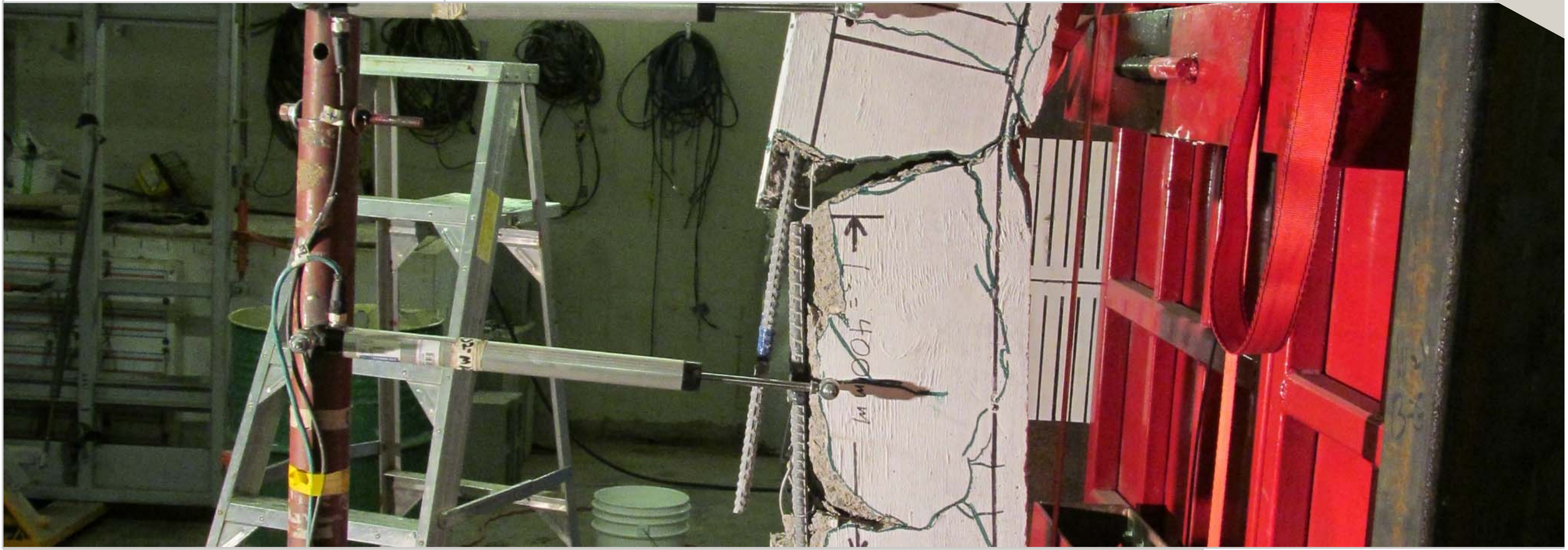


Effect of High Strain Rates of Reinforced Concrete Bond

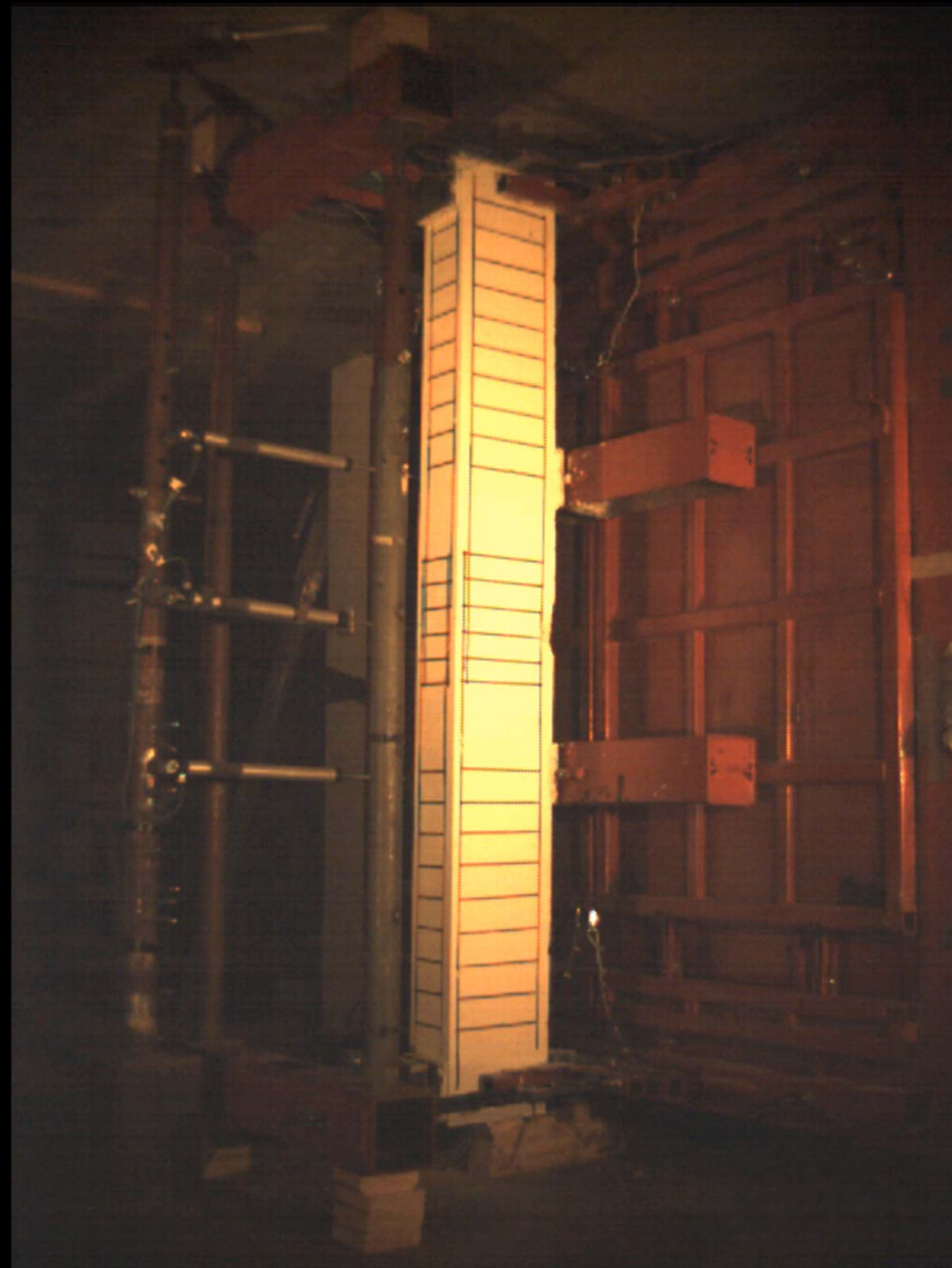
Eric Jacques, Ph.D., P.Eng.

ejacques@vt.edu

ACI Las Vegas

October 14, 2018

What does a high strain rate bond failure look like?



VIRGINIA TECH

State-of-the-Practice

- Development Length Design
  - Stringent detailing requirements
  - Ignore rate effects on bond “capacity”

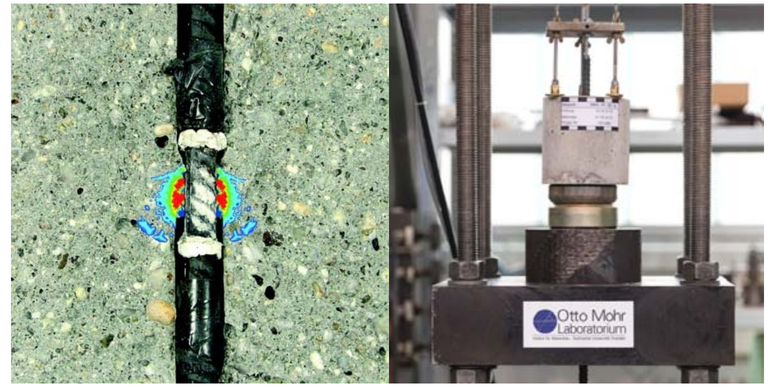
$$l_{dd} = \left(\frac{3}{40} \overbrace{\frac{SIF \times DIF \times f_y}{\lambda \sqrt{f'_c}}}^{1.17 \times 1.1 \approx 1.30} \frac{\psi_t \psi_e \psi_s}{\left(\frac{c_b + K_{tr}}{d_b} \right)} \right) d_b \geq 300\ mm$$

The Challenge:
Does not address detailed design, assessment of existing, or contribute to state-of-the-art

State-of-the-Art

Weathersby (2003)

Solomos & Berra (2010)



Panteki et al. (2017)

- Bond strength is improved under high strain-rate loading
  - DIF between 1.1 to 4.0 (!), $\dot{\varepsilon} \approx 0.1 - 10\ s^{-1}$
  - Concrete quality, cover depth, confinement

Small-scale, pullout tests generate an unrealistic internal stress state.

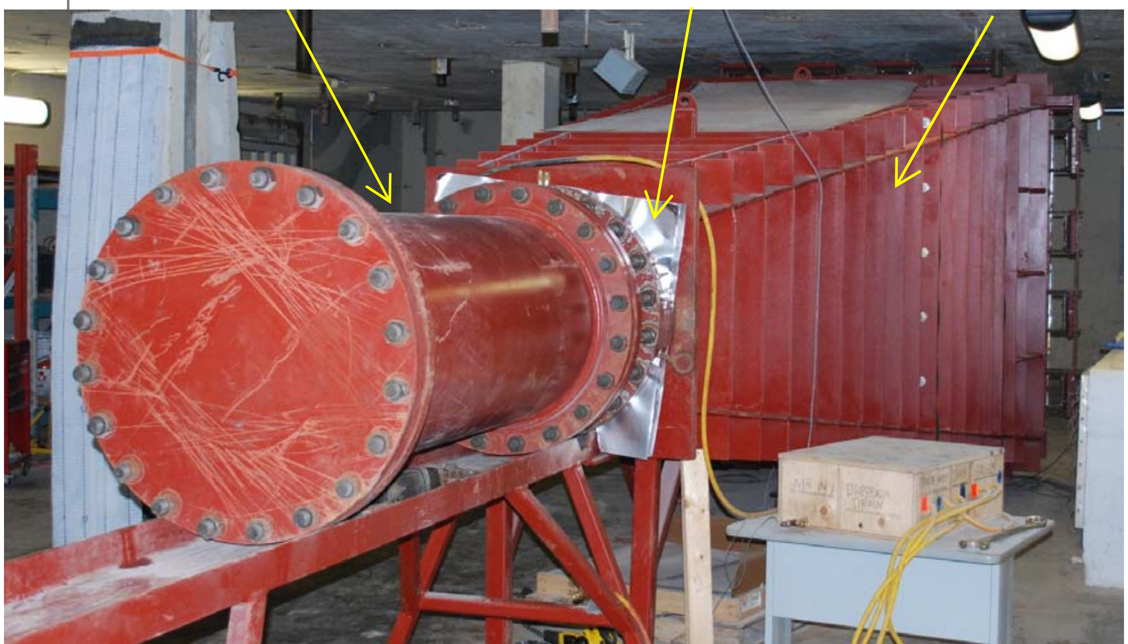
Objective

1. Establish the high strain rate bond characteristics of realistically proportioned structures
2. Understand influence of key parameters
3. Incorporate bond DIF into the design process

Scope

- Experimental shock tube tests of lap spliced beams

University of Ottawa Shock Tube



(a) Shock tube driver and expansion sections

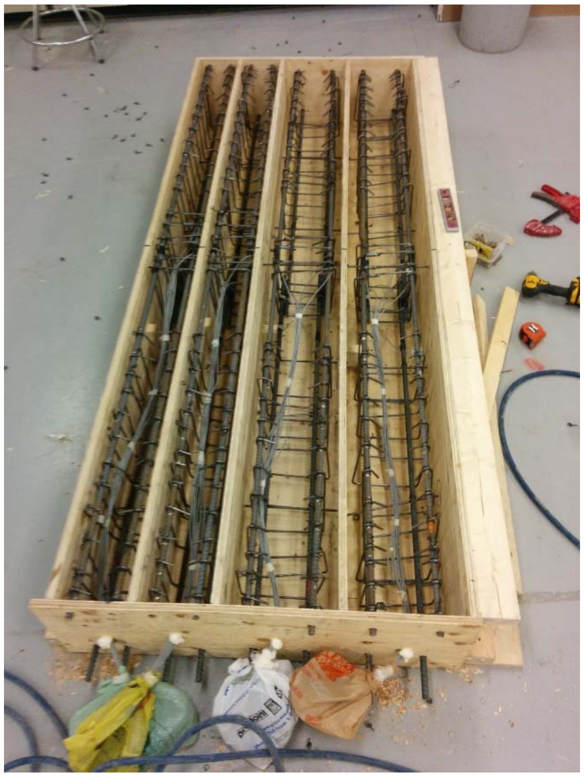
(b) Shock Tube Test Frame

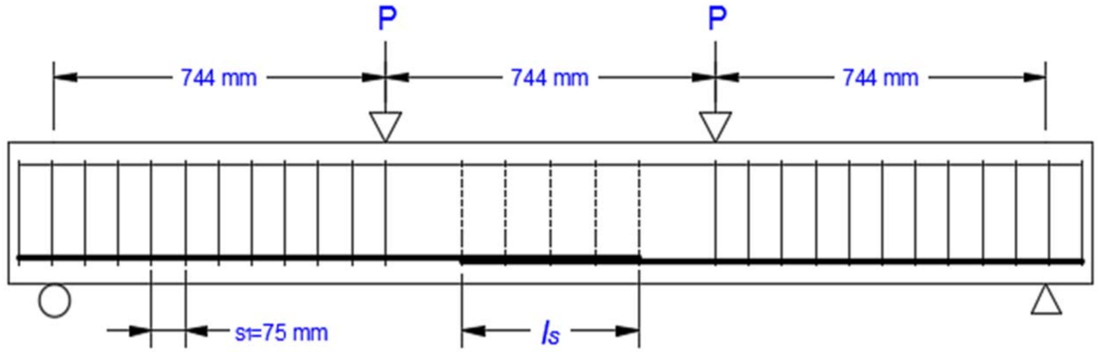
Experimental Program

- Large-scale lap spliced beams under high strain rate loading

- Effect of:
  - **Concrete strength ?**
  - **Bar size ?**
  - **Cover depth ?**
  - **Transverse reinforcement ?**

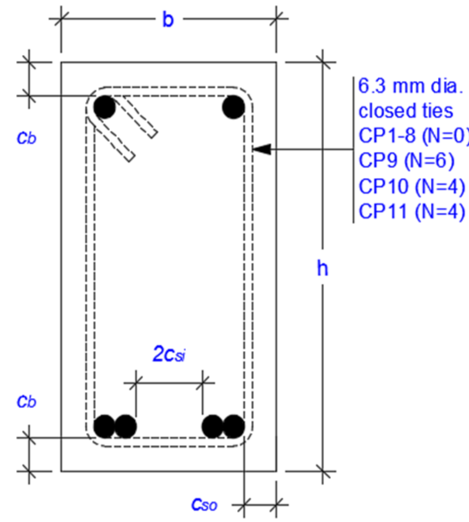
Test Specimens - Reinforcement





Splices designed to fail at 400 MPa static stress

Equal cover depths



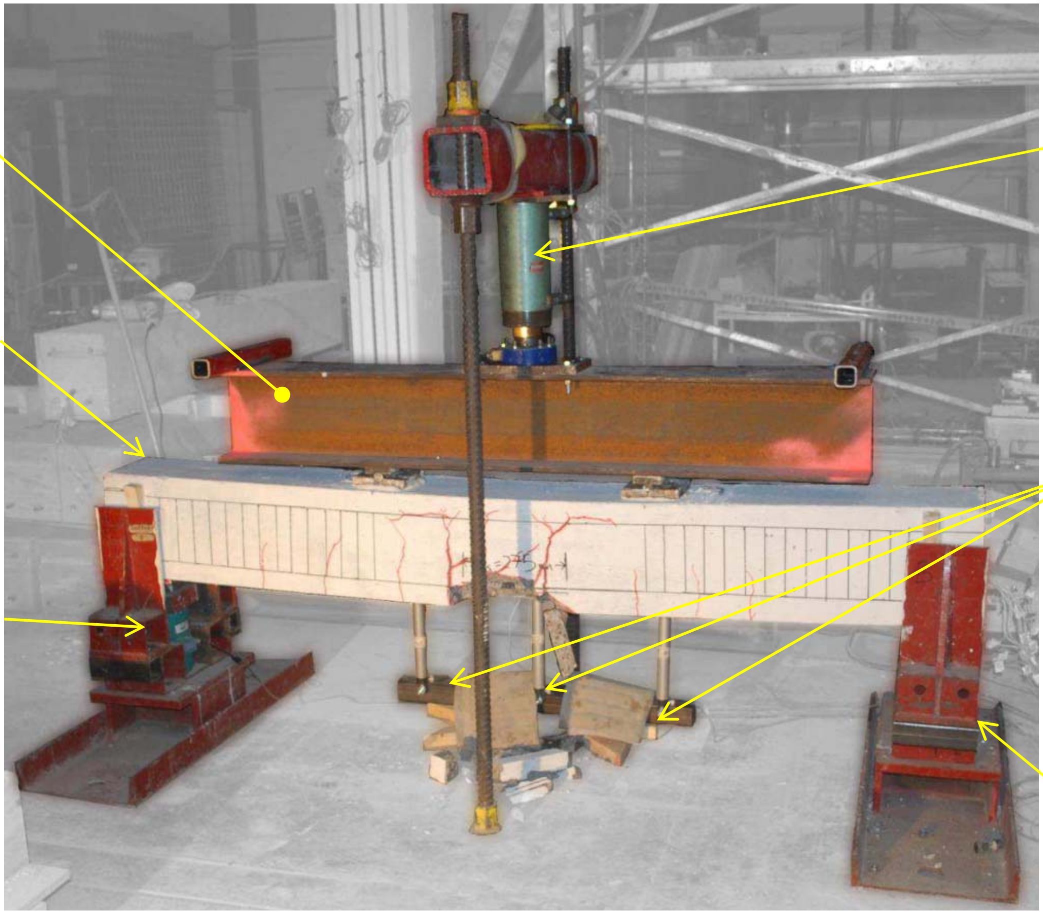
SPLICE SECTION

Test Specimens – Companion Pairs

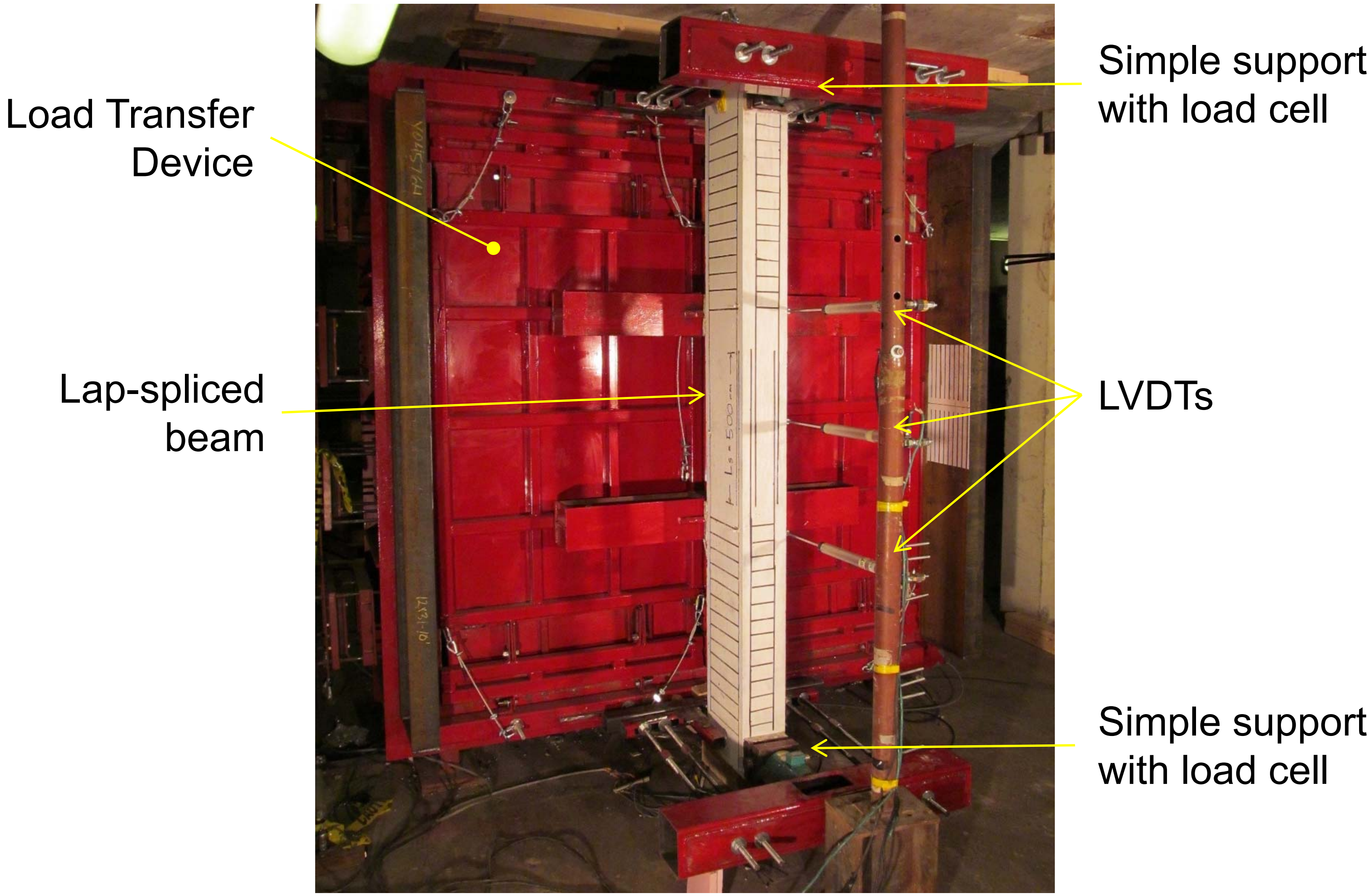
Twenty-five beams, twelve companion pairs

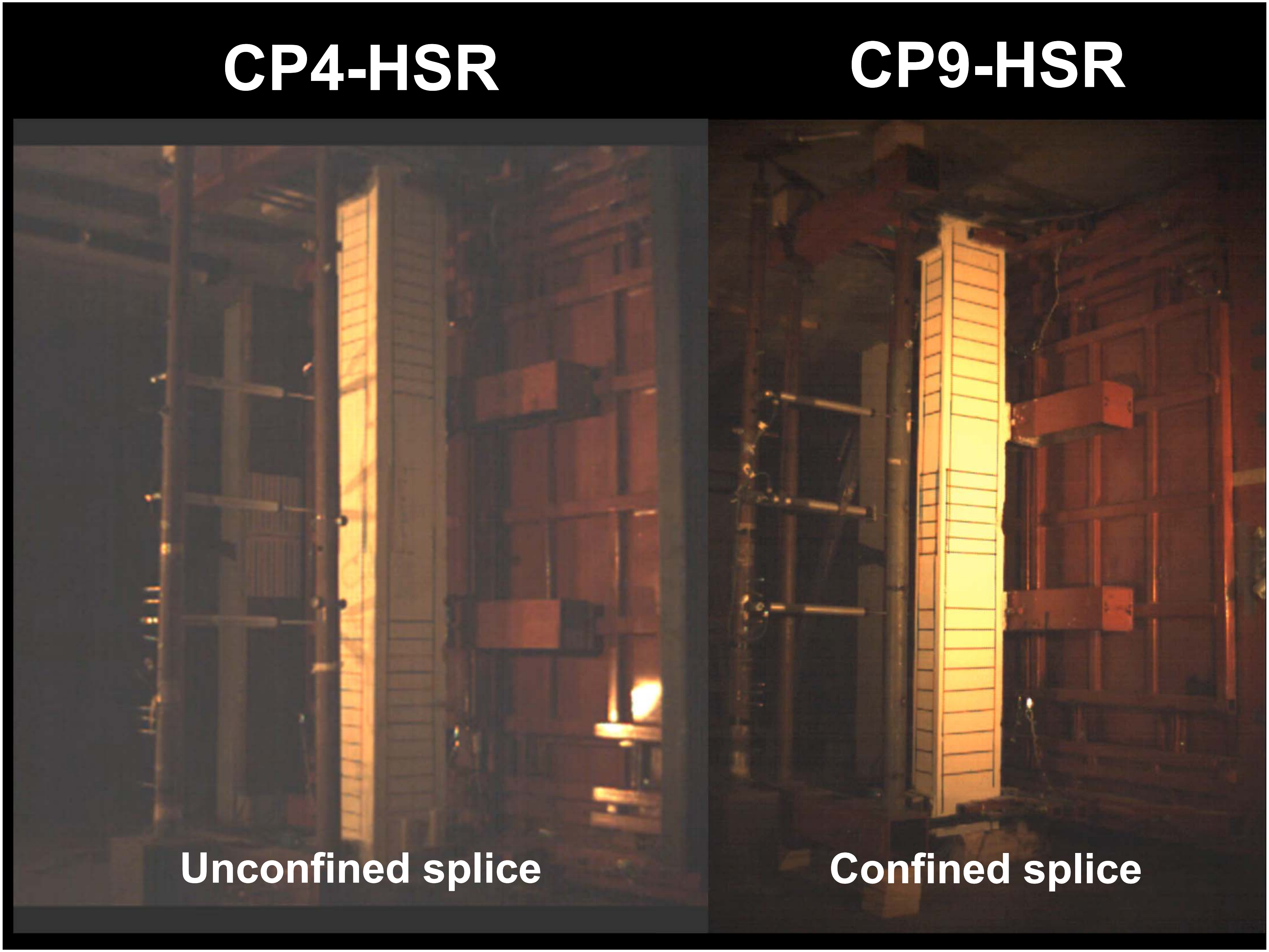
Concrete Properties	Structural Properties	Loading
• Compression f_c' – 30, 50 MPa	• Bar size – 10M, 15M, 20M • Concrete cover – 25, 38, 50 mm • Presence of confinement	• Strain-rate – $\dot{\varepsilon} \approx 10^{-6}\ s^{-1}$ – $\dot{\varepsilon} \approx 1\ s^{-1}$

Test Procedure & Instrumentation



Test Procedure & Instrumentation

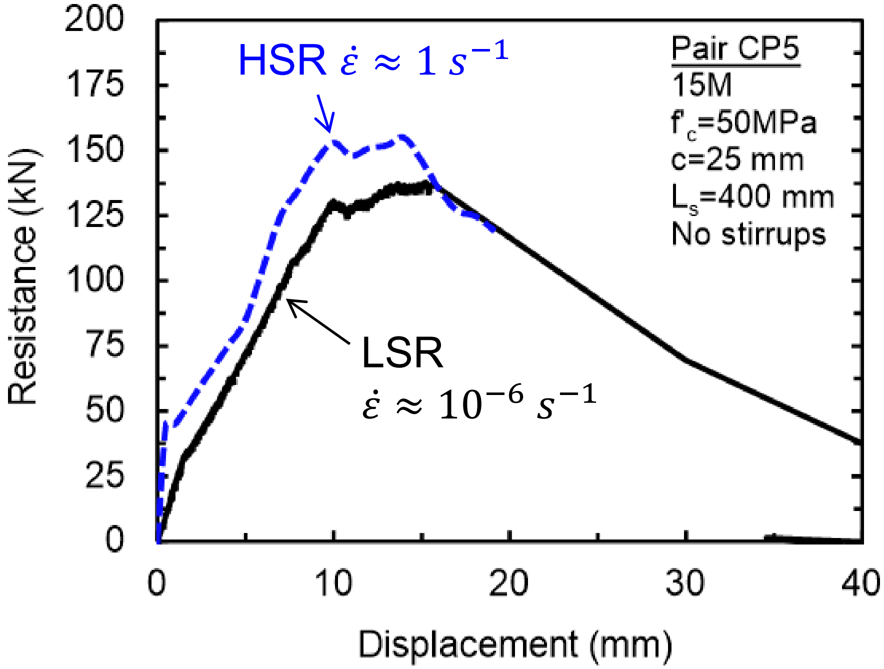



CP4-HSR
CP9-HSR
Unconfined splice
Confined splice

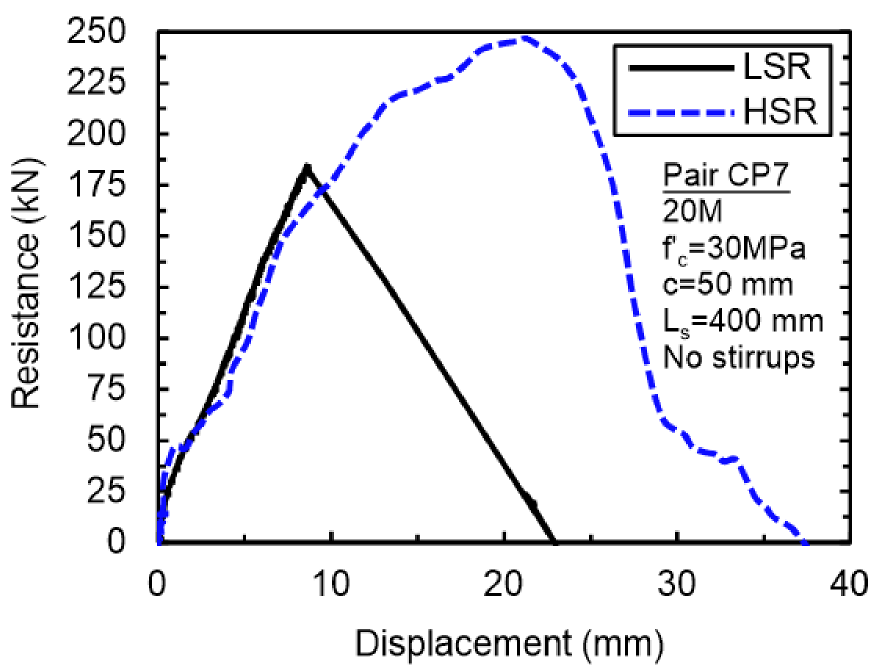
Post-Test Photographs

CP3-HSR | CP4-HSR | CP5-HSR | CP6-HSR | CP9-HSR | CP10-HSR | CP11-HSR

After Testing



Resistance (kN)
Displacement (mm)
HSR $\dot{\varepsilon} \approx 1\ s^{-1}$
LSR
$\dot{\varepsilon} \approx 10^{-6}\ s^{-1}$
Pair CP5
15M
f'c=50MPa
c=25 mm
Ls=400 mm
No stirrups



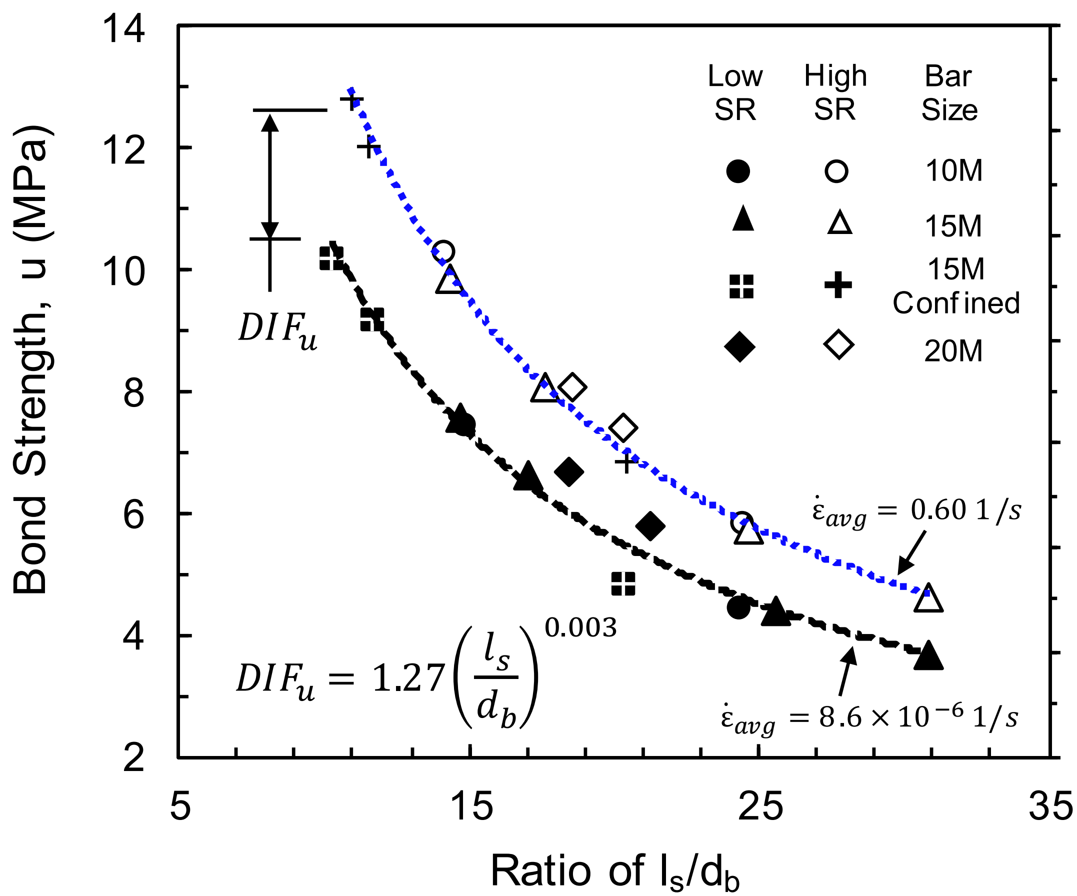
Resistance (kN)
Displacement (mm)
LSR
HSR
Pair CP7
20M
f'c=30MPa
c=50 mm
Ls=400 mm
No stirrups

Dynamic Bond Strength

- Maximum bond strength u developed at splice failure

$$u = \frac{f_s A_b}{\pi d_b l_s} \quad \text{(MPa)}$$

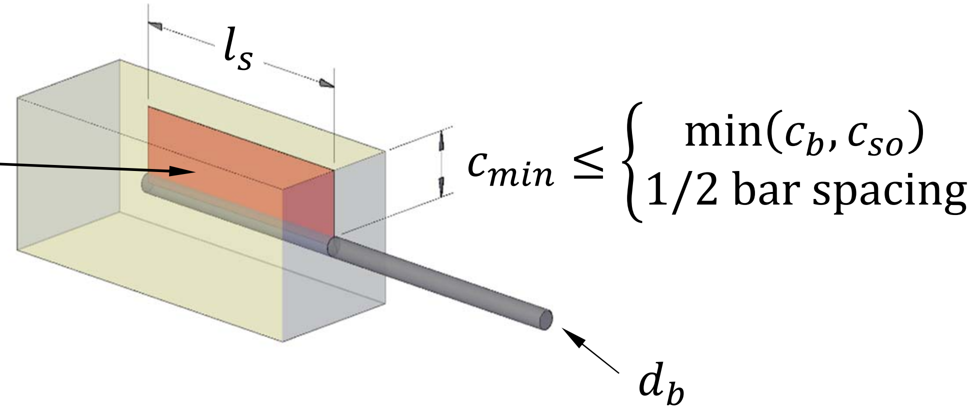
Effect of:
- Concrete strength ?
- Bar size ?
- Cover depth ?
- Transverse reinforcement ?



Dynamic Bond Force

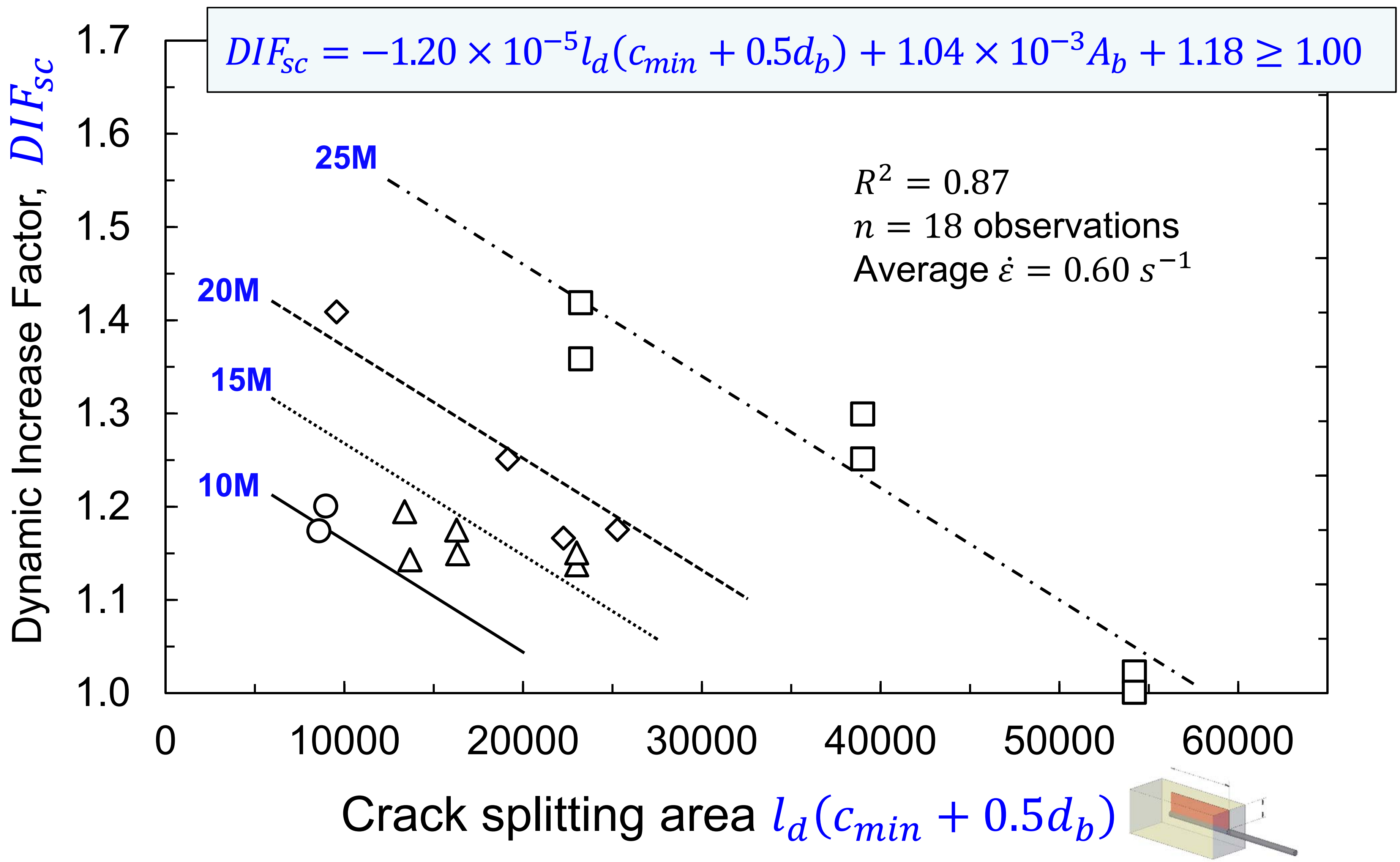
- Normalize **total bond force** $T_b = f_s A_b$ w.r.t to ${f_c'}^{0.25}$ to investigate influence of structural configuration

Crack splitting area:
$l_s(c_{min} + 0.5d_b)$



Strain rate sensitivity of **structural configuration**: $DIF_{sc} = \dfrac{\text{Dynamic}}{\text{Static}} = \dfrac{T_{db}/{f_{dc}'}^{0.25}}{T_b/{f_c'}^{0.25}}$

Influence of Structural Configuration for Unconfined Splices

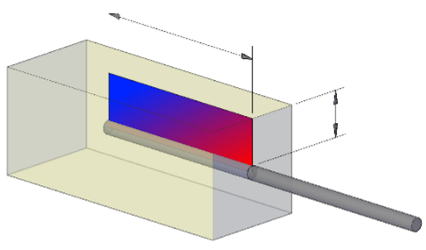


Practical Significance

$$DIF_{sc} = \underbrace{-1.20 \times 10^{-5} l_d (c_{min} + 0.5 d_b)}_{①} + \underbrace{1.04 \times 10^{-3} A_b}_{②} + 1.18 \geq \underbrace{1.00}_{③}$$

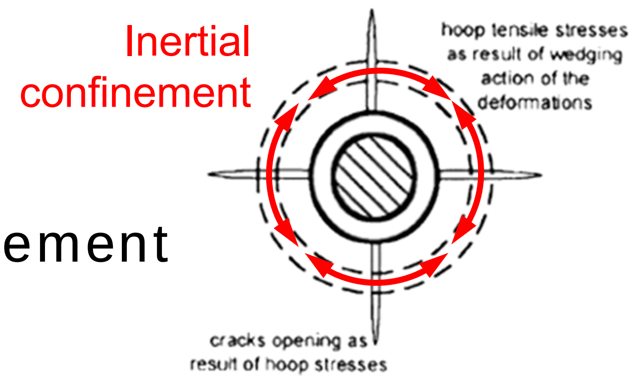
① $\uparrow l_d (c_{min} + 0.5d), \downarrow DIF_{sc}$

- Bond forces are not uniform
- Bond failures are localized & incremental



② $\uparrow A_b, \uparrow DIF_{sc}$

- Wedging action of lugs
- Activates lateral inertial confinement



③ Lower limit DIF_{sc} indicates no strain rate decrease

Protective Design

1. Minimum dynamic development length l_{dd} shall be calculated by:

$$l_{dd} = \frac{1}{DIF_{l_d}} \left(\frac{3}{40} \frac{S_{f_y}}{\lambda \sqrt{S_{f_c'}}} \frac{\psi_t \psi_e \psi_s}{\left(\frac{c_b + K_{tr}}{d_b} \right)} \right) d_b \geq 300\ mm$$

where:

$S_{f_y} = ASF \times DIF$ for steel

$S_{f_c'} = ASF \times DIF$ for concrete

$DIF_{l_d} = -1.10 \times 10^{-5} l_d d_{cs} + 8.50 \times 10^{-4} A_b + 1.11 \geq 1.00$

2. Valid for far-range blast effects $Z > 1.2\ m/kg^{1/3}$
3. Check development for all other load combinations
4. Satisfy all detailing requirements specified in ASCE/SEI 59-11

Reduction in dynamic development length of $\approx 15\%$ compared with current practice

Summary

1. Established the high strain rate bond characteristics of realistically proportioned reinforced concrete structures

2. Understand influence of key parameters

3. Incorporate bond DIF into the design process

Thank you!

Eric Jacques, Ph.D., P.Eng.
Assistant Professor
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061
ejacques@vt.edu
(540) 231-2903

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