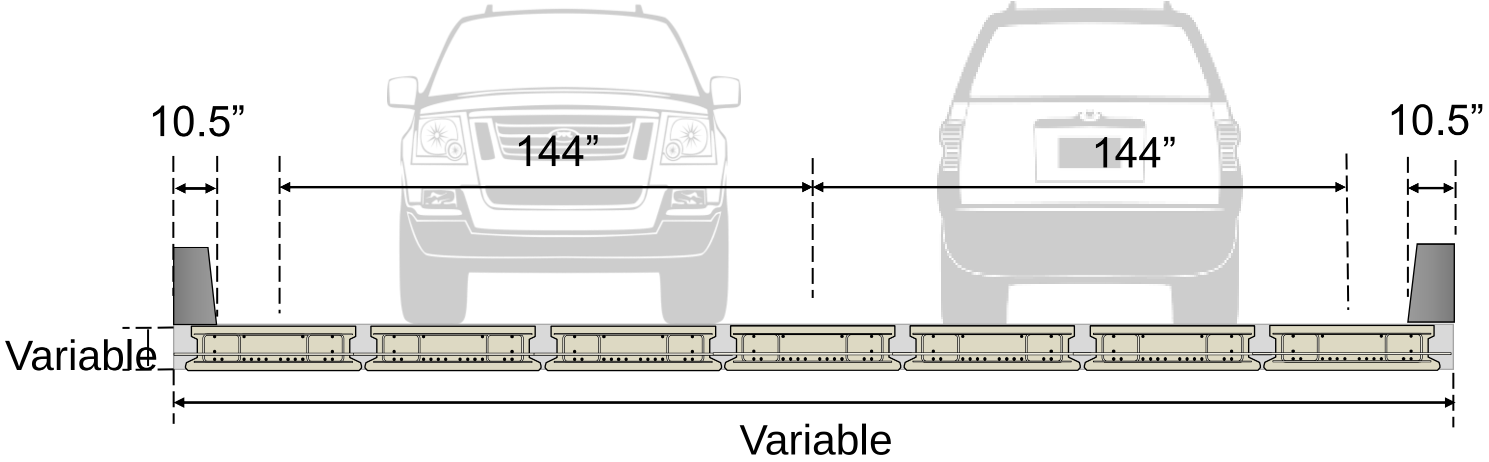
# Implementation

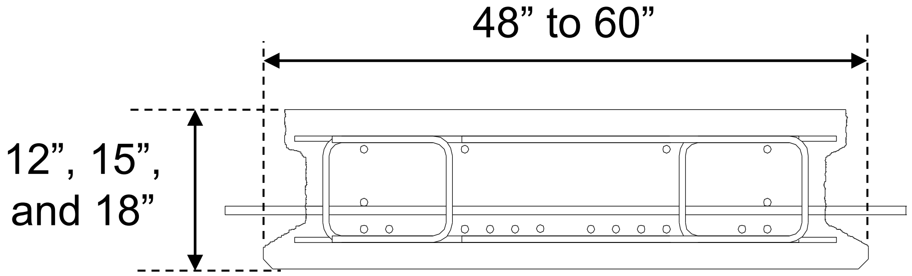
- Span Ranges and Approximate Number of Strands*

| *Span (ft)* | *FSB* | |
|---|---|---|
| | *48 in.* | *60 in.* |
| *20* | *12 (8)* | *12 (9)* |
| *30* | *12 (12)* | *12 (15)* |
| *40* | *15 (15)* | *15 (18)* |
| *50* | *18 (16)* | *18 (21)* |
| *55* | *18 (-)* | *18 (25)* |
| *60* | *21 (22)** | *21 (26)** |
| *70* | *24 (27)** | *24 (33)** |
| *80* | *30 (33)** | *27 (43)** |

*Non-standard thicknesses
Legend: Thickness (#strands)

*Using FDOT Design MathCAD Program




Reference: Chitty, F., Freeman, C., and Garber, D. (2020) “Joint Design Optimization for Accelerated Construction of Slab Beam Bridges”

# Thank You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