VIRGINIA TECH

Department of Civil and Environmental Engineering

Structural Engineering and Materials

Development of Design Recommendations for Hooked Bar Lap Splices

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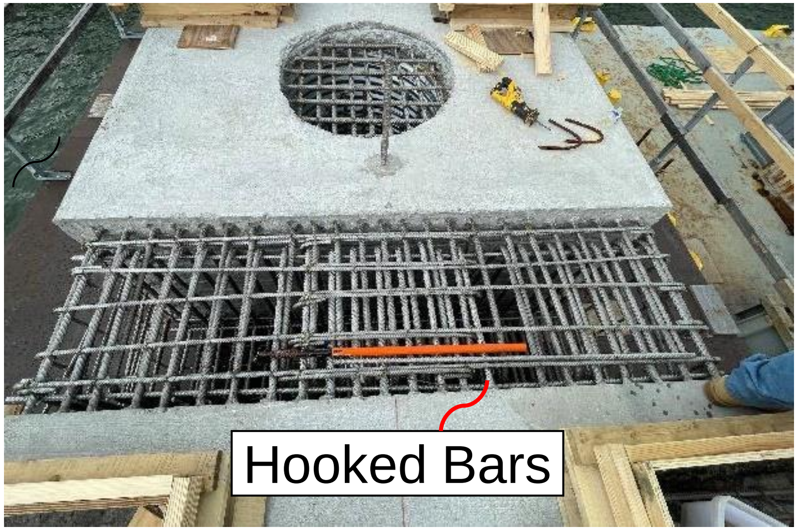
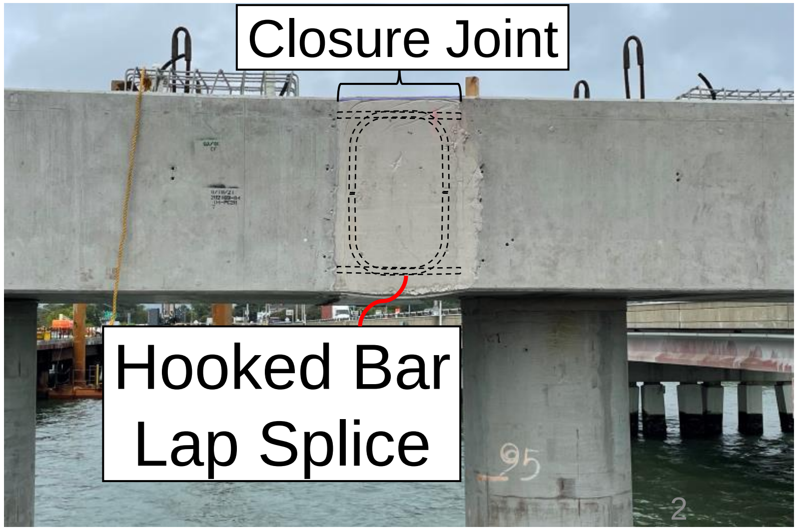
Background

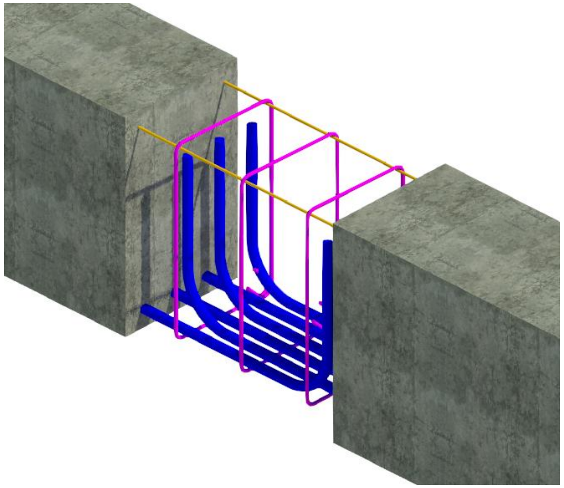
Hooked Bar Lap Splices

- Used to reduce required splice lengths in precast concrete construction
- Presently no code guidance; design of splices is speculative
- Research aims to develop design recommendations for hooked splices

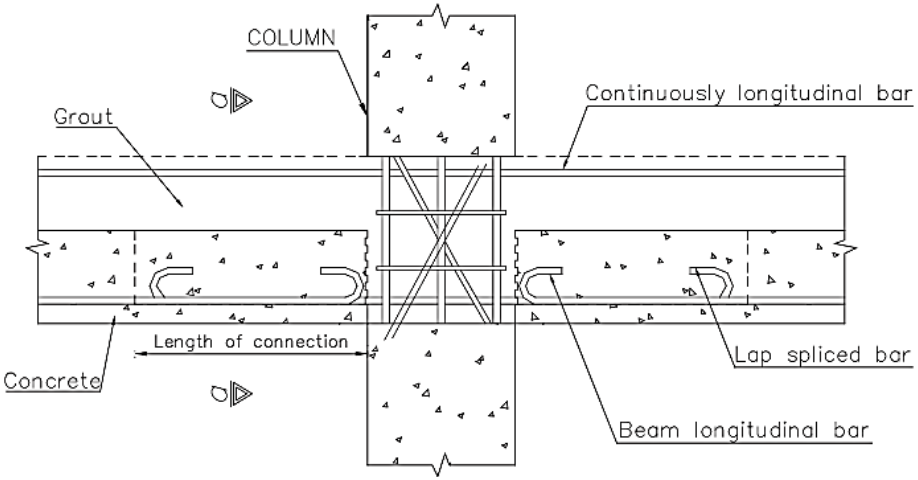




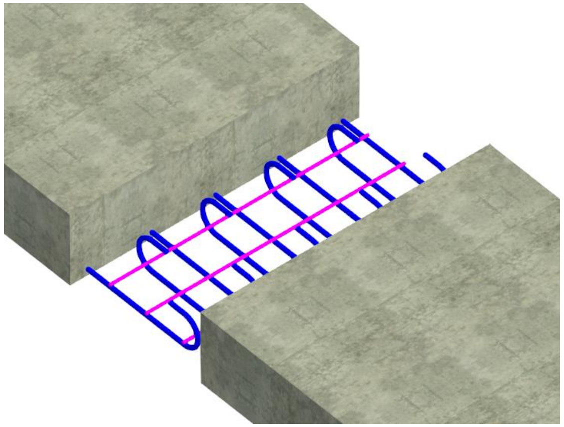
Applications of Hooked Bar Lap Splices



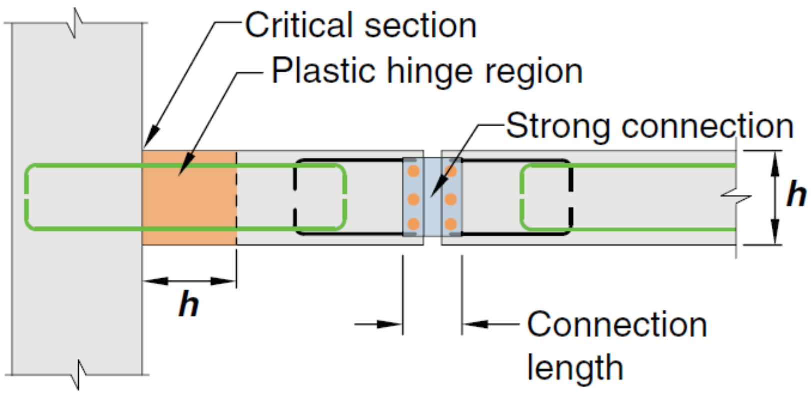
Beam-to-Beam



Precast Moment Frame (Parastesh et al. 2014)



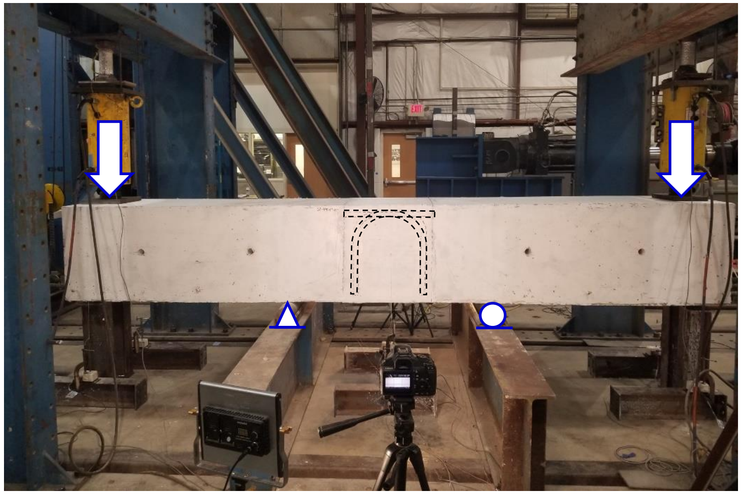
Deck-to-Deck



(a) Beam-to-beam connection

Precast Moment Frame (ACI 318 2019)

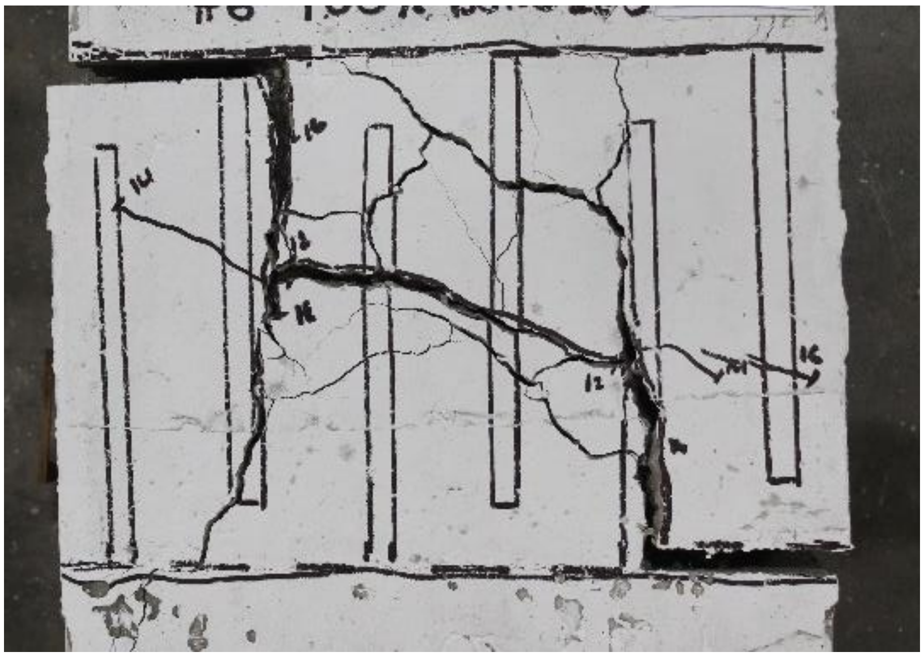
Experimental Tests form Basis for Design Recommendations

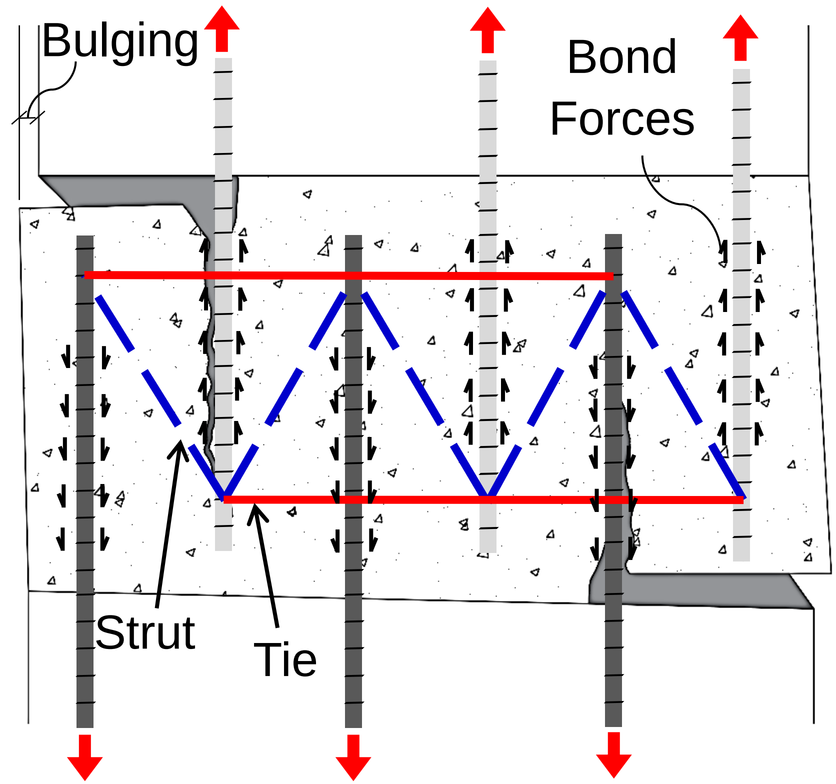


Review of Testing Program

- 64 specimens in test matrix examining the influence of: splice length, concrete strength, bar size, splice spacing, cover, hook shape, number of layers of hooks, beam depth, casting position, transverse reinforcement, bar bundles, and steel fibers

Resistance Mechanism of Hooked Bar Lap Splices





Simplified Resistance Mechanism of Noncontact Hooked Bar Lap Splices

Database for Developing Design Equation for Hooked Bar Lap Splices

Question: Can existing hooked bar development length equations be used to design hooked bar lap splices?

- Consider 54 of 64 test specimens
- Exclude atypical configurations (e.g., fiber-reinforced concrete)

Summary of Parameters in Hooked Bar Lap Splice Database

Parameter	Range
Lap Length l_s	7.83–35.75 in.
Bar Diameter d_b	0.75–1.41 in.
Splice Spacing s_l	0.75–8.11 in.
Minimum of Side and Top Cover c_{min}	1.42–3.26 in.
Concrete Compressive Strength f_{cm}	3.26–5.86 ksi
Splice Strength f_s	38.9–81.0 ksi

Development Length Equations Considered

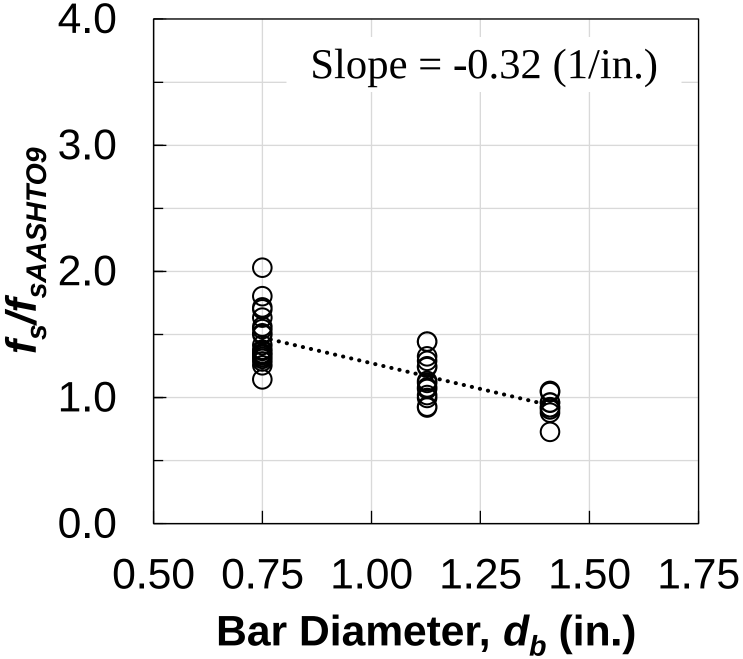
Development Length Equations Examined as Basis for Hooked Bar Lap Splice Equation

Reference	Development Length Equation	Recast Equation for Stress
ACI 318-19	$l_{dh} = \frac{f_y \Psi_e \Psi_r \Psi_o \Psi_c}{55\lambda\sqrt{f_{cm}}} d_b^{1.5}$	$f_{s,ACI} = \frac{55\lambda\sqrt{f_{cm}} l_s}{\Psi_e \Psi_r \Psi_o \Psi_c d_b^{1.5}}$
AASHTO 9th Ed.	$l_{dh} = \frac{f_y \lambda_{cw} \lambda_{rc}}{50\lambda\sqrt{f_{cm}}} d_b$	$f_{s,AASHTO9} = \frac{50\lambda\sqrt{f_{cm}} l_s}{\lambda_{cw}\lambda_{rc} d_b}$
AASHTO 10th Ed.	$l_{dh} = 0.17 d_b \lambda_{rl} \lambda_{cf} \lambda_{rc} \left(\frac{f_y - \frac{F_h}{A_b}}{350\lambda f_{cm}^{0.25}} \right)^2$	$f_{s,AASHTO10} = \frac{F_h}{A_b} + 350\lambda f_{cm}^{0.25} \sqrt{\frac{l_s}{0.17\lambda_{rl}\lambda_{cf}\lambda_{rc} d_b}}$

Evaluation Approach: Test-to-Calculated Stresses

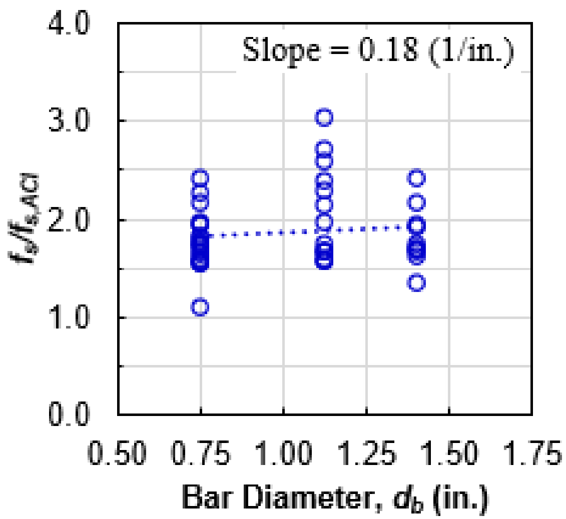
Can divide experimental stresses f_s by calculated stresses using any of the design equations (e.g.,$f_{s,AASHTO9}$) to calculate the test-to-calculated stress ratio (e.g., $f_s/f_{s,AASHTO9}$)

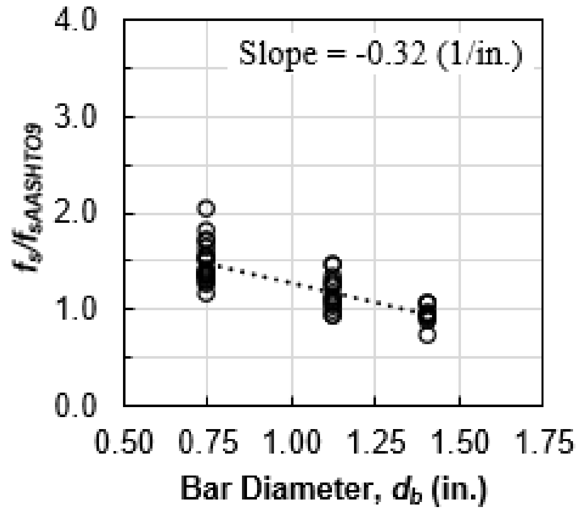
- Perfect agreement: $f_s/f_{s,AASHTO9} = 1.0$
- Conservative: $f_s/f_{s,AASHTO9} > 1.0$
- Unconservative: $f_s/f_{s,AASHTO9} < 1.0$
- Ideally, minimize COV of $f_s/f_{s,AASHTO9}$

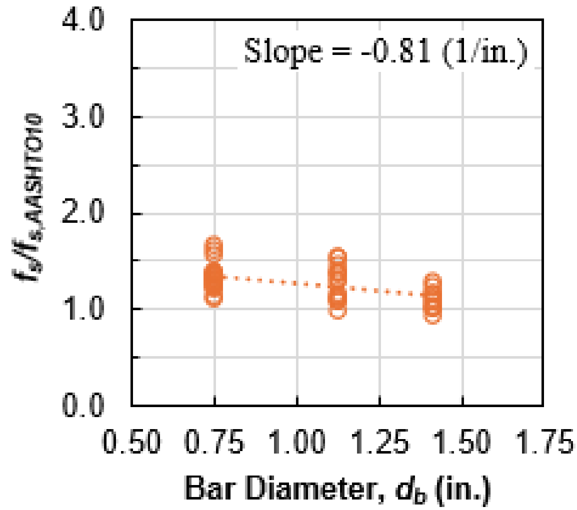


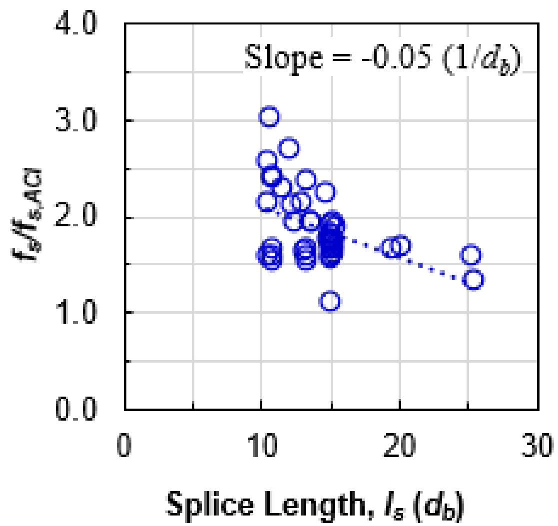
Sample Plot of Test-to-Calculated Stress Ratios (Slope of 0 is Ideal)

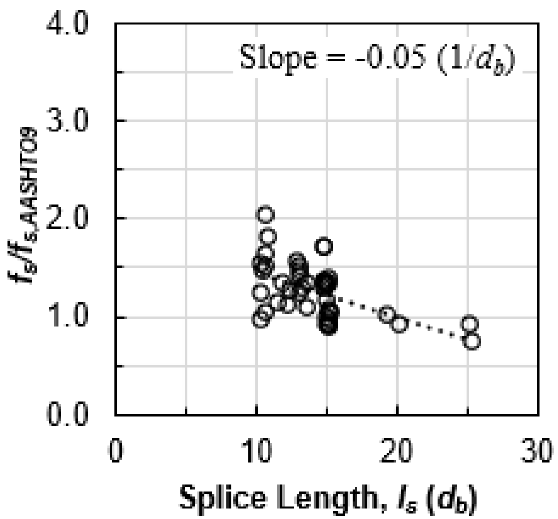
ACI 318-19	AASHTO 9th Edition	AASHTO 10th Edition
Mean = 1.87	Mean = 1.24	Mean = 1.26
COV = 0.20	COV = 0.23	COV = 0.13

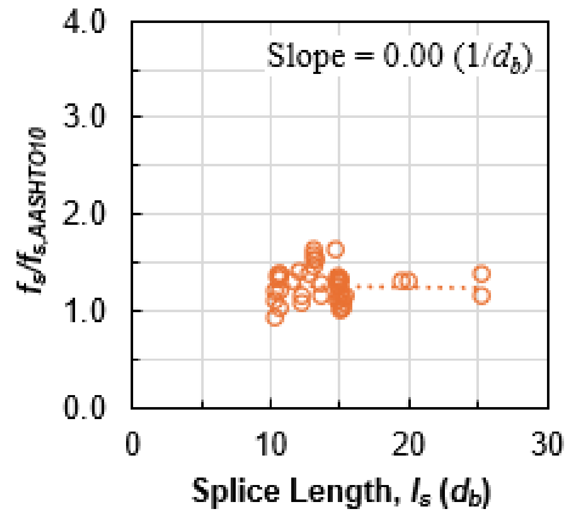




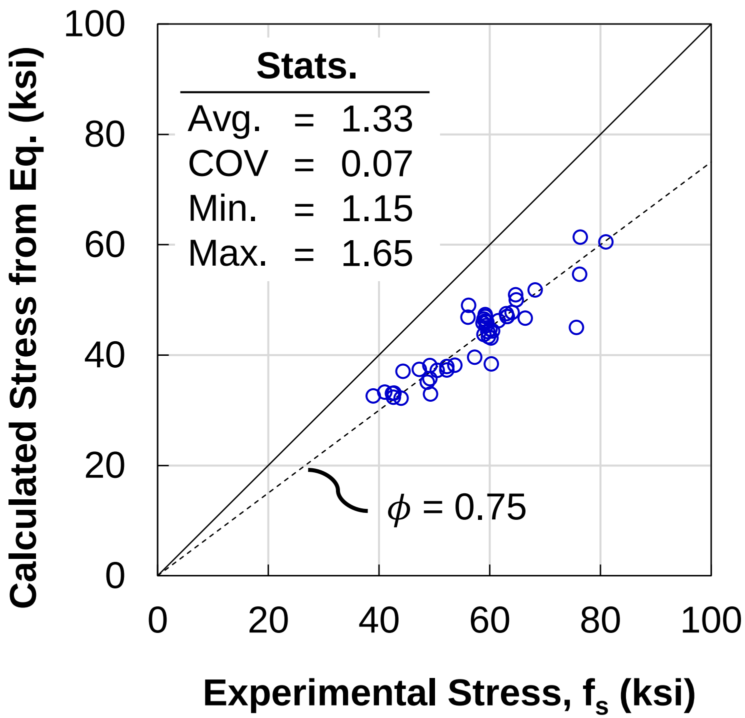








Design Equation for Required Splice Length of Hooked Bars



Regression…

$$l_s = \left(\frac{f_y^{1.5} s_l^{0.05}}{8{,}000\sqrt{f_c'}\left(\frac{c_{min}}{d_b} + K_{tr}\right)^{0.33}} \right) d_b^{1.5}$$

[lb, in.]

l_s: lap length of hooked bars

f_y: yield strength of reinforcing bars

s_l: inter-splice bar spacing

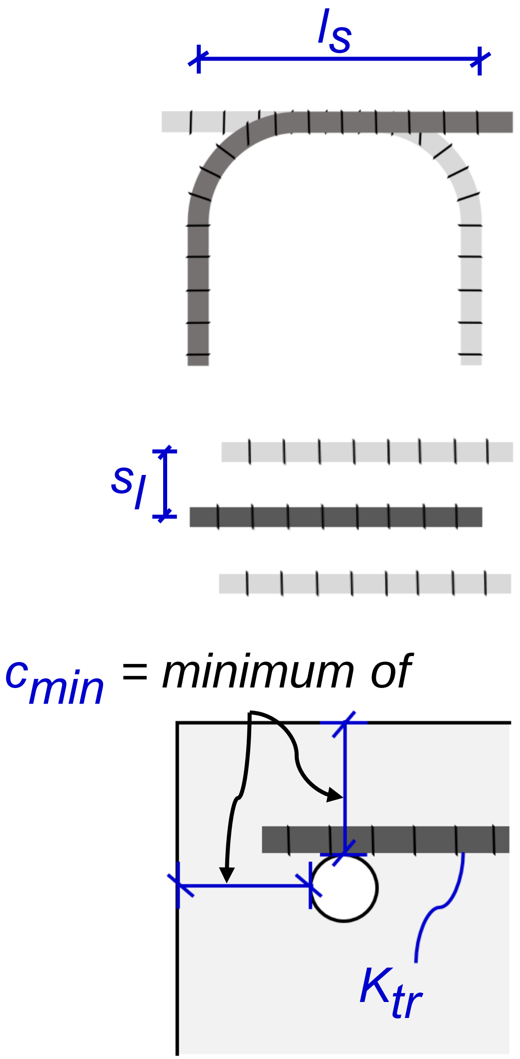
d_b: diameter of reinforcing bar

f_c': specified concrete compressive strength

c_{min}: minimum clear cover

K_{tr}: index of transverse reinforcement

Design Equation for Required Splice Length of Hooked Bars



Section through Splice

$$l_s = \left(\frac{f_y^{1.5} s_l^{0.05}}{8{,}000\sqrt{f_c'}\left(\frac{c_{min}}{d_b} + K_{tr}\right)^{0.33}} \right) d_b^{1.5} \quad \text{[lb, in.]}$$

l_s: lap length of hooked bars;

f_y: yield strength of reinforcing bars

s_l: inter-splice bar spacing

d_b: diameter of reinforcing bar

f_c': specified concrete compressive strength

c_{min}: minimum clear cover

K_{tr}: index of transverse reinforcement

Transverse Reinforcement, K_{tr}

$$K_{tr} = 6.5NA_{tr1}$$

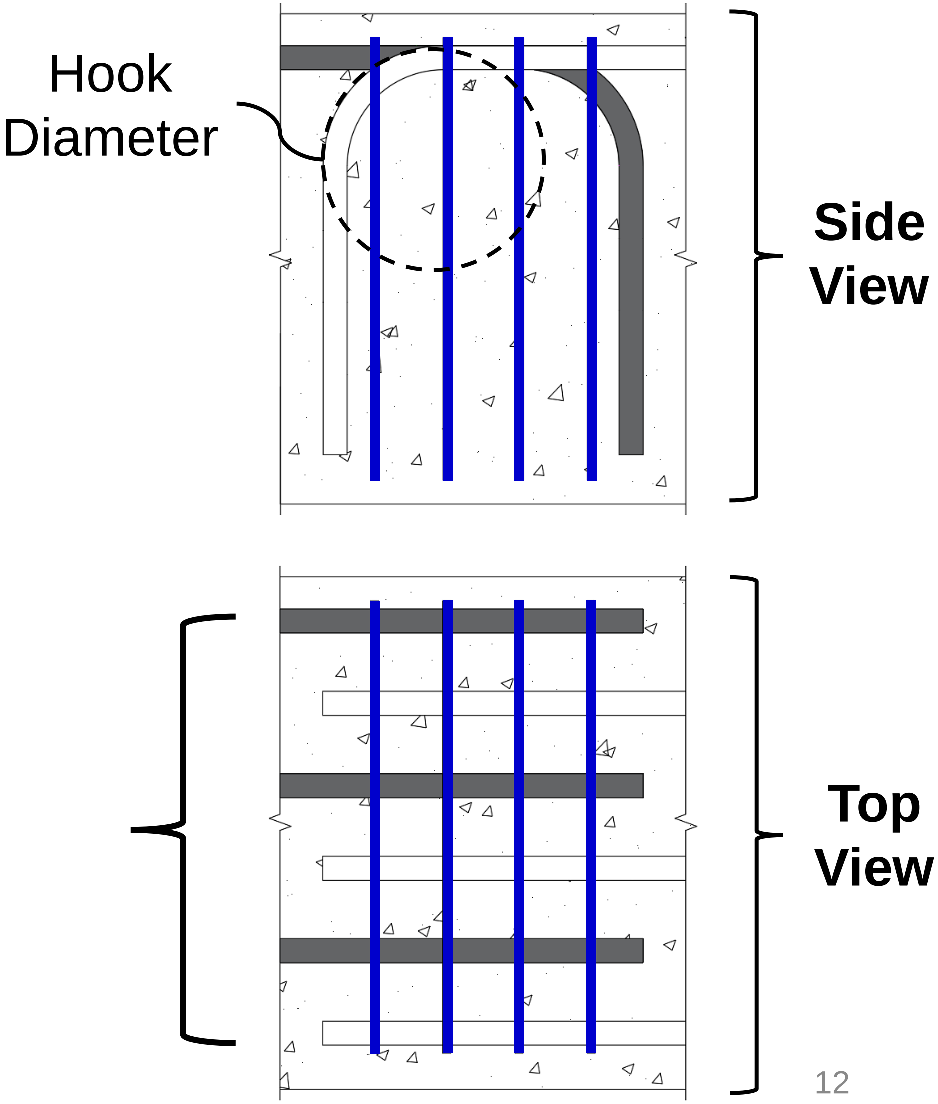
N: number of legs of transverse reinforcement within one outer bend diameter from the top of the hook;

A_{tr1}: area of one leg of transverse reinforcement

Example

N = 4 (4 ties within lap length)

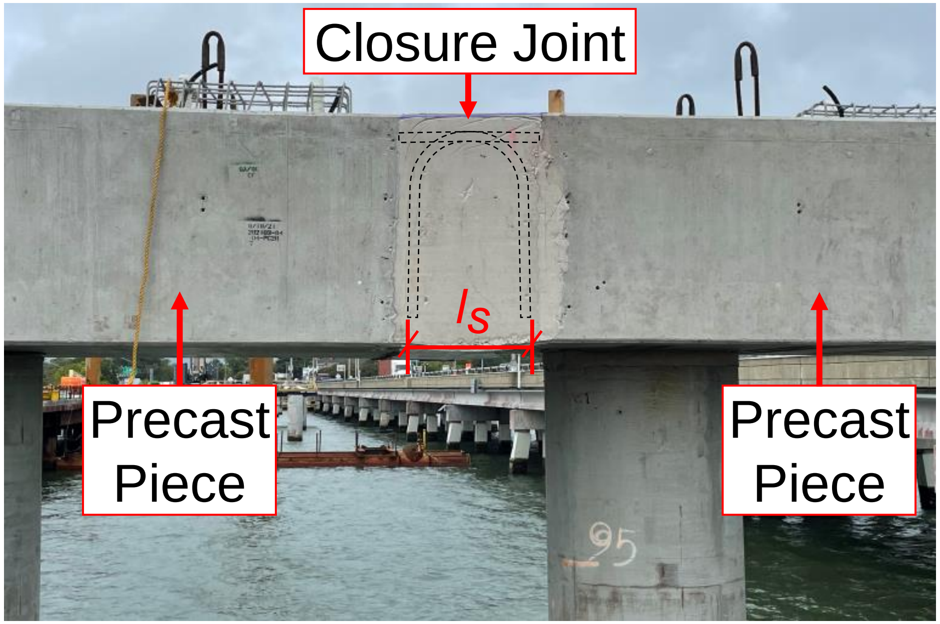
$$K_{tr} = 6.5(4)A_{tr1} = 26A_{tr1}$$



Design Example: Precast Bent Cap

Determine Required Splice Length of Hooked bars

- Similar to Hampton Roads Bridge Tunnel Expansion Project
- Design parameters
    - ❖ Cap Width, b = 72 in.
    - ❖ Required steel, $A_{s,req}$ = 15 in^2
    - ❖ Cover, c_{min} = 2 in.
    - ❖ Concrete strength, f_c' = 6 ksi
    - ❖ Normalweight concrete



Closure Joint Containing Hooked Splices Connecting Precast Pieces

Preliminary Considerations

Use 10 pairs (N_{bs} = *10)* of spliced No. 11 (d_b = 1.41 in.) hooks in primary layer of reinforcement

$$s_l = \frac{b - 2c_{min}}{2N_{bs} - 1} = \frac{72 - 2(2\text{ in.})}{2(10) - 1} = 3.58\text{ in.}$$

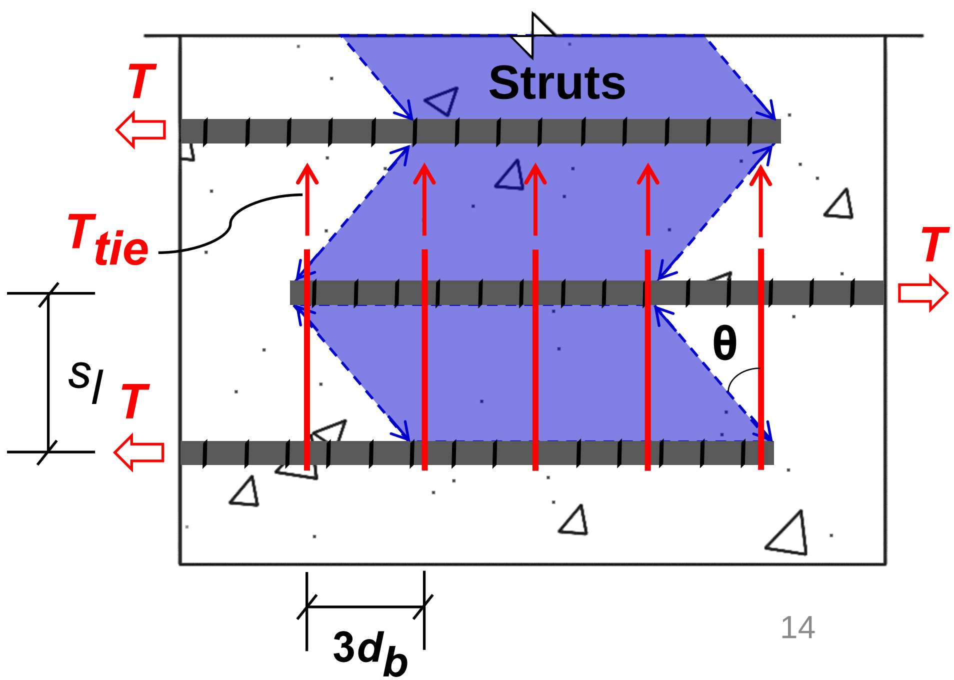
Size five ties spaced at 3d_b

$$\theta = \tan^{-1}\frac{3d_b}{s_l} = 50°$$

$$T = A_b f_y = (1.56\text{ in}^2)(60\text{ ksi}) = 94\text{ kips}$$

$$T_{tie} = \frac{0.25T}{\tan\theta} = 20\text{ kips}$$

$$A_{tie} \geq \frac{T_{tie}}{\phi f_{yt}} = \frac{20\text{ kips}}{0.9(60\text{ ksi})} = 0.37\text{ in}^2$$



Required Hooked Bar Splice Length

Use two-bar bundles of No. 4 bars as tie reinforcement

$$K_{tr} = 6.5NA_{tr1} = 7.5(5)(0.4\ \text{in}^2) = 13$$

$$\frac{c_{min}}{d_b} + K_{tr} = \frac{2}{1.41} + 13 = 14.4$$; Limited to 8.0 for splice length equation

$$l_s = \left(\frac{{f_y}^{1.5} {s_l}^{0.05}}{8{,}000\sqrt{f_{c'}}\left(\frac{c_{min}}{d_b} + K_{tr}\right)^{0.33}}\right) {d_b}^{1.5};\ l_s = \left(\frac{60{,}000^{1.5} 3.58^{0.05}}{8{,}000\sqrt{6{,}000}(8)^{0.33}}\right) 1.41^{1.5}$$

$$l_s = 21\ \text{in.}$$

What if the Design Used Only Straight Bars?

Use the same bond and anchorage parameters to calculate the required lap length per Article 5.10.8.4.3 of AASHTO LRFD (2020)

$$l_s = 1.3 \times 2.4 d_b \frac{f_y}{\sqrt{f_c'}} \left(\frac{\lambda_{rl} \lambda_{cf} \lambda_{rc} \lambda_{er}}{\lambda} \right)$$

$$l_s = 1.3 \times 2.4(1.41) \frac{60{,}000}{\sqrt{6{,}000}} \left(\frac{1.3 \times 1 \times 0.4 \times 1}{1} \right) = 56.0 \text{ in.}$$

Design Summary:

- The required straight bar splice length is 56.0 in., ~ 35 in. longer than that required for the hooked splices

Conclusions

1. Noncontact hooked bar lap splices transfer force through diagonal compression struts and tension ties transverse to the lapped bars
2. The ACI 318-19, AASHTO LRFD (9^{th} ed.), and AASHTO LRFD (10^{th} ed.) development length equations were found to be ineffective to design hooked bar lap splices
3. Based on test results from 54 beam specimens, a design equation for the minimum required lap length of hooked bars was developed with a COV of test-to-calculated stresses of 7%

Are there any Questions at this Time?

References:

American Association of State Highway and Transportation Officials (AASHTO). 2020. *LRFD Bridge Design Specifications*. 9th ed. Washington, DC: 1,867 pp.

American Concrete Institute (ACI). 2019. *Building Code Requirements for Structural Concrete (ACI 318-19).* Farmington Hills, MI: 623 pp.

Bayrak, O. 2023. “Approved Changes to the Ninth Edition *AASHTO LRFD Bridge Design Specifications*” Reinforcing Bar Anchorage,” *Aspire* Winter 2023: 4 pp.

Parastesh, H., I. Hajirasouliha, and R. Ramezani. 2014. “A New Ductile Moment-Resisting Connection for Precast Concrete Frames in Seismic Regions: An Experimental Investigation,” *Engineering Structures* 70: pp. 144–157.

The Following are Extra Slides to Address Questions

Approach to Developing New Equation for Hooked Bar Lap Splices

All three of the hooked bar development length equations were deficient in some manner and could be improved

- Will develop an empirical equation for the strength of hooked bar lap splices using the same database and multivariable power regression

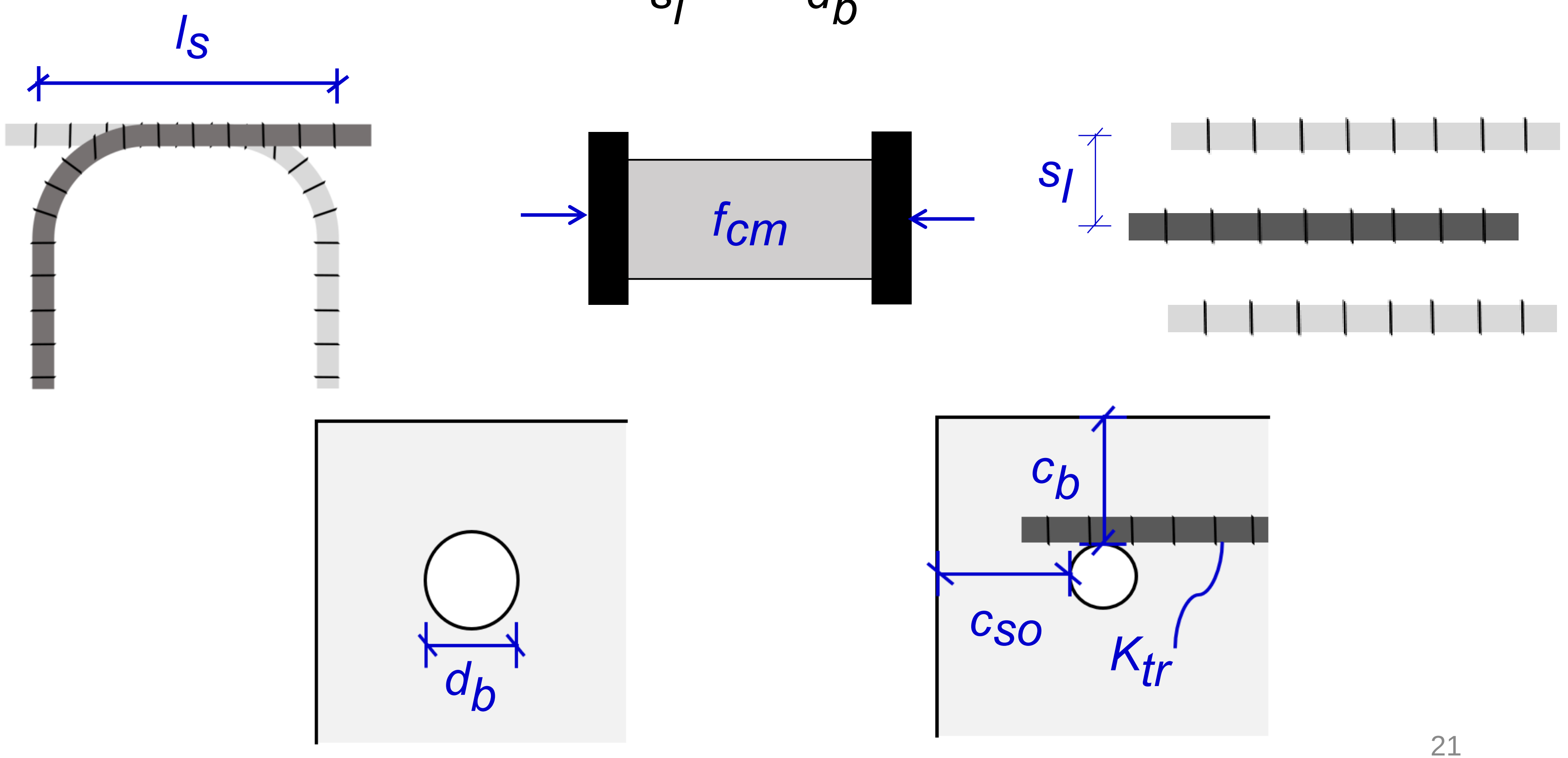
Select powers (p_1) to minimize sum of squared differences between experimental and predicted splice strength:

$$f_s{}^{p} = p_1 l_s{}^{p_2} f_{cm}{}^{p_3} d_b{}^{p_4} s_l{}^{p_5} \left(\frac{\text{Cover}+K_{tr}}{d_b}\right)^{p_6}$$

- Transverse reinforcement term, K_{tr}, also determined using regression

Descriptive Equation for Strength of Hooked Bar Lap Splices

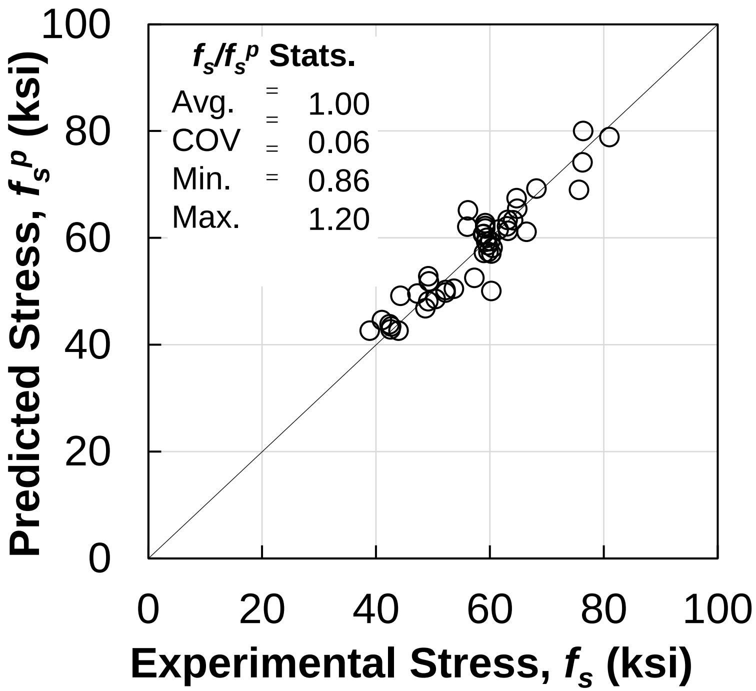
$$f_s^{\,p} = \frac{570\, l_s^{0.67} f_{cm}^{0.33} \left(\frac{0.1c_{so} + 0.6c_b}{d_b} + K_{tr} \right)^{0.22}}{s_l^{0.033} d_b^{1.00}}$$ **[lb, in.]**

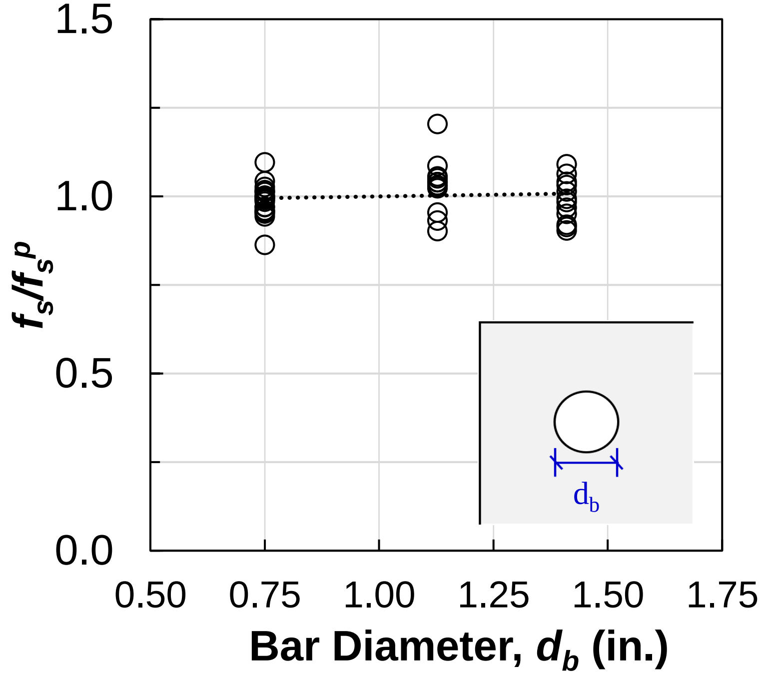


Performance of Descriptive Equation

Question: How well does the equation characterize strength?

- Mean test-to-calculated stress ratio = 1.00; COV = 0.06

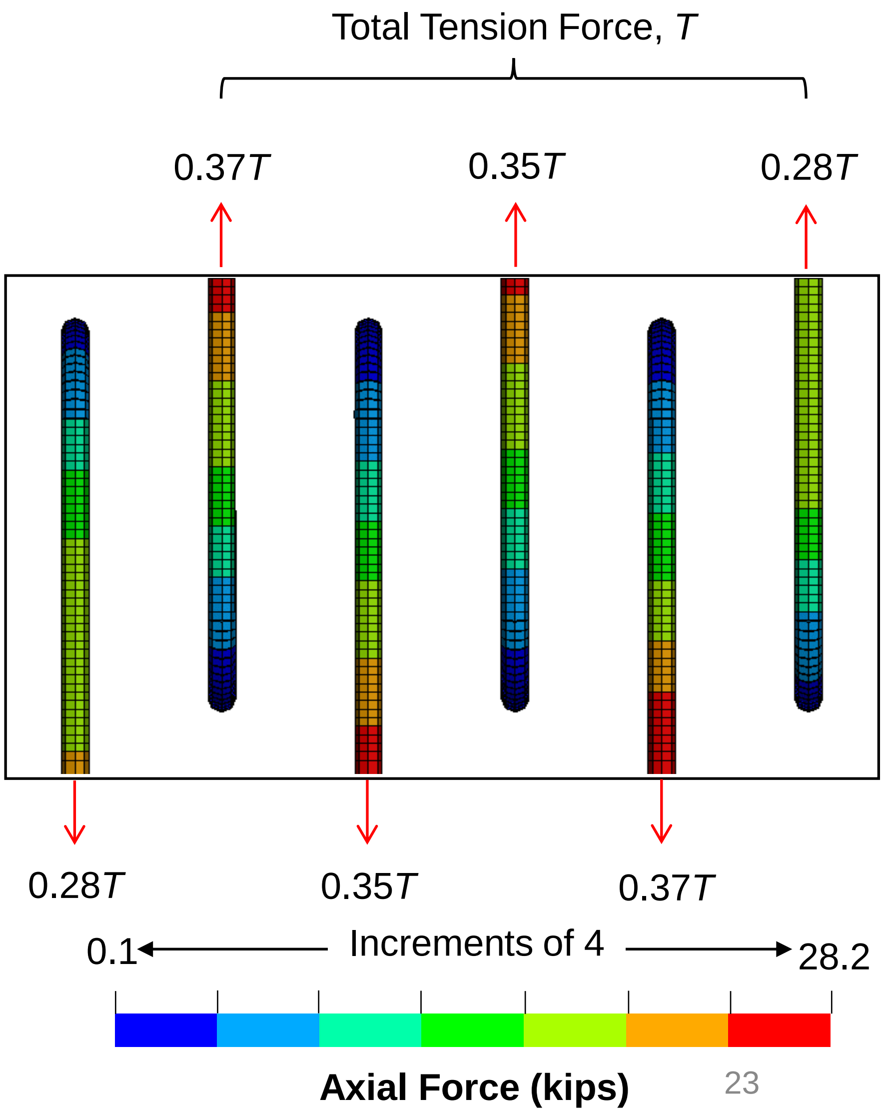




Design Equation for Splice Strength

Need to convert descriptive equation to design equation through simplification and use of safety factor

- Simplification: replace cover term with minimum cover, c_{min}
- Safety factor: could use $\Phi = 0.90$; use 0.75 to ensure all bars yield. Needed because edge bars carry less force



Design Equation for Splice Strength (cont.)

Includes Phi Factor

$$f_s{}^p = \frac{400 l_s{}^{0.67} f_{cm}{}^{0.33} \left(\frac{c_{min}}{d_b} + K_{tr}\right)^{0.22}}{s_l{}^{0.033} d_b{}^{1.00}}$$

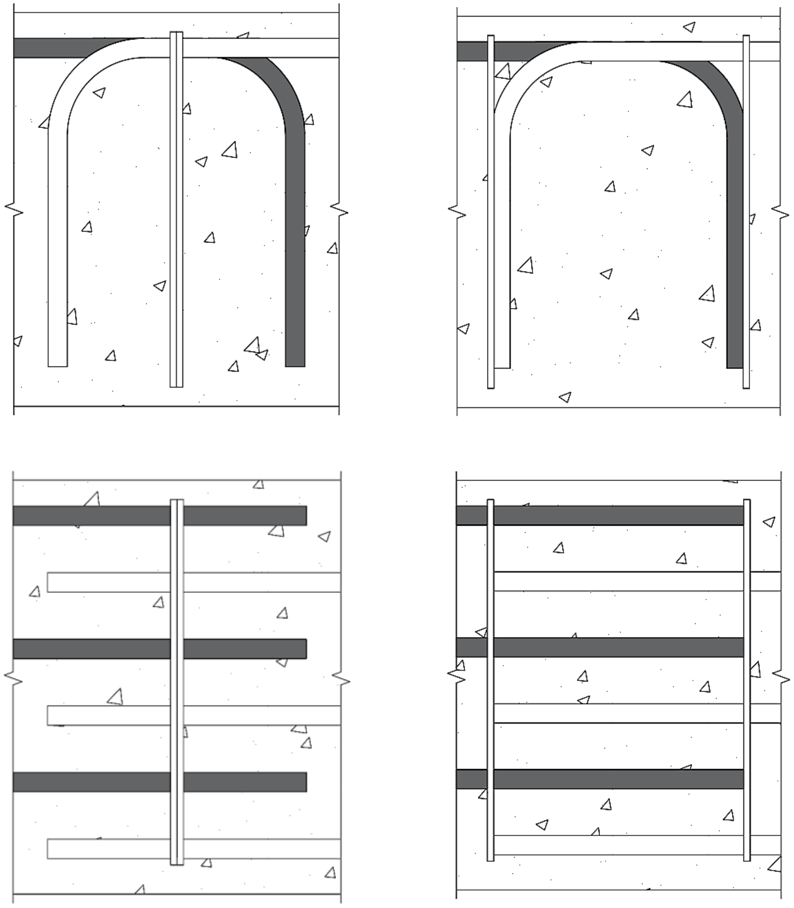
Mean = 1.33; COV = 0.07; 0% predictions < experimental strengths

Rearrange to solve for splice length as a function of splice strength.

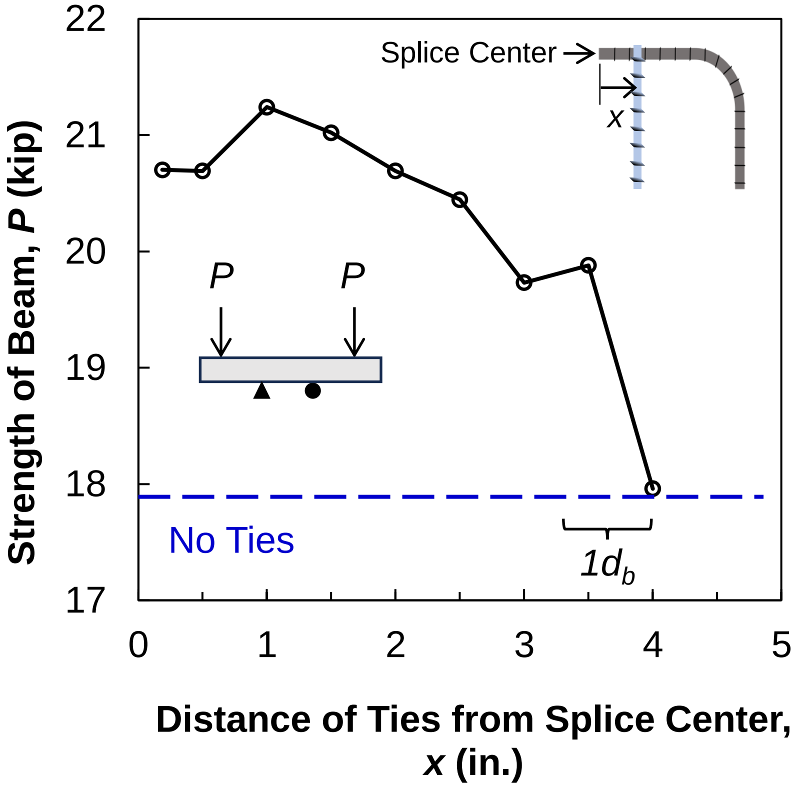
$$l_s = \left(\frac{f_y{}^{1.5} s_l{}^{0.05}}{8{,}000\sqrt{f_c'}\left(\frac{c_{min}}{d_b} + K_{tr}\right)^{0.33}}\right) d_b{}^{1.5}$$

Perpendicular Ties Should not be Within $1d_b$ from Splice Ends

Range of Possible Tie Locations



Use Parametric Study in Nonlinear FE Analysis to Investigate

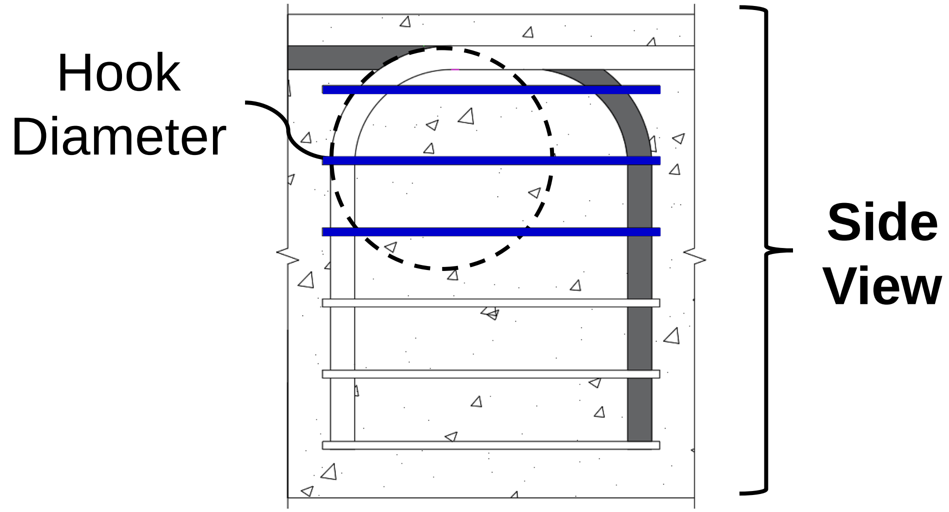


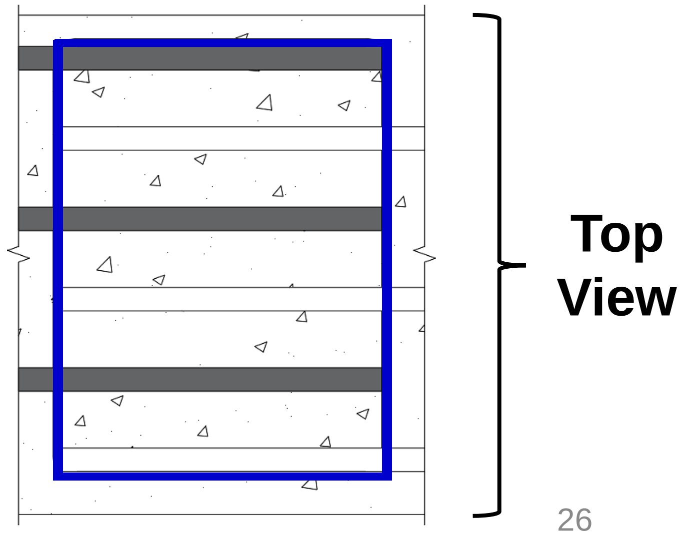
Transverse Reinforcement, K_{tr}

$$K_{tr} = 6.5NA_{tr1}$$

N: number of legs of transverse reinforcement within one outer bend diameter from the top of the hook;

A_{tr1}: area of one leg of transverse reinforcement





Parallel Confining Reinforcement

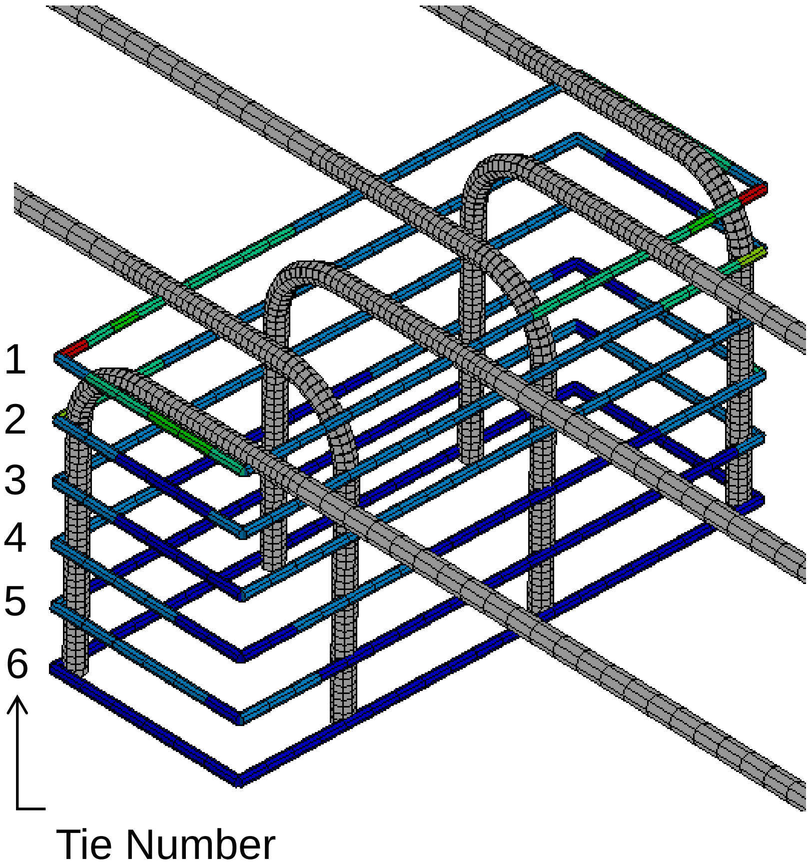
Within one outer bend diameter from top

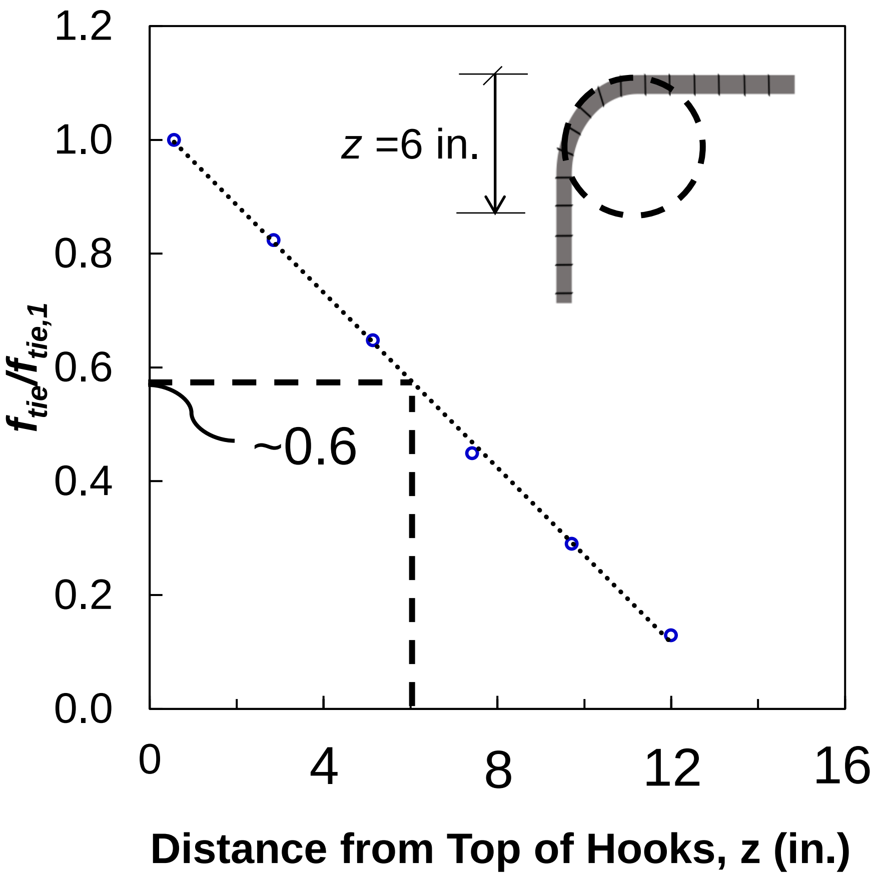
Example

N = 6 (3 ties within hook diameter, 2 legs per tie)

$$K_{tr} = 6.5(6)A_{tr1} = 39A_{tr1}$$

Parallel Ties Should not be Outside Outer Bend Diameter





f_{tie} = average stress in legs of tie transverse to splices

$f_{tie,1}$ = value of f_{tie} in Tie Number 1 (near top of hook)

Transverse Reinforcement, K_{tr}

$$K_{tr} = 6.5NA_{tr1}$$

N: number of legs of transverse reinforcement within one outer bend diameter from the top of the hook;

A_{tr1}: area of one leg of transverse reinforcement

Transverse (Lacer) Bars

Example

N = 2 (Legs confining the edge hooks)

$$K_{tr} = 6.5(2)A_{tr1} = 13A_{tr1}$$