NATIONAL ACADEMIES Sciences Engineering Medicine

TRB TRANSPORTATION RESEARCH BOARD

TRB Webinar: Steel Bridge Shear Stud—Research and Design Provisions

June 22, 2023

2:00 PM – 3:30 PM

TRB Webinar: Steel Bridge Shear Stud – Research & Design Provisions

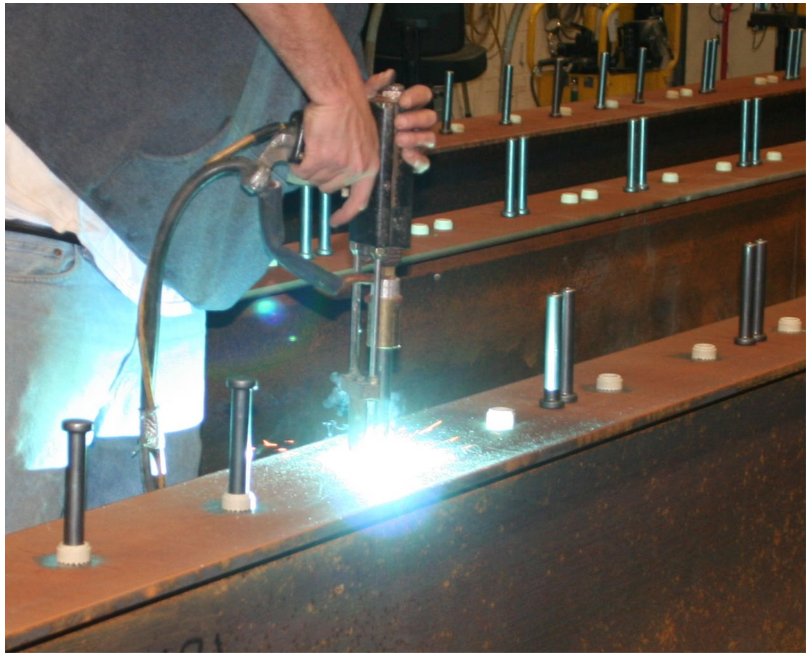
EXPERIMENTAL TESTING ON STRENGTH & FATIGUE RESISTANCE OF CLUSTERED SHEAR STUDS

Jason Provines, P.E.
Virginia Transportation Research Council, VDOT

June 22, 2023

Shear Studs

- Provide composite action between steel girder and concrete deck



Motivation for 2011 FHWA Shear Stud Research

- **Accelerated bridge construction (ABC)**
  - Clustered studs at extended spacing to facilitate precast decks?

Motivation for 2011 FHWA Shear Stud Research

- **2010 AASHTO BDS Strength Limit State**

$$Q_n = \underbrace{0.5Asc\sqrt{f'_c E_c}}_{\text{Concrete crushing}} \leq \underbrace{A_{sc}F_u}_{\text{Steel tension}}$$

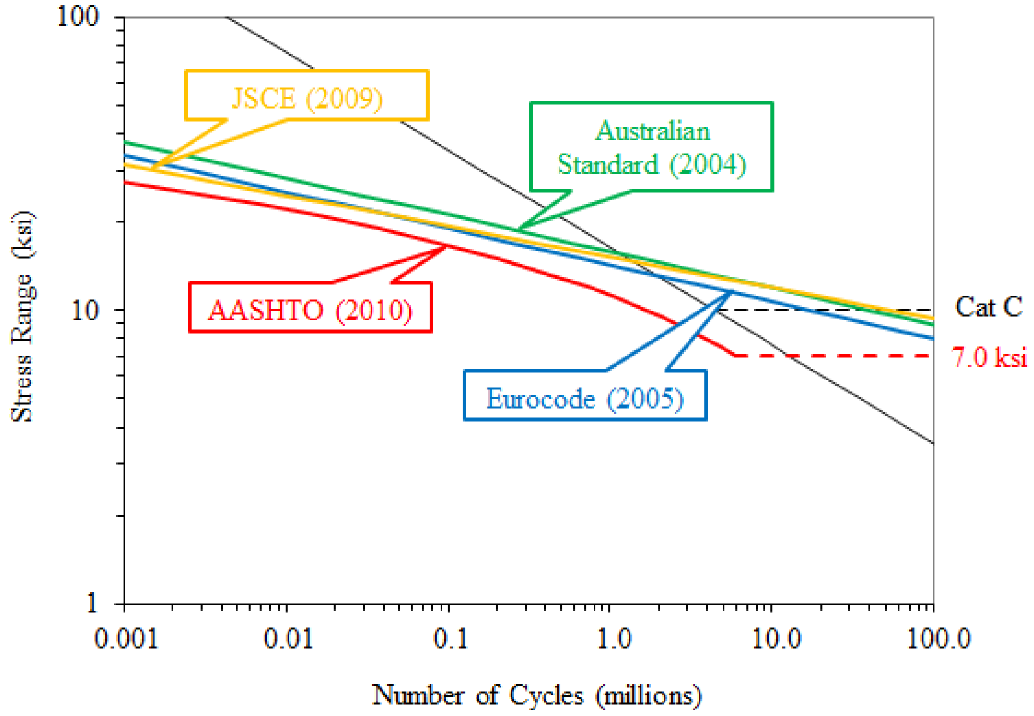
- Concrete – greater local demand due to clusters?
- Steel – unconservative, regardless of clusters?
- Alter spacing limits to accommodate clusters?
  - Max = 24”
  - Min longitudinal = 6*d*

Motivation for 2011 FHWA Shear Stud Research

- **2010 AASHTO BDS Fatigue Limit State**

Fatigue I: $Z_r = 5.5d^2$
Fatigue II: $Z_r = (34.5 - 4.28 \log N)\, d^2$

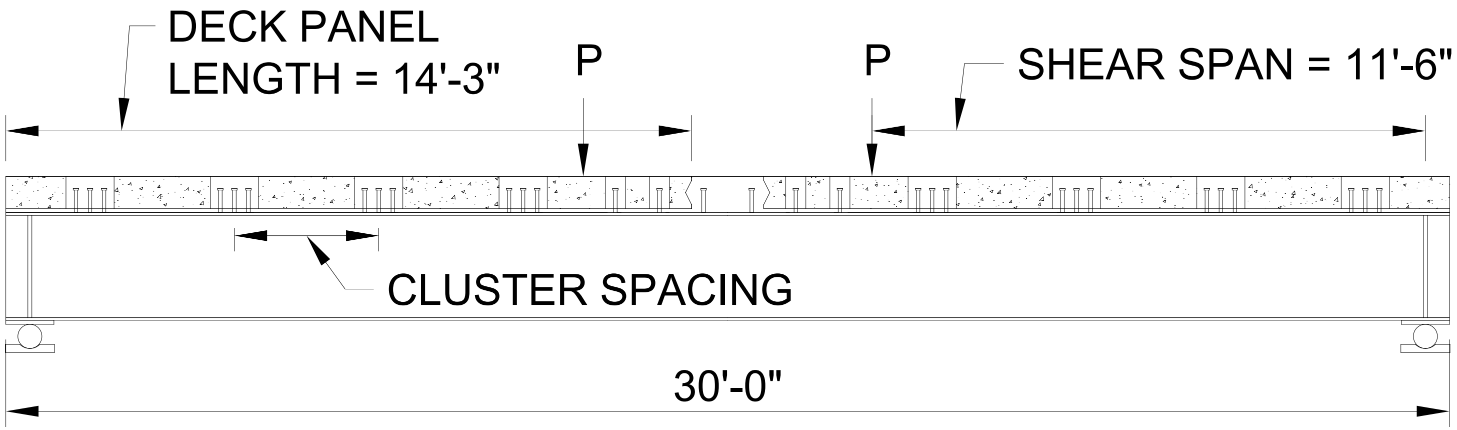
- Semi-log format?
- Too conservative for Fatigue I (infinite life)?

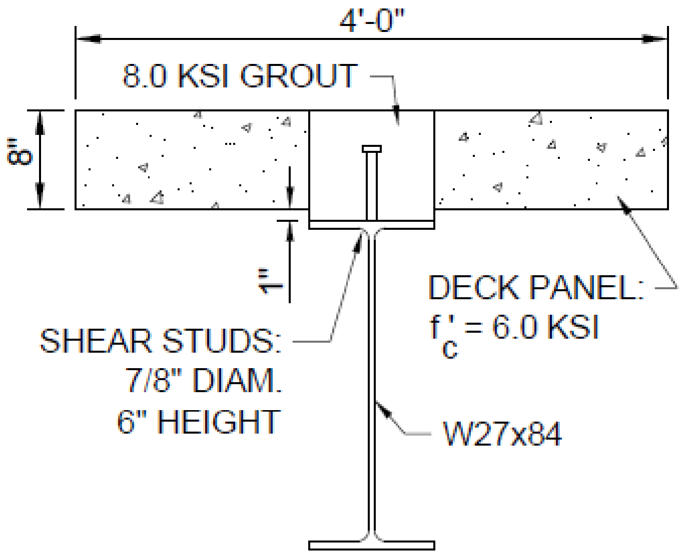


Large-Scale Experimental Testing

- **16 specimens**
  - Partial composite action to force stud failure
  - # studs constant in each shear span

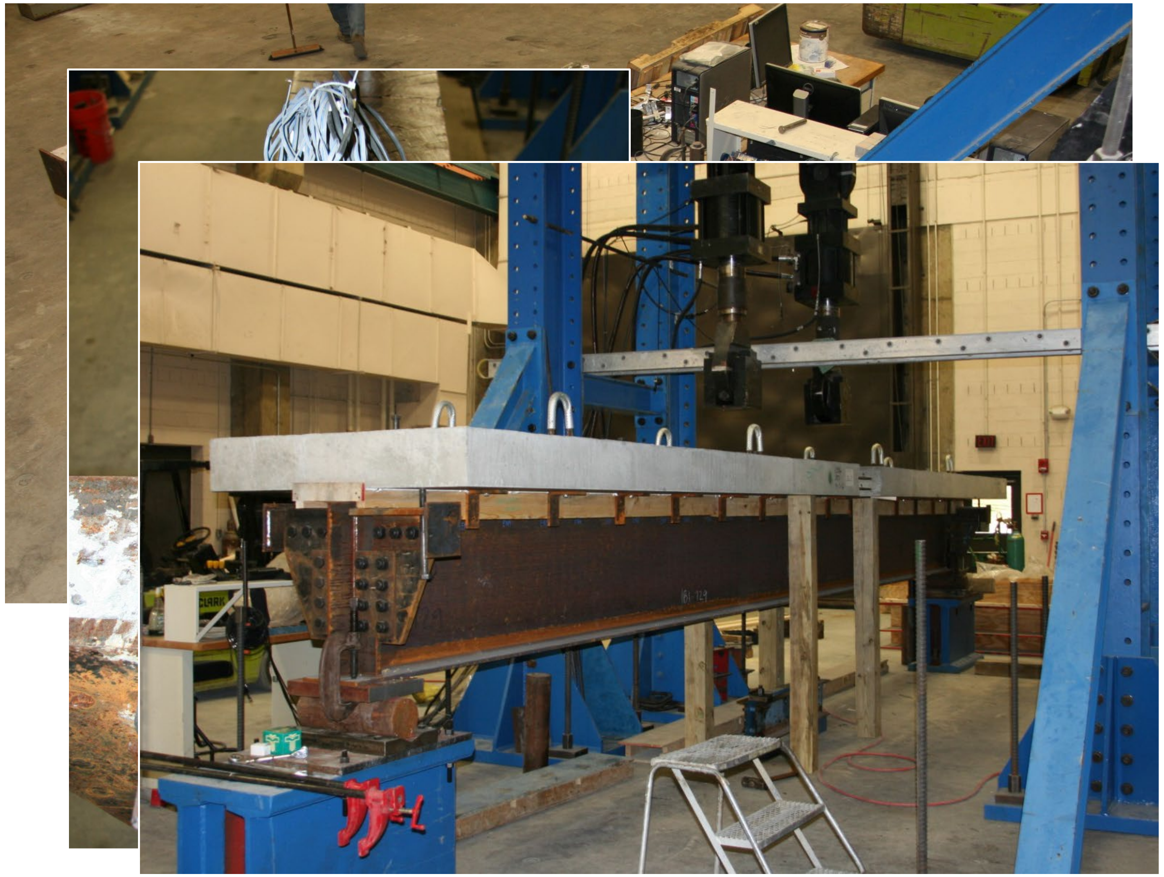
Stud Cluster Spacing	# Static Tests	# Fatigue Tests
12”	1	3
24”	1	3
36”	1	3
48”	1	3

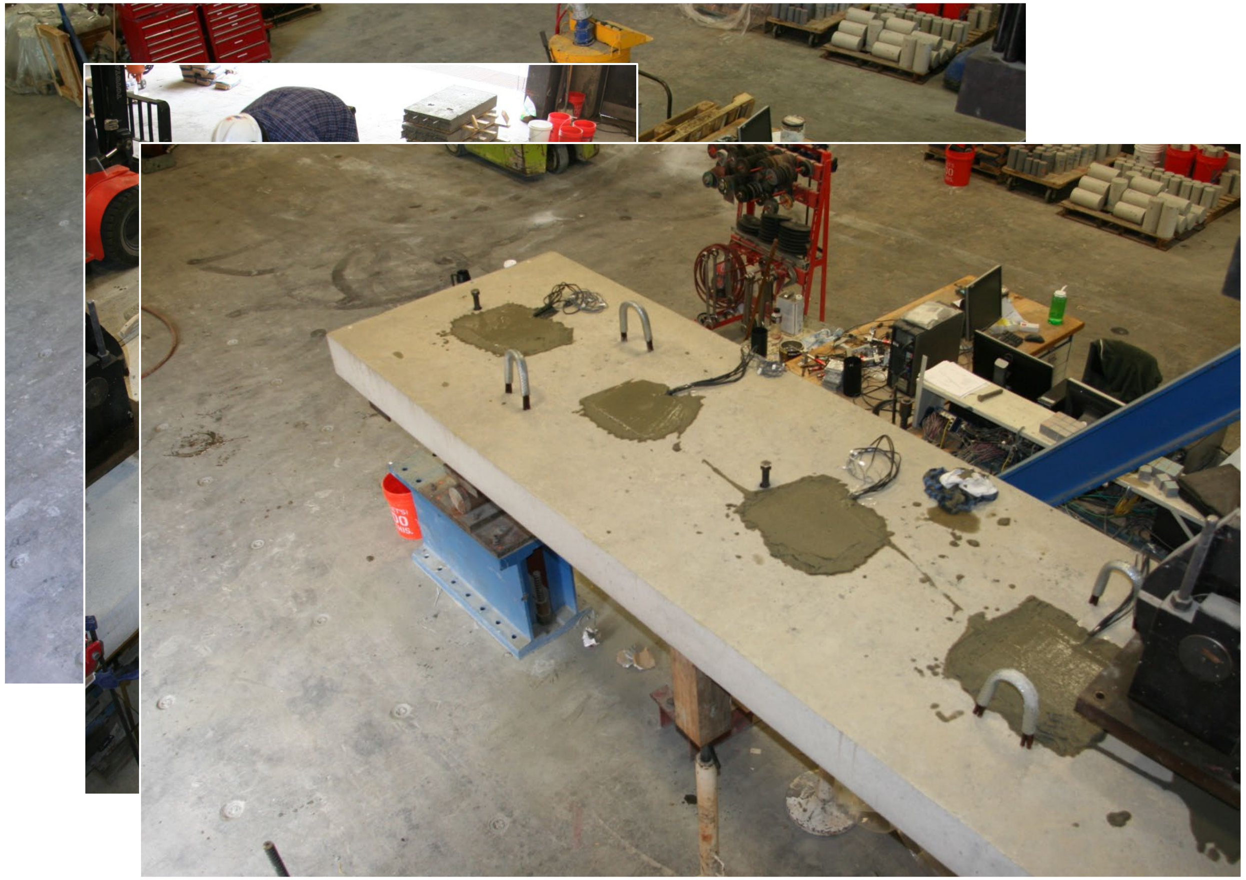




Large-Scale Experimental Testing

- Specimen construction





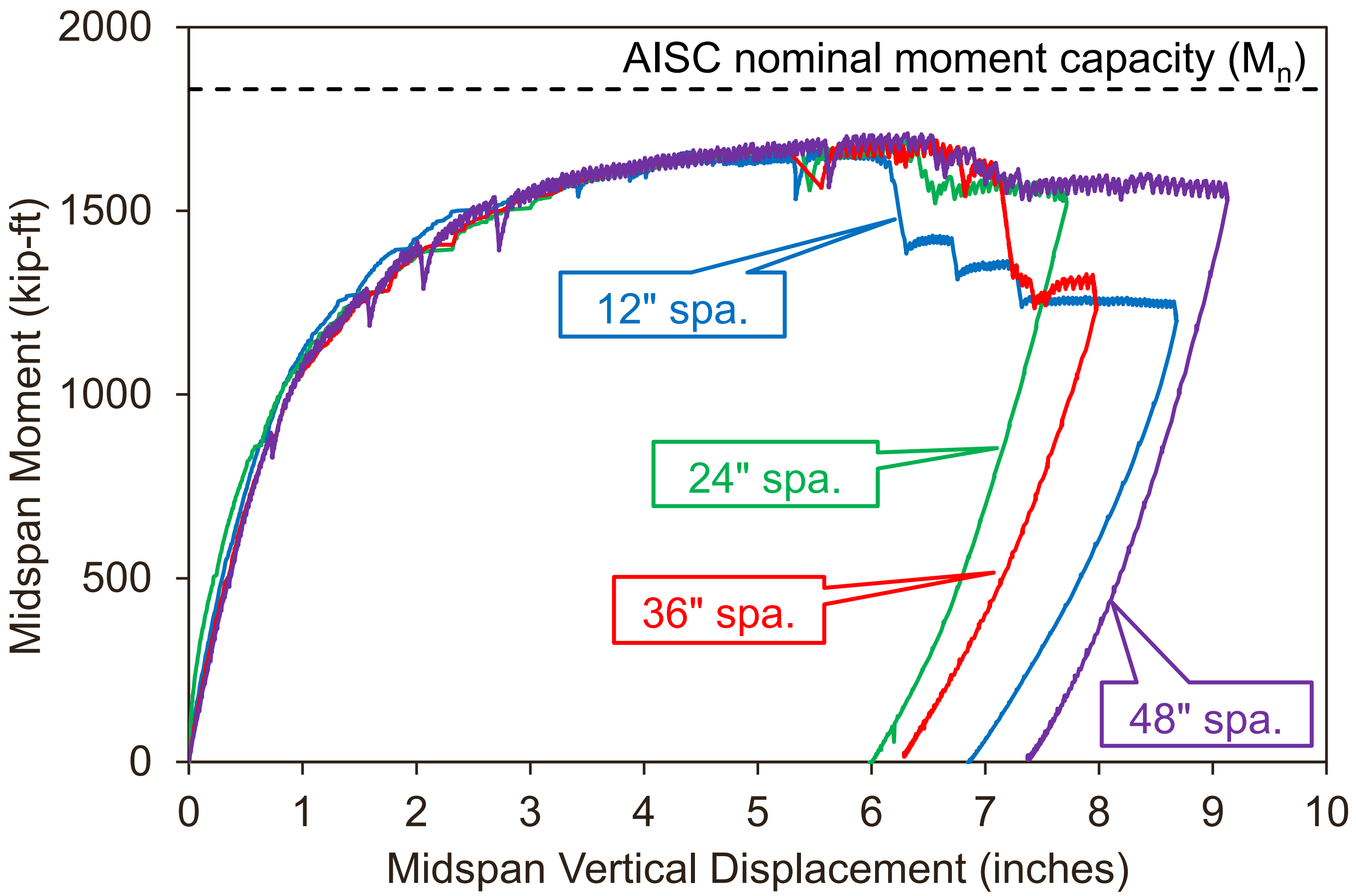
Large-Scale Static Test Results

- **Displacement increased until load dropped**

Large-Scale Static Test Results

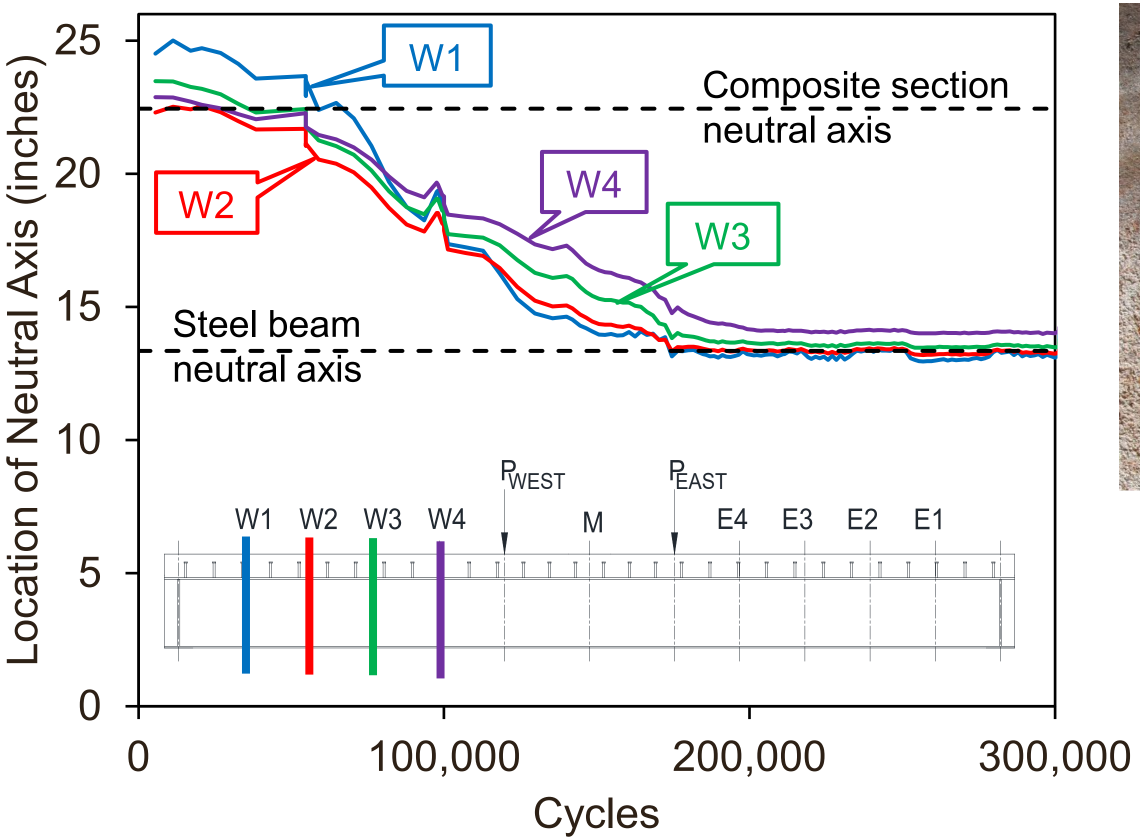
- Similar performance, regardless of cluster spacing
- Moment capacity equation unconservative
  - “Shear factor” required in front of AASHTO stud strength equation

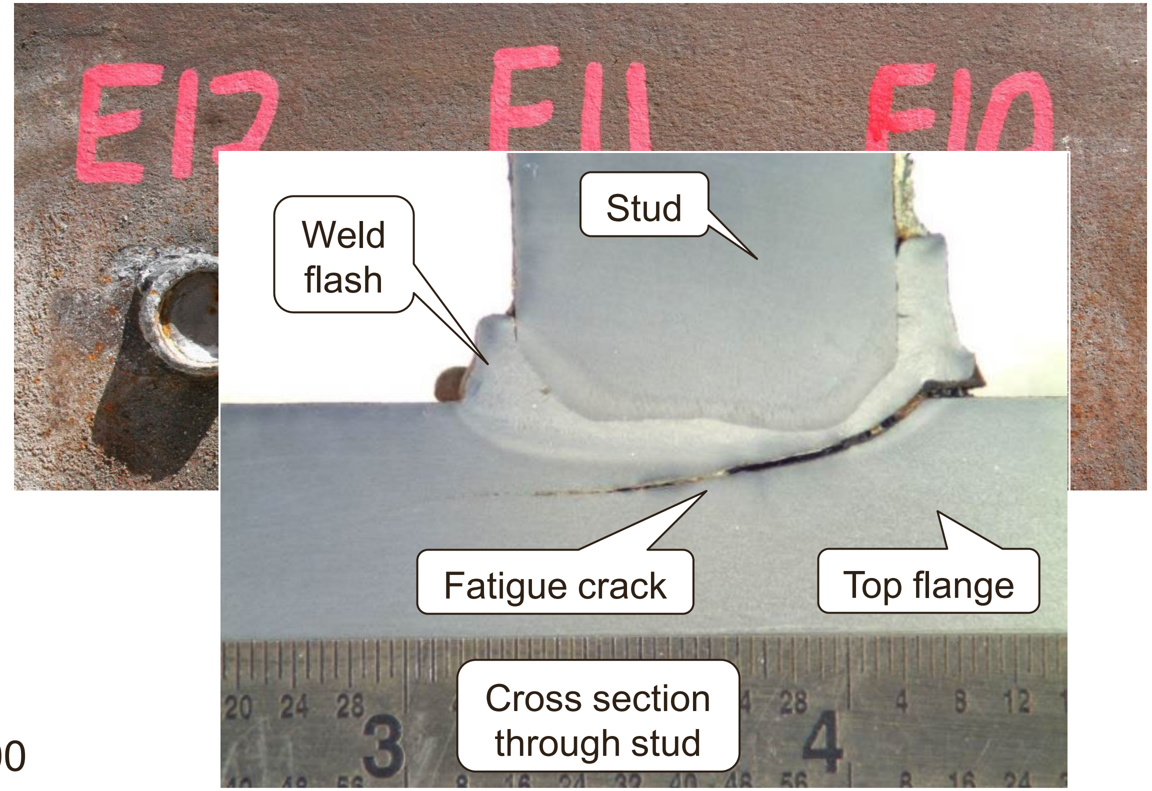
Stud Cluster Spacing	“Shear Factor”
12”	0.71
24”	0.75
36”	0.75
48”	0.78



Large-Scale Fatigue Test Results

- Cycled under constant stress range at base of studs
- What is failure?
  - Defined as complete loss of composite action in a cross section





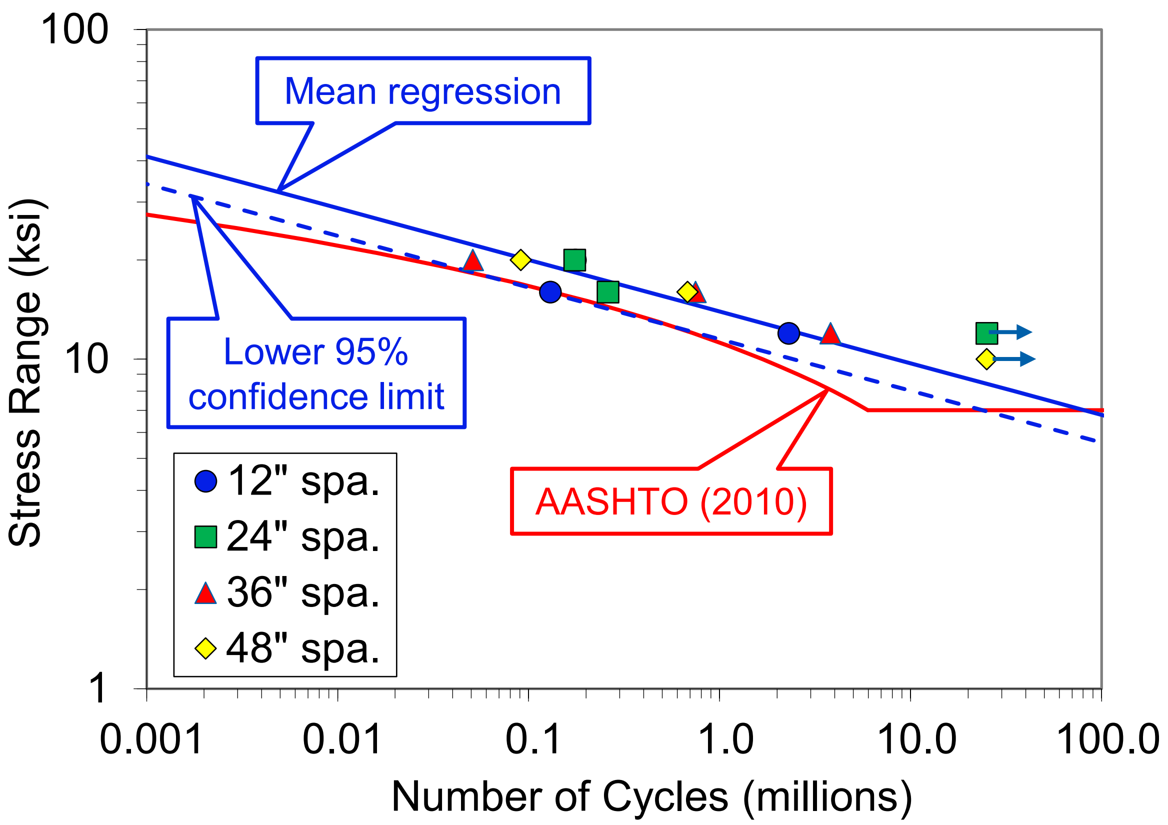
Large-Scale Fatigue Test Results

- Similar performance, regardless of cluster spacing
- CAFT of 7.0 ksi is reasonable
- Data follows log-log equation
- Regression equation with 95% confidence limit:

$$S_r = \left(\frac{A}{N}\right)^{\frac{1}{m}}$$

A = 577,00 x 10^8

m = 6.4



Small-Scale Experimental Testing

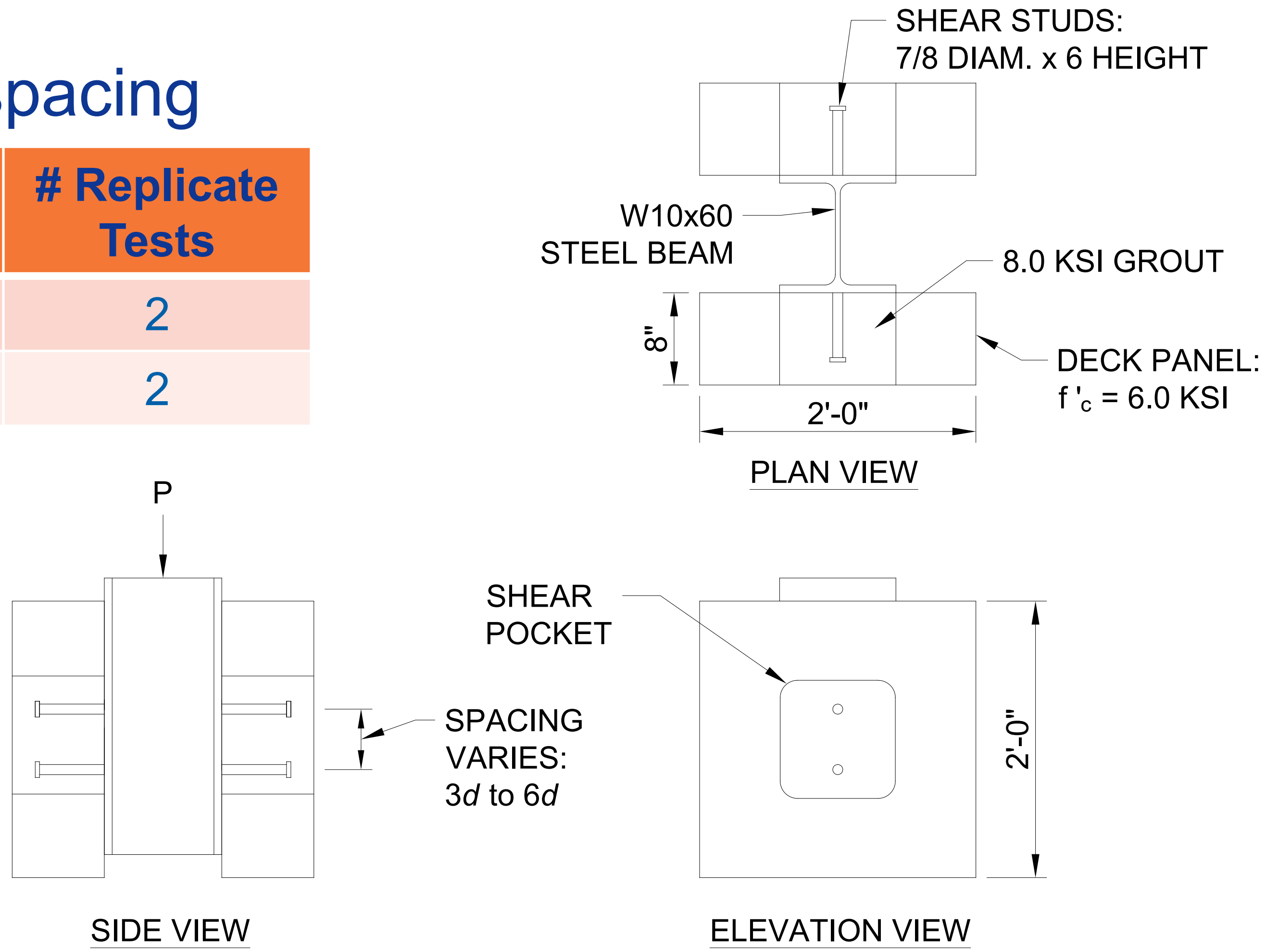
- **38 "push out" specimens**
  - 24 static tests to investigate spacing

Stud Spacing Orientation	Stud Spacing	Deck Type	# Replicate Tests
Longitudinal	*3d*, *4d*, *5d*, *6d*	CIP, PC	2
Transverse	*3d*, *4d*	CIP, PC	2

CIP = cast-in-place, PC = precast

  - 14 fatigue tests

Deck Type	# Replicate Tests
PC	14



Example of longitudinal spacing, PC deck specimen

Small-Scale Experimental Testing

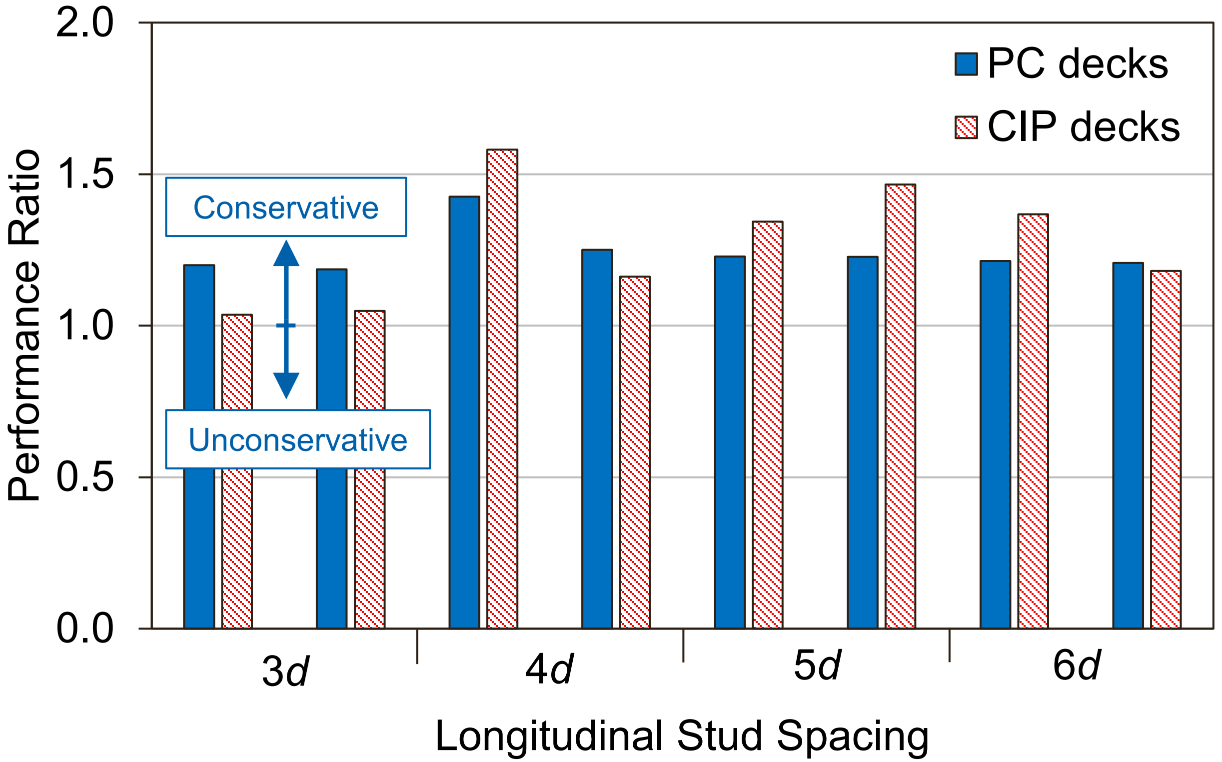
- **Specimen construction**

Small-Scale Static Test Results – Longitudinal Spacing

- Compared experimental load to calculated load

$$\text{Performance Ratio} = \frac{\text{Experimental load}}{\text{Min strength (stud, concrete, grout)}}$$

- Good performance for both CIP and PC decks
- Recommend min longitudinal spacing of 4*d*



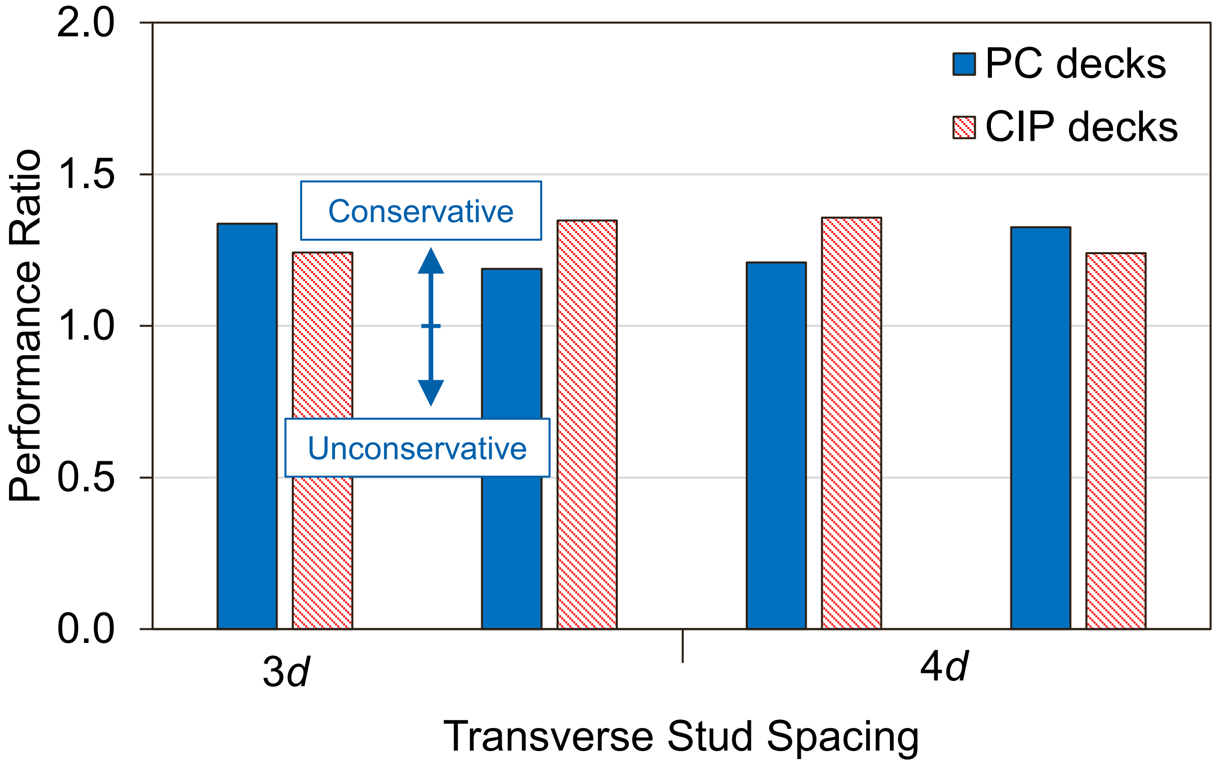
CIP = cast-in-place, PC = precast

Small-Scale Static Test Results – Transverse Spacing

- Compared experimental load to calculated load

$$\text{Performance Ratio} = \frac{\text{Experimental load}}{\text{Min strength (stud, concrete, grout)}}$$

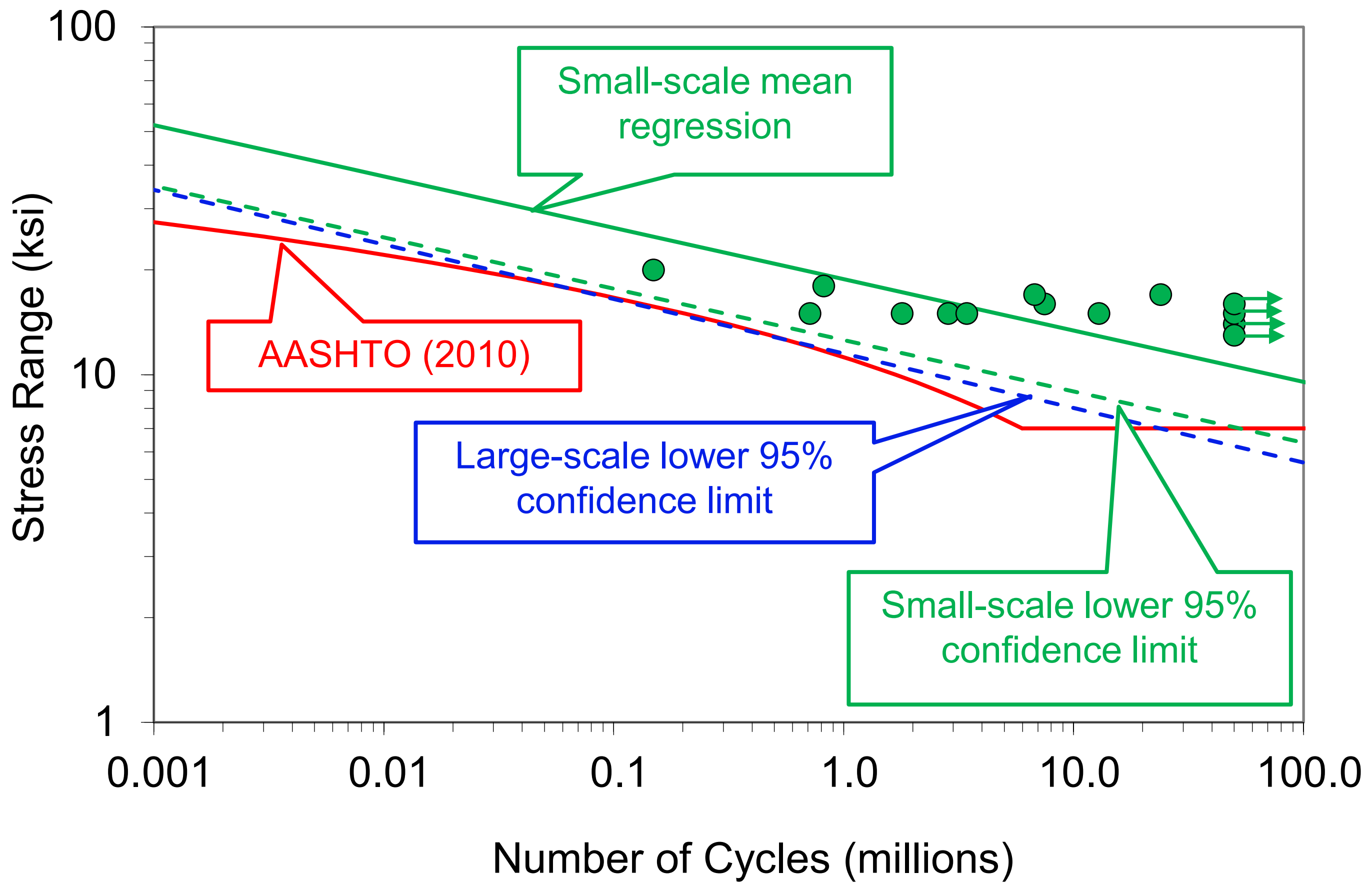
- Good performance for both CIP and PC decks
- Recommend min transverse spacing of 3*d*



CIP = cast-in-place, PC = precast

Small-Scale Fatigue Test Results

- Failure = when one or both decks completely separated from beam
- Similar behavior to large-scale tests
- Regression with m = 6.8



Conclusions

- **Max stud cluster spacing can be increased to 48”**
  - Implemented into 7th edition of AASHTO LRFD BDS (2014)
- **Current stud fatigue design equation is overly conservative**
  - Recommend log-log equation with slope of 6.4
- **Current stud strength design equation is unconservative**
  - Recommend shear factor of 0.70
- **Min stud spacing requirements can be decreased**
  - Recommend min longitudinal spacing of 4*d*
  - Recommend min transverse spacing of 3*d*

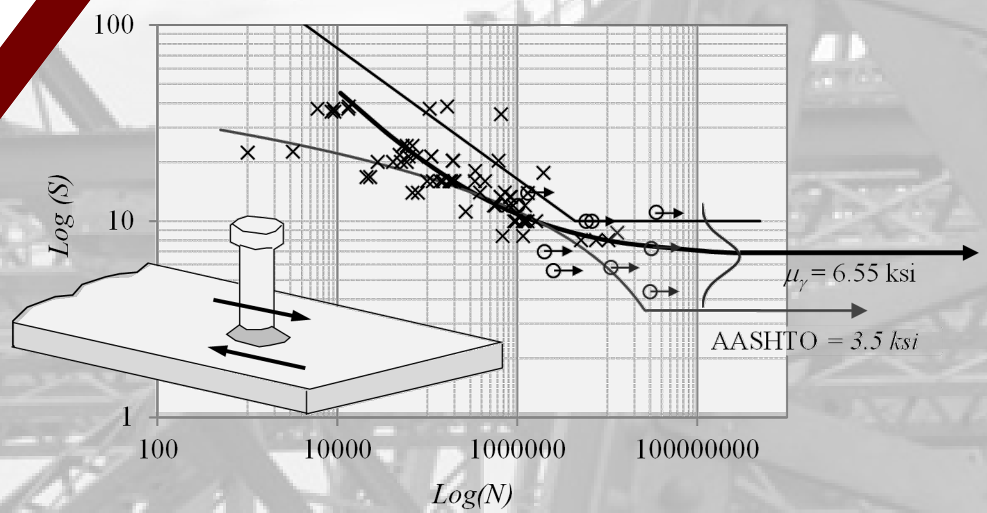
UNIVERSITY OF ARKANSAS

SSRL Steel Structures Research Lab
University of Arkansas, Department of Civil Engineering

CEREC Grady E. Harvell Civil Engineering Research and Education Center

TRB Webinar: Steel Bridge Shear Stud – Research & Design Provisions

Recent Investigations into the Behavior of Headed Shear Studs in Composite Bridge Girders

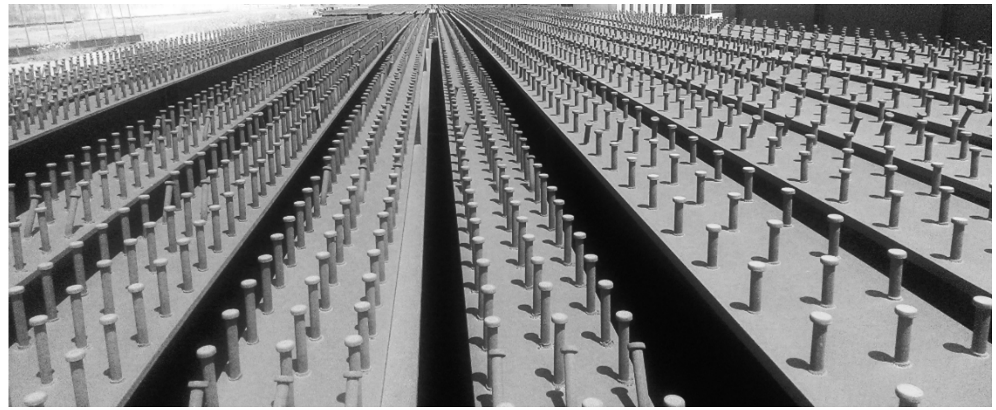


June 22nd 2023

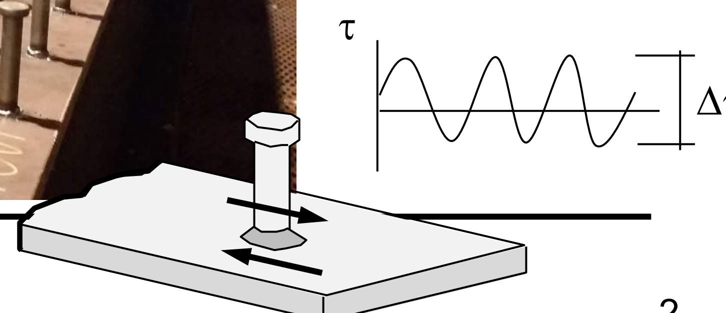
Gary S. Prinz, Ph.D., P.E.

Associate Professor
University of Arkansas

Motivation

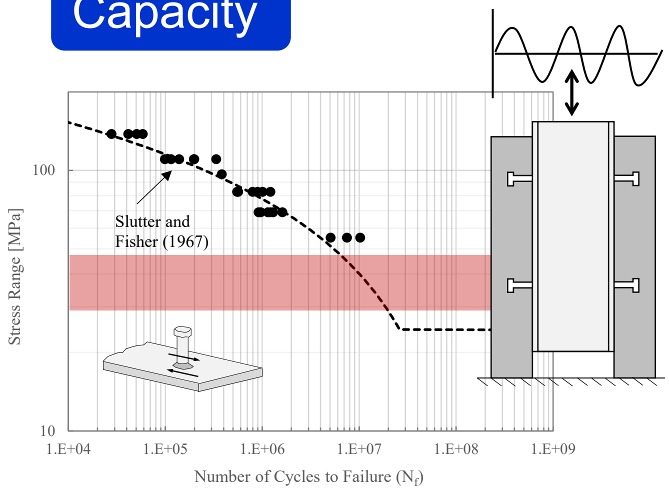


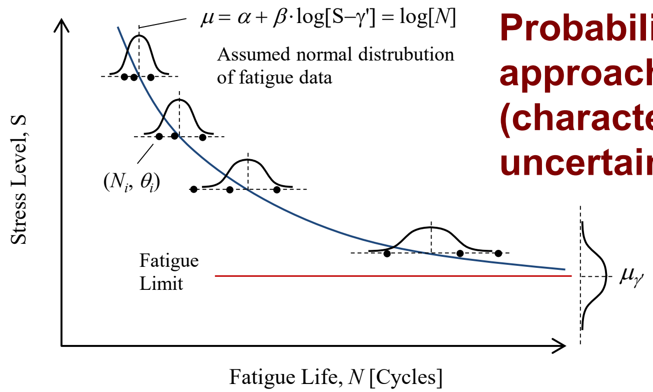
Fatigue limit states often govern the number of required shear studs



Fatigue: Demands and Capacities

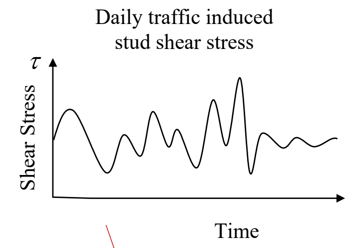
Capacity

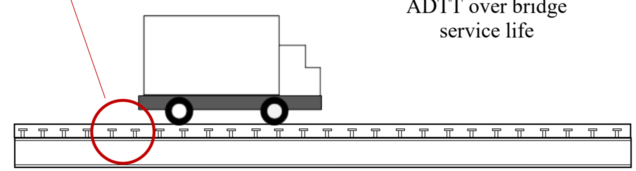


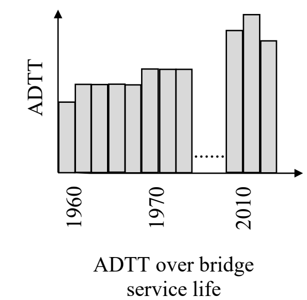


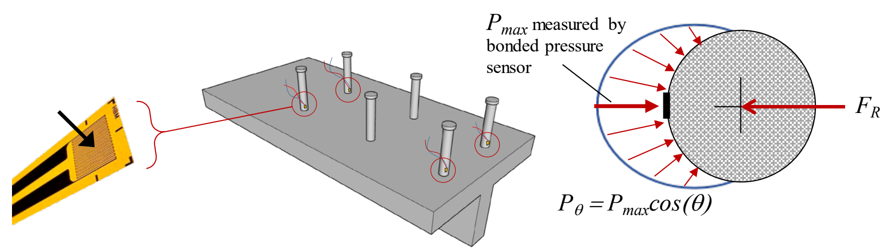
Probabilistic approach (characterize uncertainty)

Demand

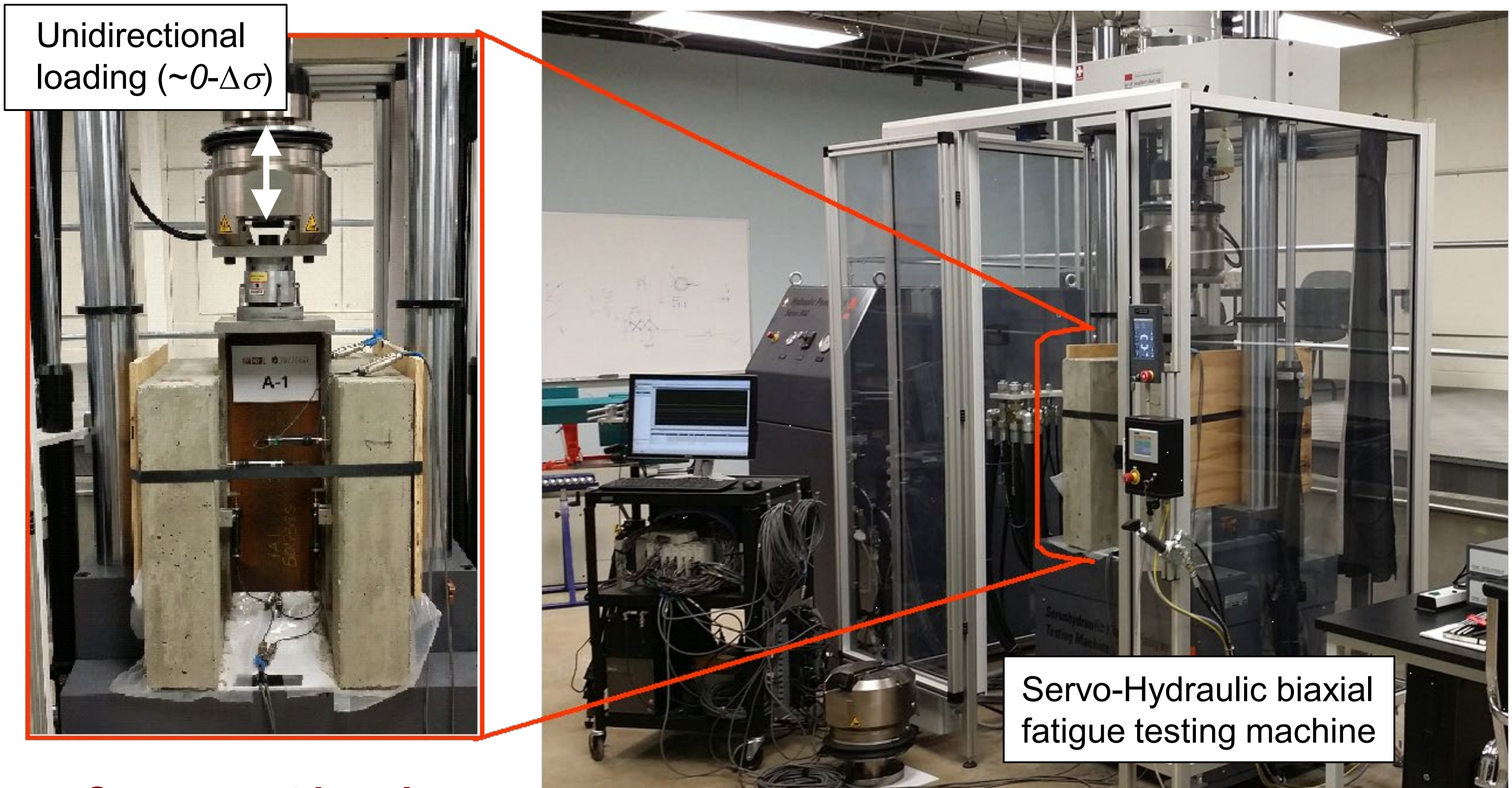






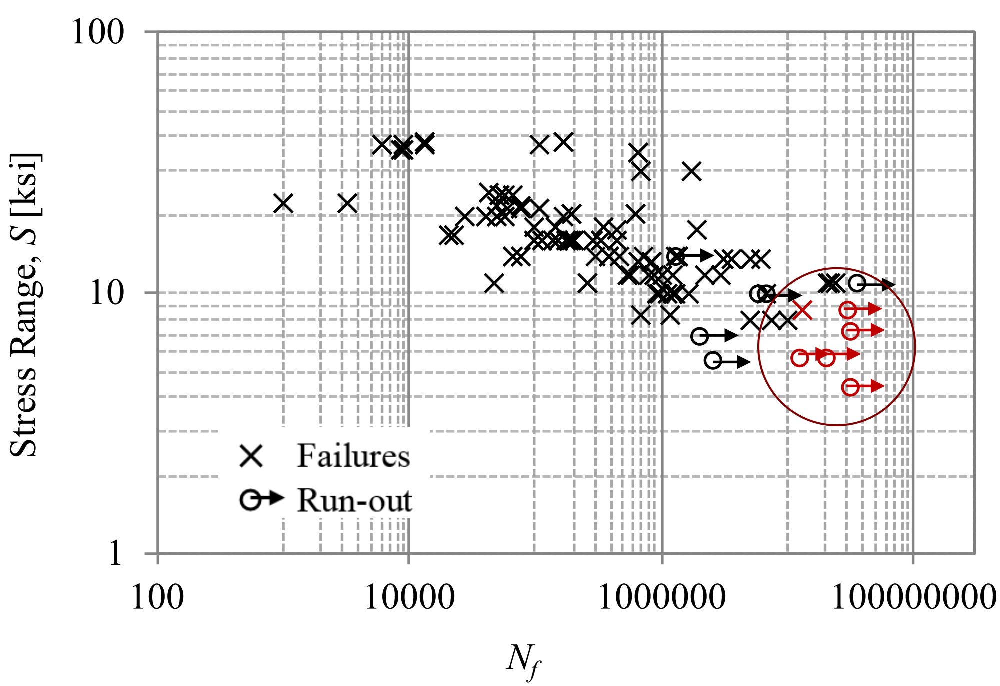


Experimental Tests



Component Level

Characterizing Uncertainty



<u>106 data points</u>

- ¾” studs

  Other stud diameters compared with final S-N curve

- Unidirectional loading (no reversed cycles)

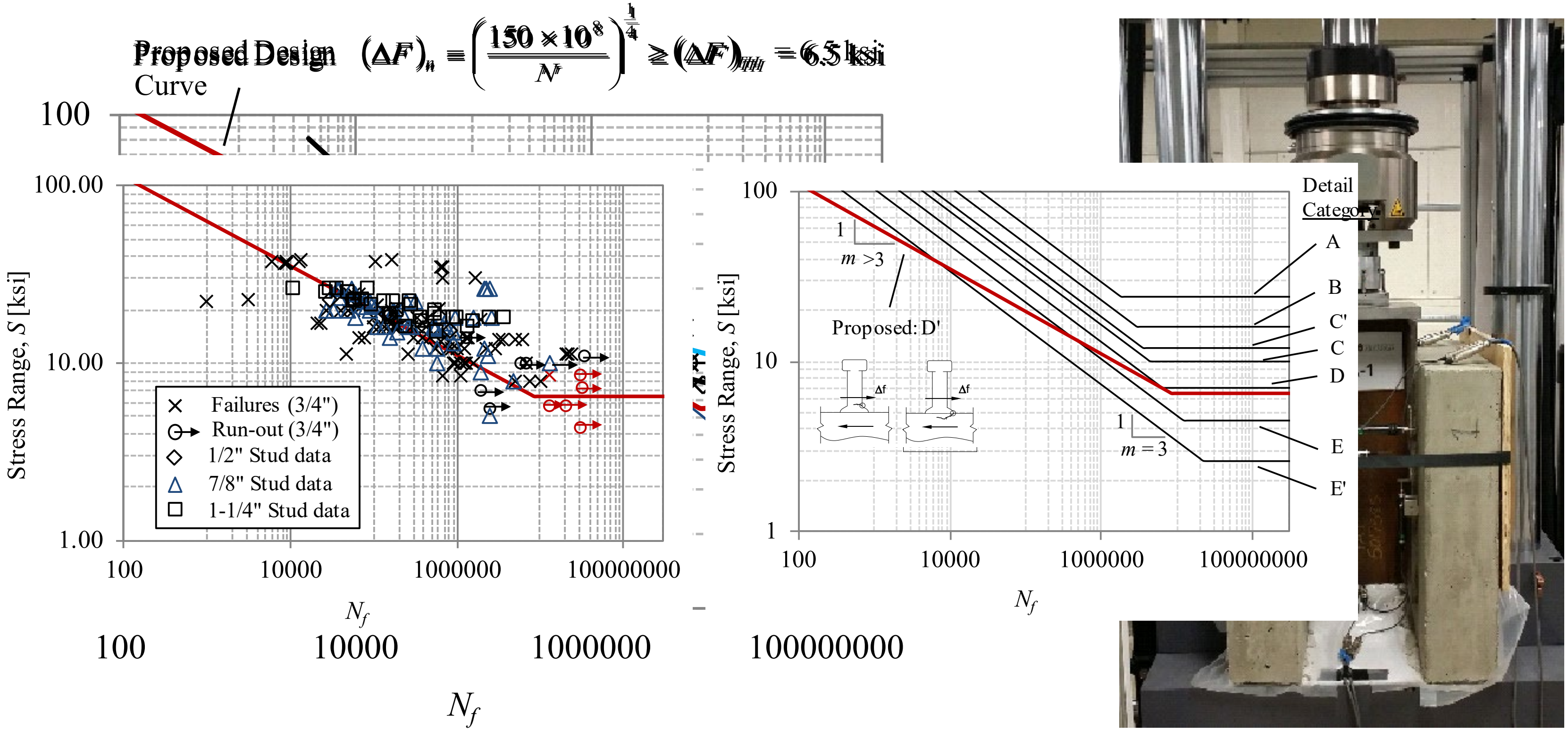
- Constant amplitude stress range (no variable amplitude data)

- Failure in the stud shank or weld

Stud Fatigue Capacity Findings

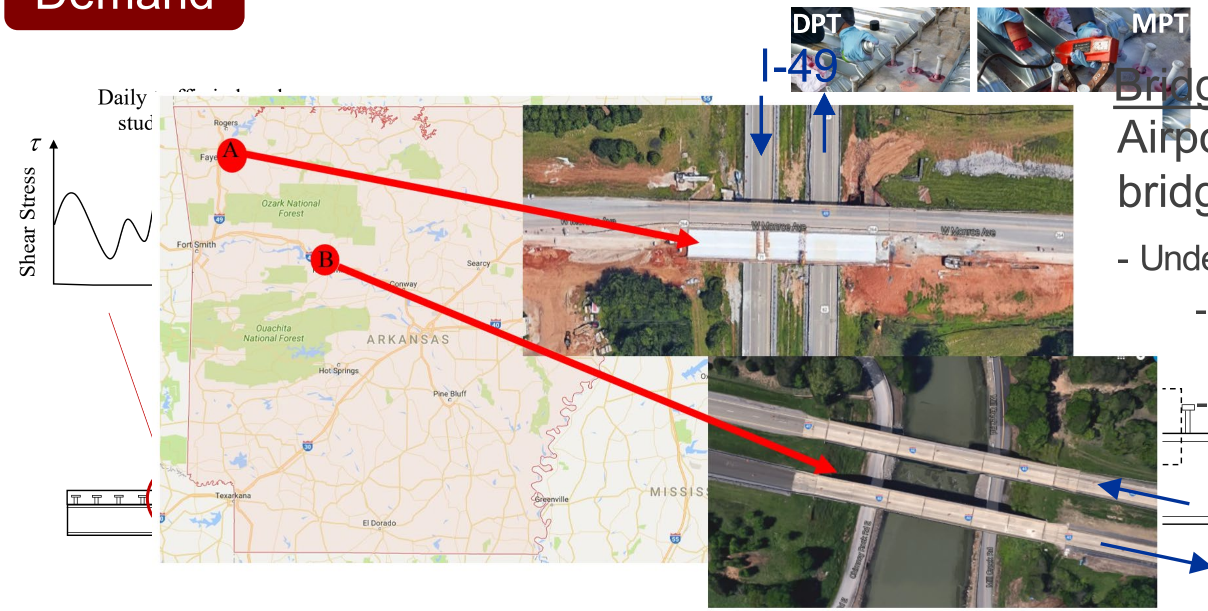
Recent Fatigue **Capacity** Research

Proposed Design Curve $(\Delta F)_n = \left(\dfrac{150 \times 10^8}{N}\right)^{\frac{1}{4}} \geq (\Delta F)_{TH} = 6.5\ \text{ksi}$



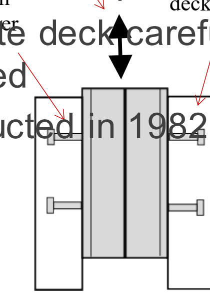
In Service Bridge Fatigue Investigations

Demand



Bridge A:
Airport road overpass bridge in Lowell AR

- Undergoing lane expansion
  - Concrete deck carefully removed
  - Constructed in 1982



Bridge B: I-40 EB Bridge in Russellville AR

- Girders removed from service
- Concrete deck carefully removed
- Constructed in 1965

1 Estimation of traffic demands and accumulated damage within existing bridge girder

2 Bridge girder removed from service following decades of traffic loading and sectioned for fatigue specimens

3 Cast new concrete slabs on stud specimen and fatigue test to determine remaining fatigue life

Estimated ADTT from ADT

- Traffic data gathered from 1985 onward

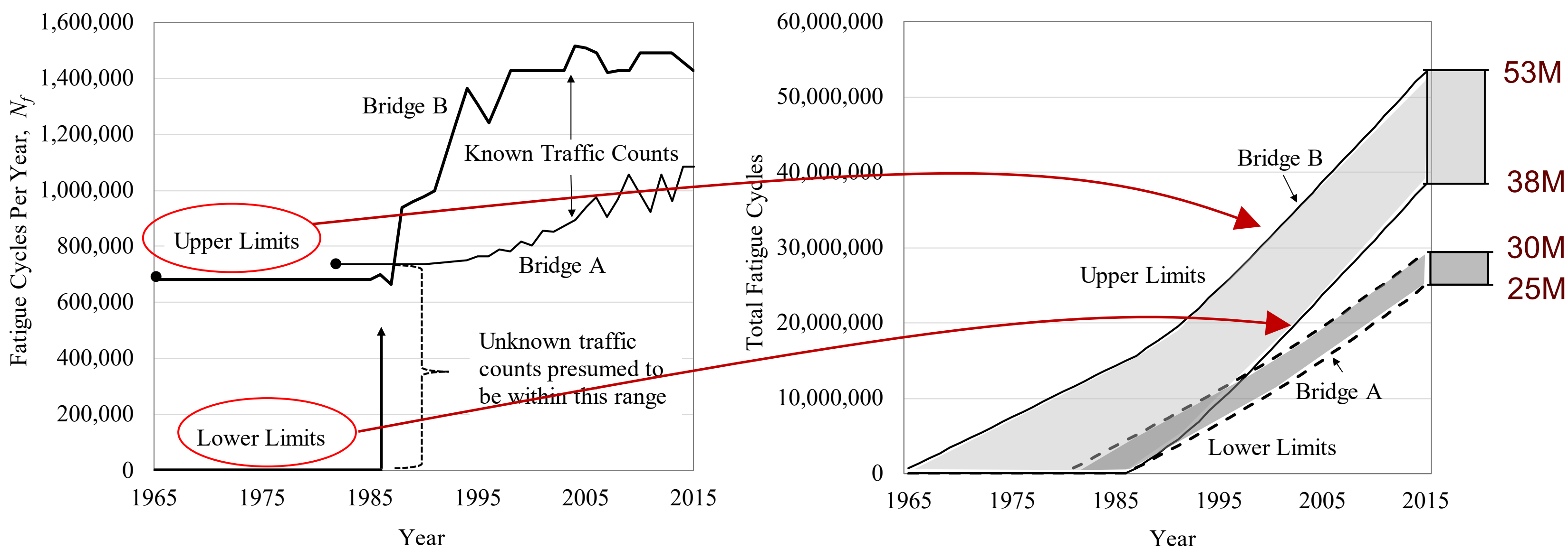


Table C3.6.1.4.2-1—Fraction of Trucks in Traffic

Class of Highway	Fraction of Trucks in Traffic
Rural Interstate	0.20
Urban Interstate	0.15
Other Rural	0.15
Other Urban	0.10

ADTT = 0.2(ADT)

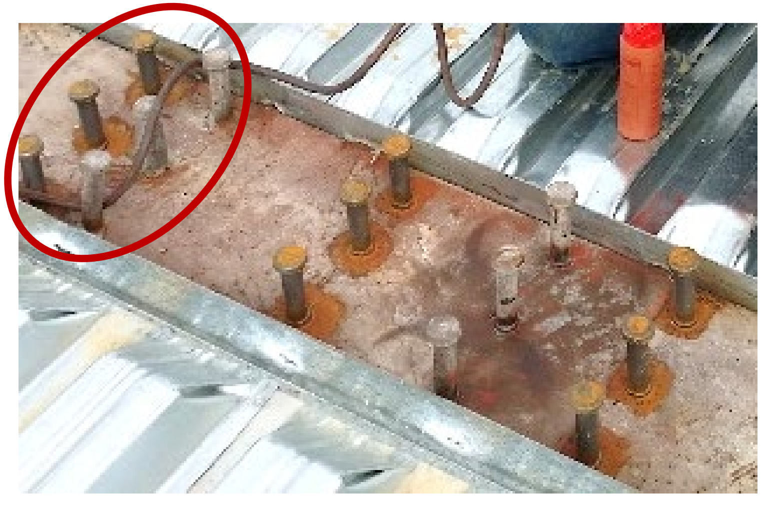
Note: Between 2010 and 2013 **10,191** overweight permits were issued for the eastbound lane of Bridge B along I-40. Westbound lane had 3x.

Non-Destructive Testing

Bridge A: (Lowell AR)

Design pitch: infinite life (8” c.c. at ends, 17” c.c. at mid-span)

Constructed pitch: Finite life (10” c.c. at ends, 20” c.c. at mid-span)



DPT alone was inconclusive, MPT indicated no cracks

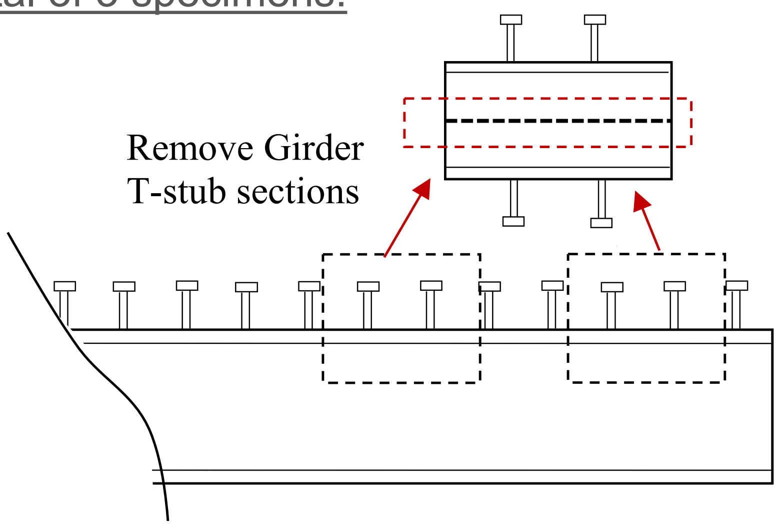
Destructive Fatigue Testing

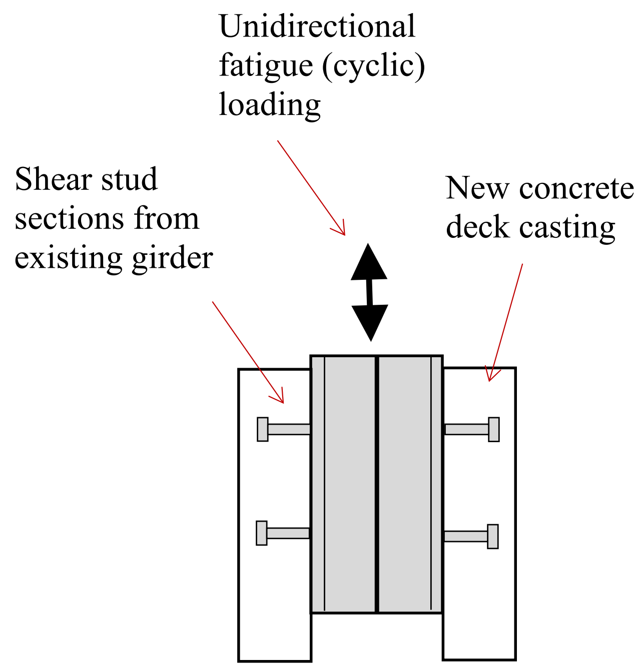
Bridge B: (I-40, Russellville AR)

Age = 50 years   Truck cycles: 38-53M

No stud fatigue cracks found following deck removal, therefore destructive specimens fabricated for determination of residual life.

Total of 3 specimens:





Reminder: Between 2010 and 2013 **10,191** overweight permits were issued for the eastbound lane of Bridge B along I-40. Westbound lane had 3x.

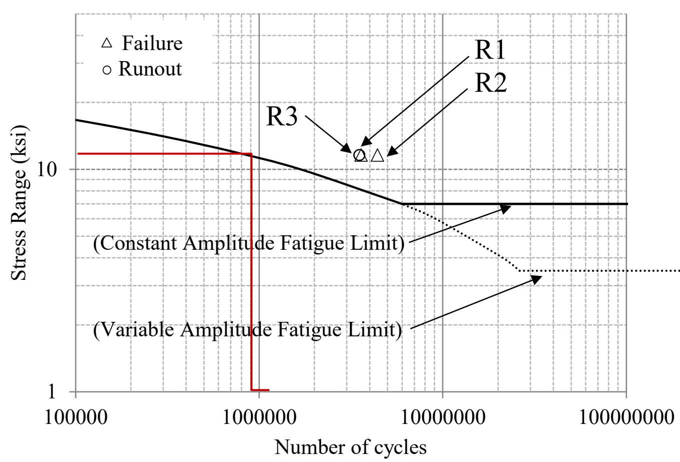
Destructive Fatigue Testing Results

Bridge B: (I-40, Russellville AR)

Age = 50 years   Truck cycles: 38-53M

Specimen Number	Average Concrete Compressive Strength [psi]	Applied Stress Range [ksi]	Loading Rate [Hz]	Number of Cycles	Failure (F) or Runout (R)
R1	7624	11.6	3	3,590,011	F
R2	6842	11.6	4	4,415,003	F
R3	6884	11.6	4	3,519,001	R

Exceeded Expectation by 400+%



Expected life @11.6ksi ≈ 850,000

Note: Between 2010 and 2013 **10,191** overweight permits were issued for the eastbound lane of Bridge B along I-40. Westbound lane had 3x.

Demands on Clustered Studs?

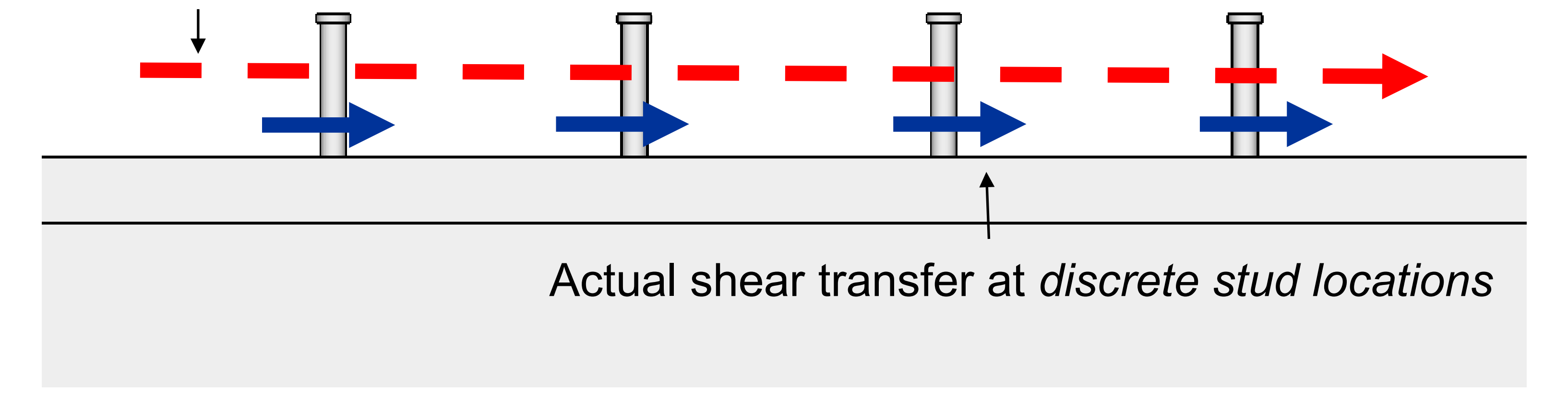
Shear stud demands somewhat questionable

- Will discuss parametric investigation and experimental verification

$$V_{sr} = \frac{V * Q}{I}$$

V_{sr} – horizontal fatigue shear (kip/in.)
V – vertical shear force under loading
Q – first moment of short-term area of deck
I – moment of inertia of short-term composite section

Assumed *uniform* shear flow



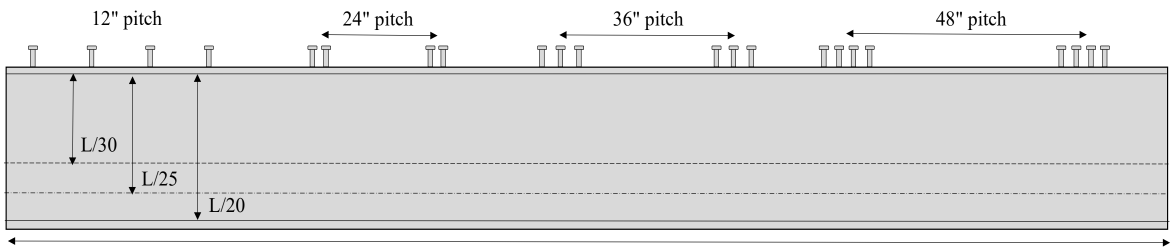
Actual shear transfer at *discrete stud locations*

Parametric Investigation

2 Girder Spans

3 Girder Depths (L/30, L/25, L/20)

4 Stud Spacing (12”,24”,36”,48”)



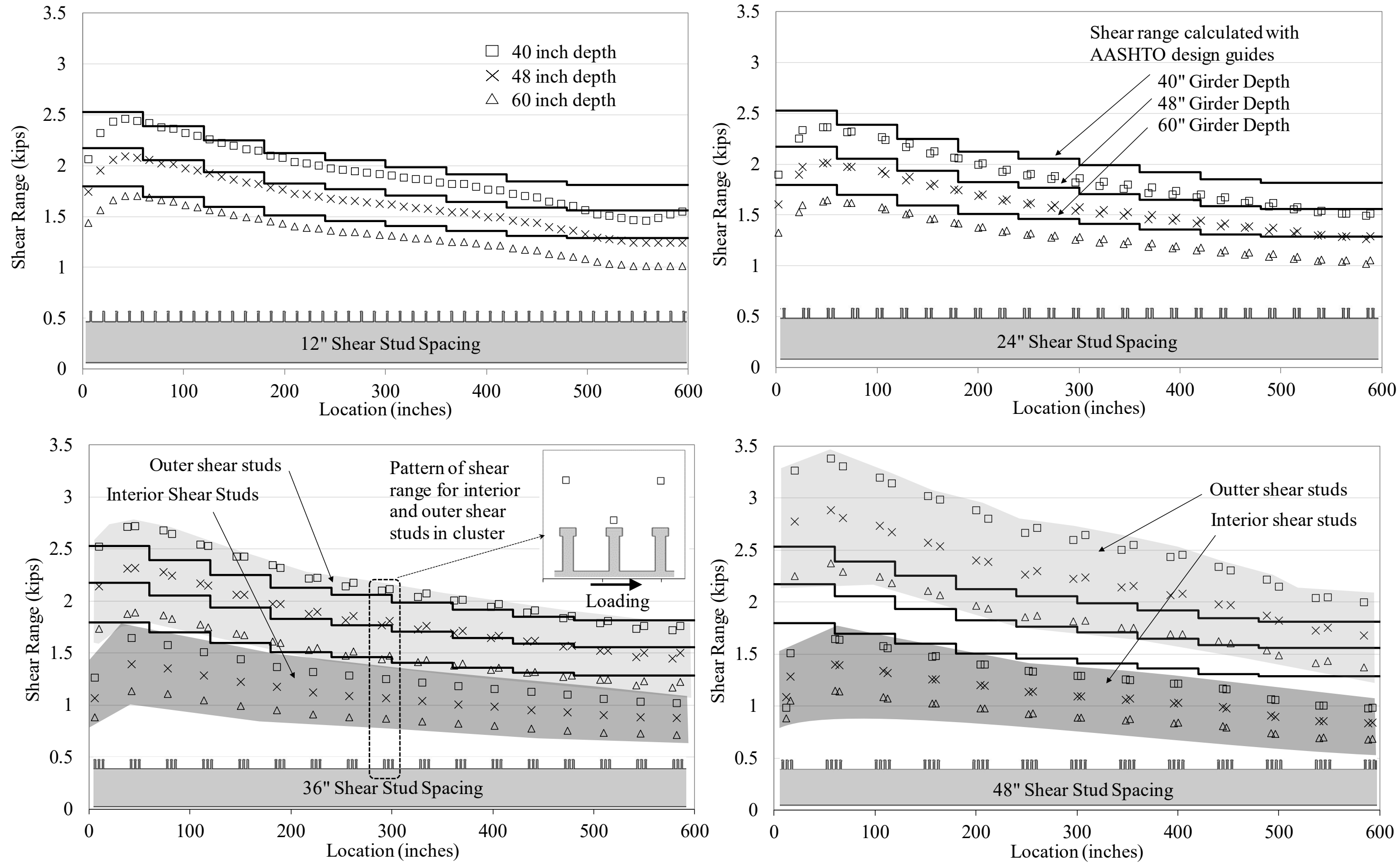
24 Finite Element models:

Created in ABAQUS

Girder	Span (ft)	Depth (in)	Pitch (in)
1A	100	40	12
1B	100	40	24
1C	100	40	36
1D	100	40	48
2A	100	48	12
2B	100	48	24
2C	100	48	36
2D	100	48	48
3A	100	60	12
3B	100	60	24
3C	100	60	36
3D	100	60	48
4A	200	80	12
4B	200	80	24
4C	200	80	36
4D	200	80	48
5A	200	96	12
5B	200	96	24
5C	200	96	36
5D	200	96	48
6A	200	120	12
6B	200	120	24
6C	200	120	36
6D	200	120	48

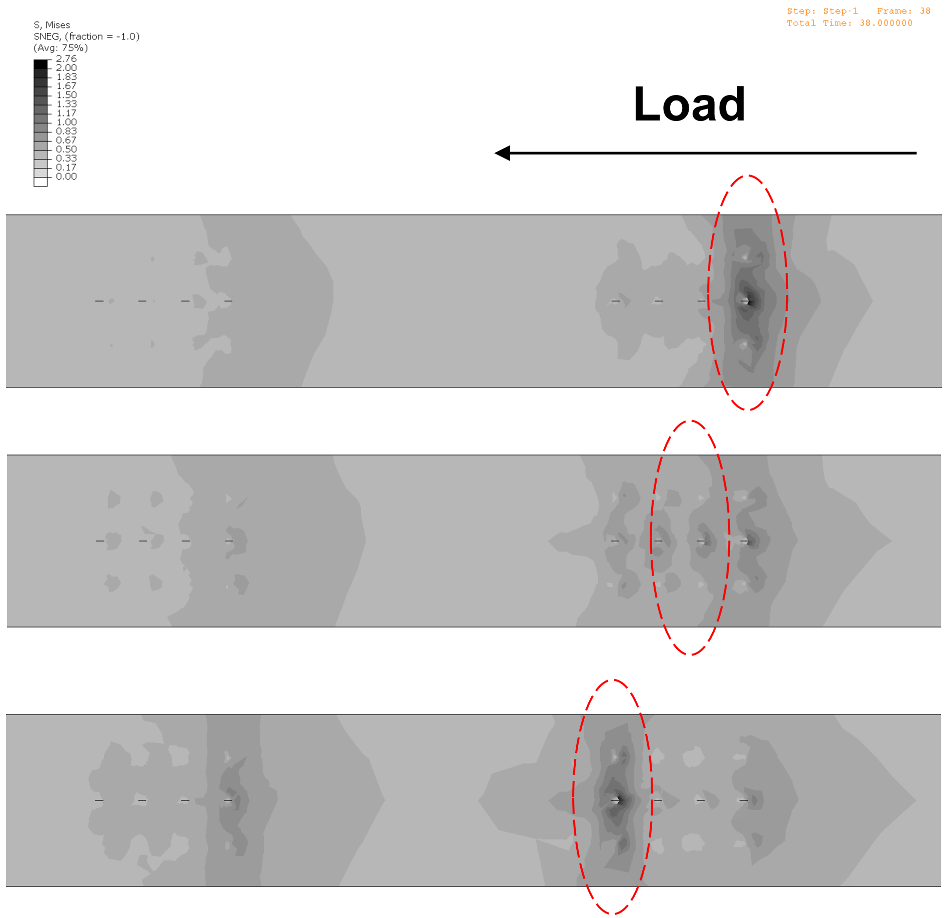
Parametric Investigation

Results



Parametric Investigation

Results



Parametric Investigation

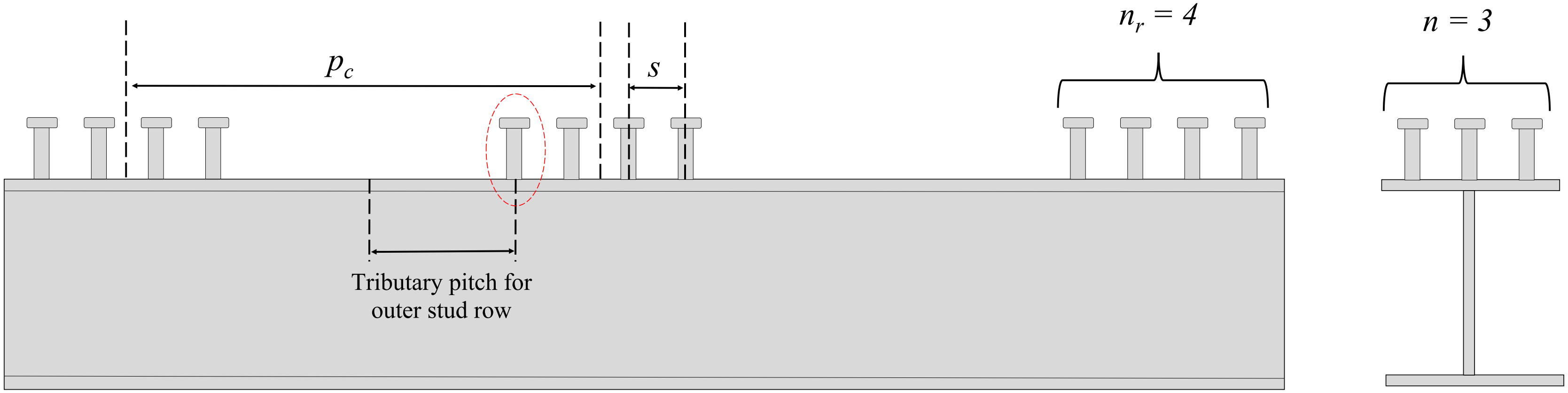
Development of Demand Equations for Clustered Studs

$$\frac{p_c}{2} - \frac{(n_r - 1)s}{2}$$

$$\left(\frac{p_c}{2} - \frac{(n_r - 1)s}{2}\right)\left(\frac{1}{n}\right)V_{SR} = \Delta F$$

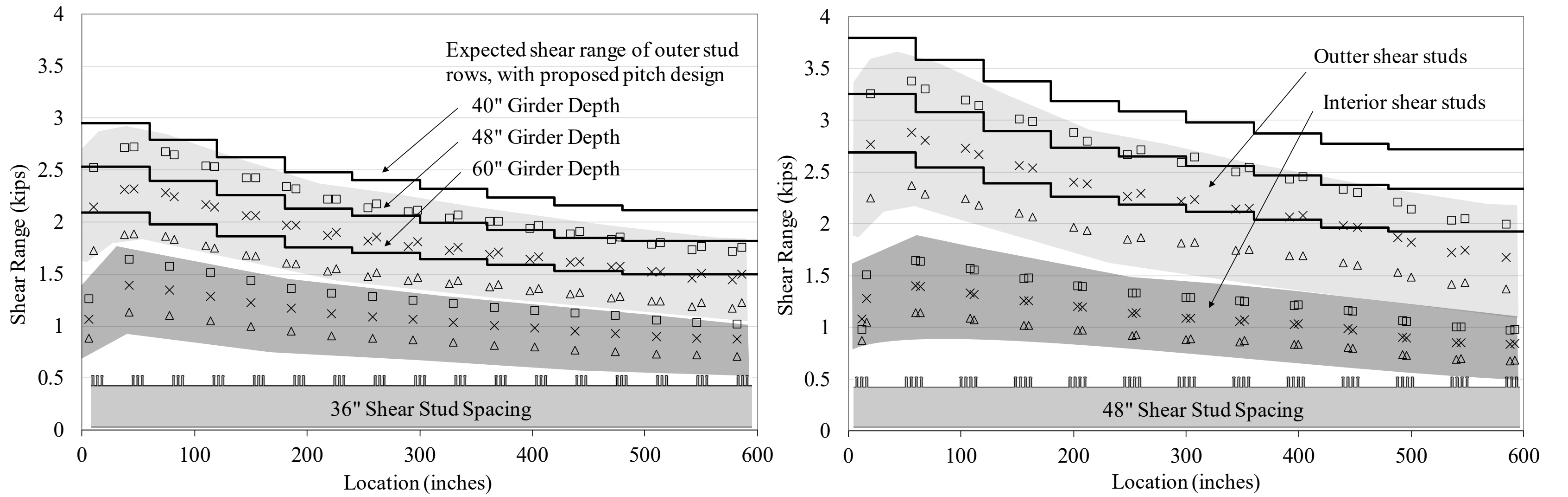
$$\Delta F \leq Z_r \quad \text{or} \quad 1 \leq \frac{Z_r}{\Delta F}$$

$$\boldsymbol{p_c \leq \frac{2nZ_r}{V_{SR}} + s(n_r - 1)}$$



Parametric Investigation

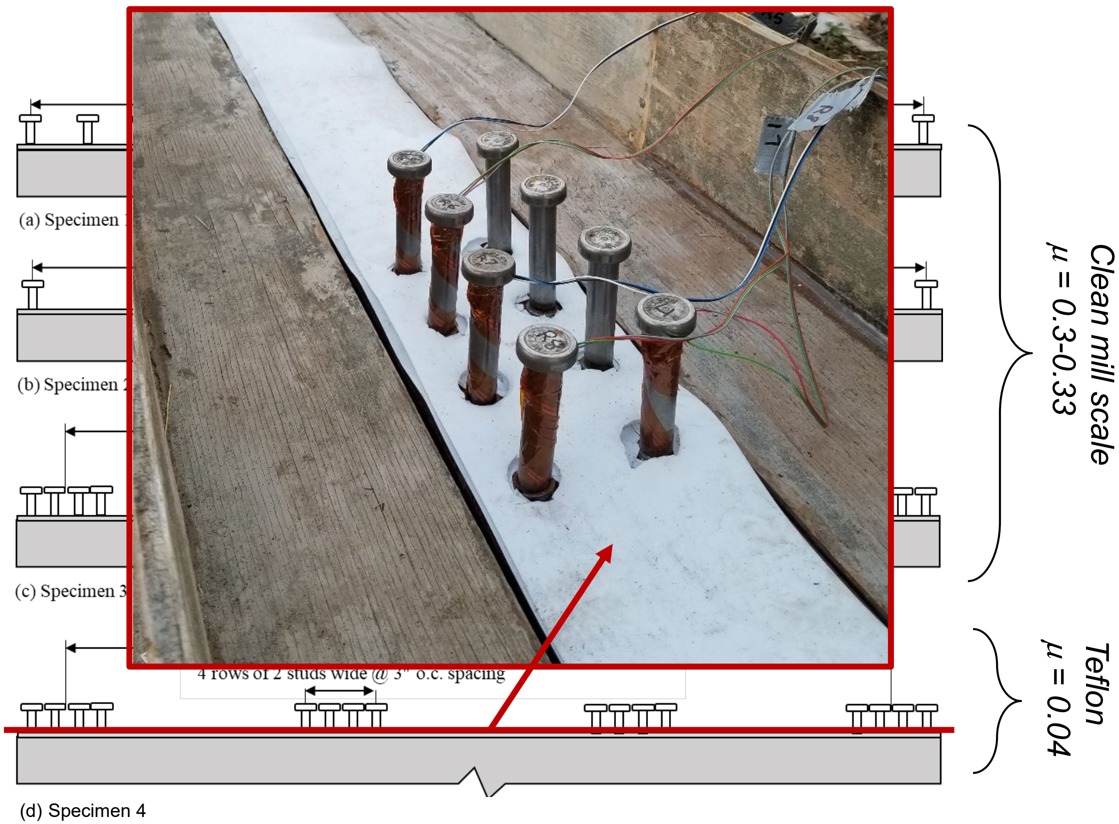
Results of Finite Element Models compared to proposed V_{SR}



Large Scale Experimental Verification

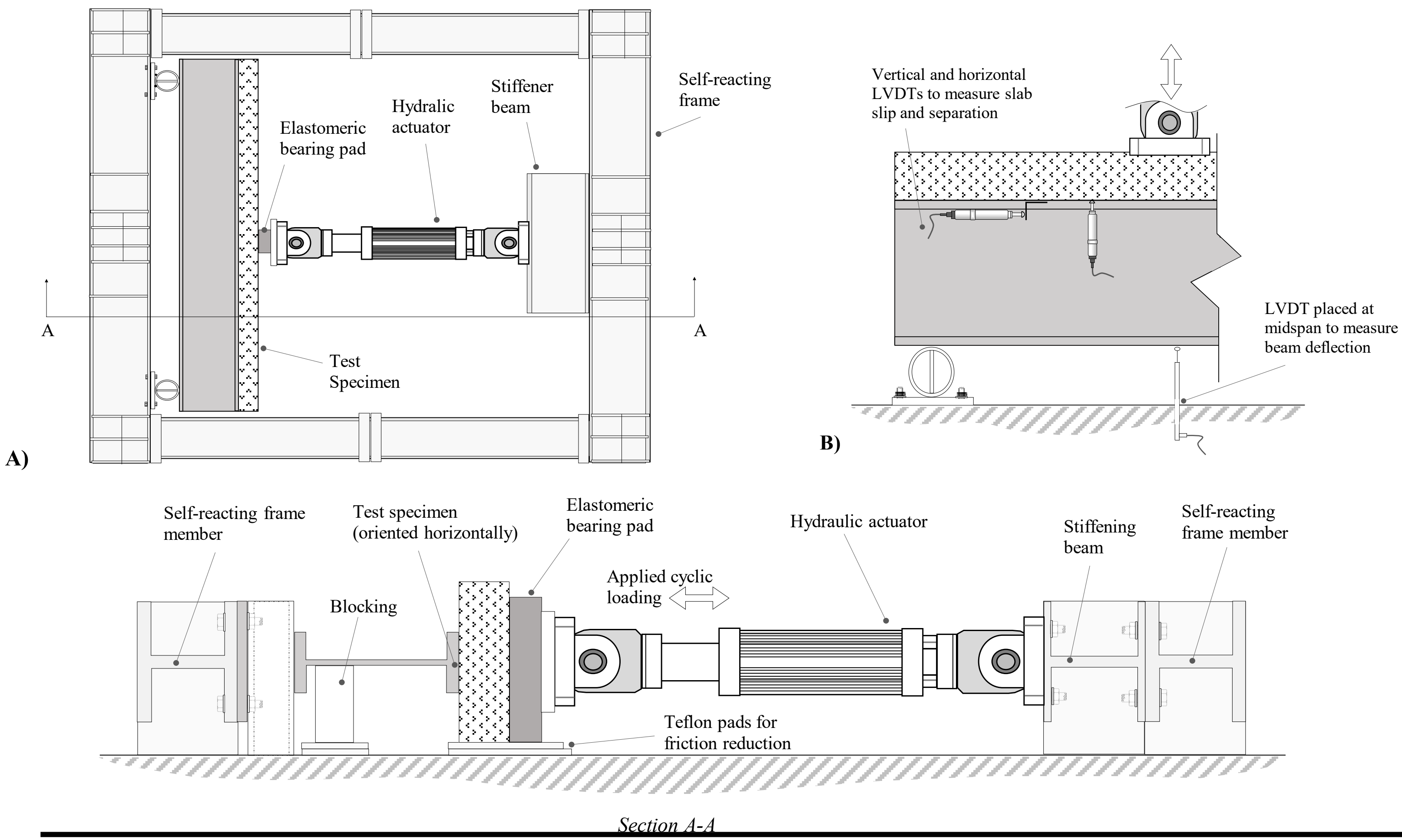
- **Fatigue Testing of Clustered Studs**
- **Measurement of Stud Demands (Captured Effect of Surface Friction)**
- **Composite and Non-Composite Girder Behavior**

Stud Force Measurement

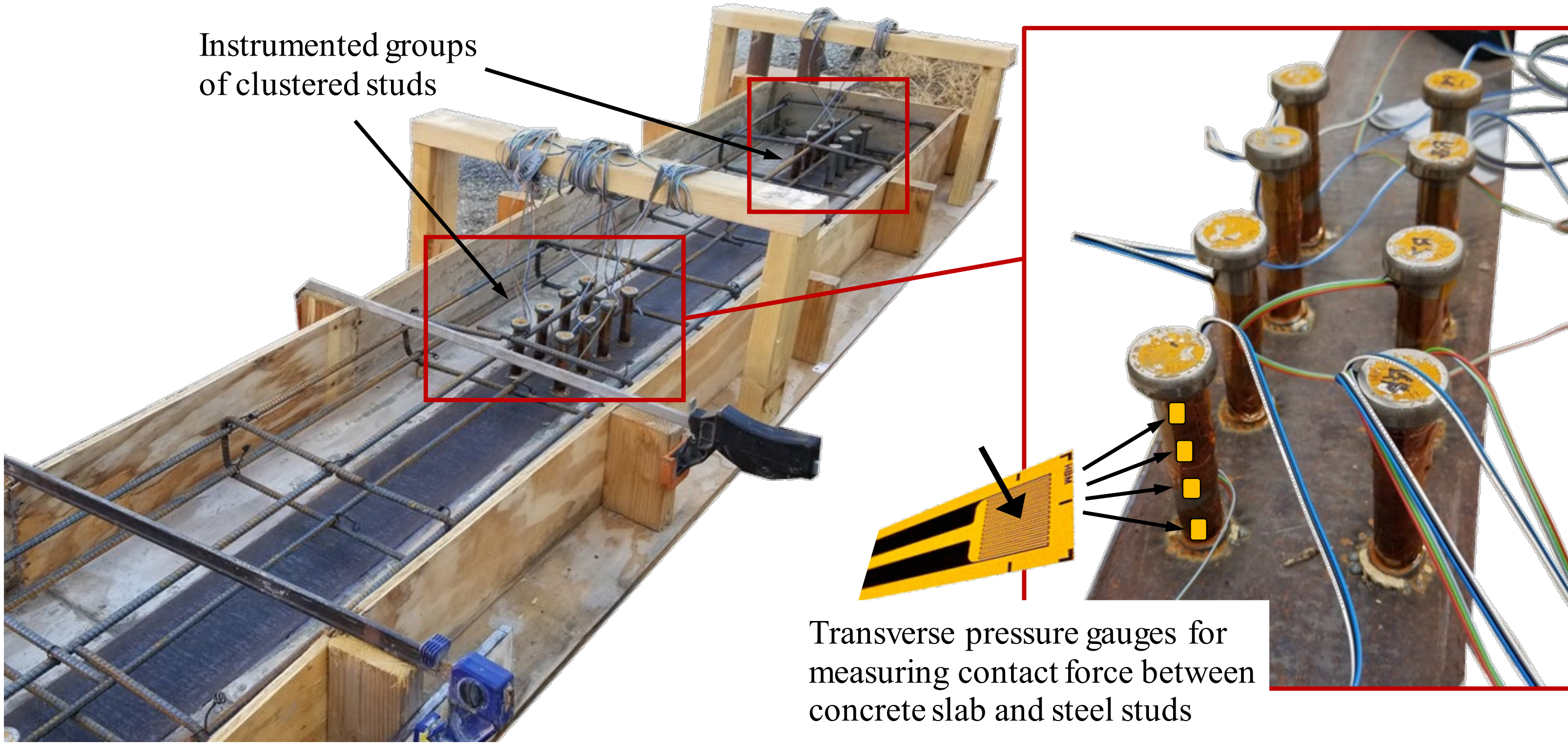


- 14' beams with varied stud pitch
- Comparison between composite and non-composite
- Consistent capacity **based on strength design provisions**
- Stud groupings up to 39"
- 3/4" x 4" studs
- 6" slab thickness

Test Setup

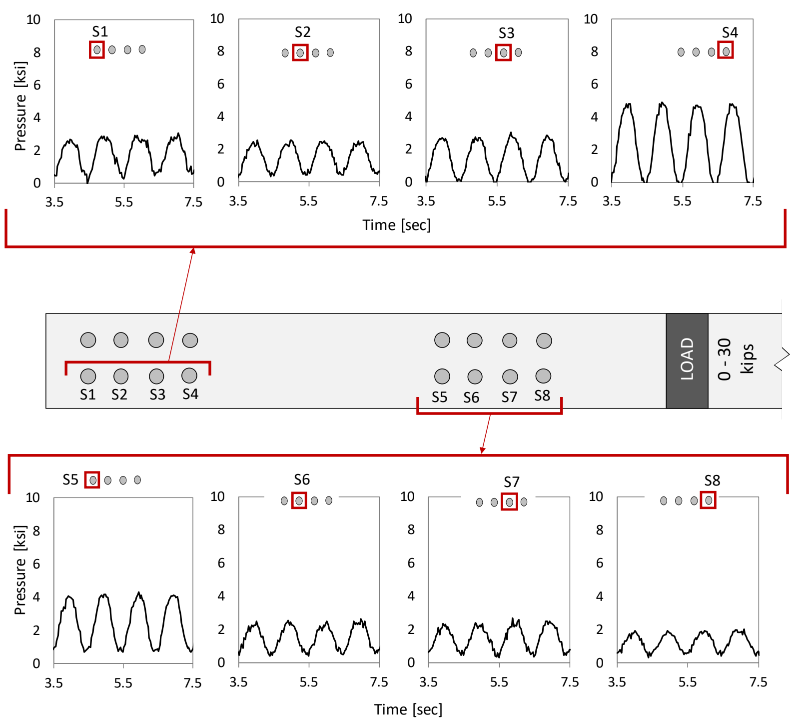

Self-reacting
frame
Stiffener
beam
Hydraulic
actuator
Elastomeric
bearing pad
A
A
Test
Specimen
A)
Vertical and horizontal
LVDTs to measure slab
slip and separation
LVDT placed at
midspan to measure
beam deflection
B)
Self-reacting frame
member
Test specimen
(oriented horizontally)
Elastomeric
bearing pad
Hydraulic actuator
Stiffening
beam
Self-reacting
frame member
Applied cyclic
loading
Blocking
Teflon pads for
friction reduction
Section A-A

Stud Force Measurement

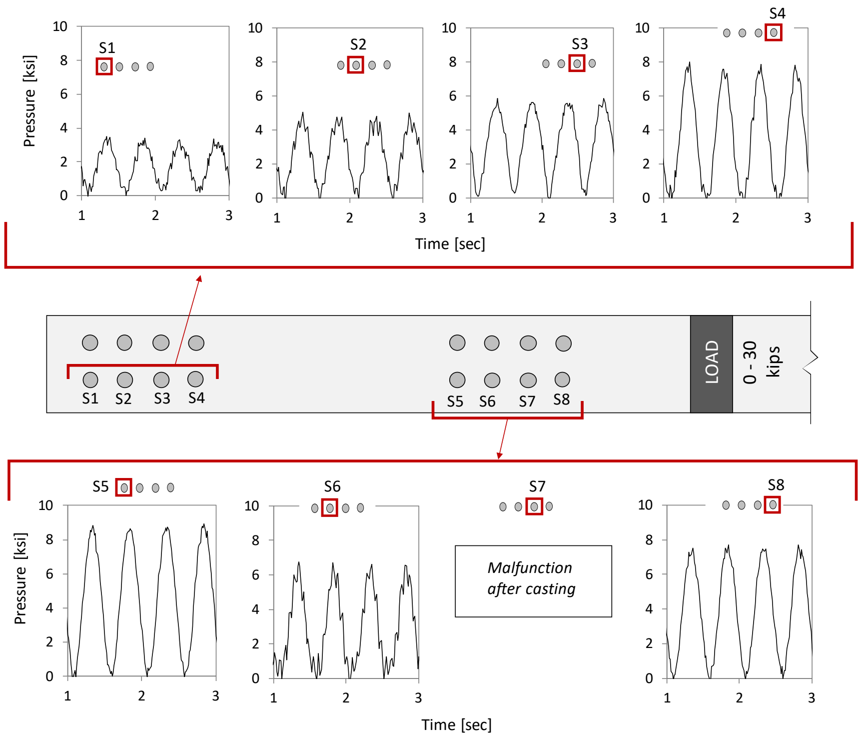


Stud Force Measurement

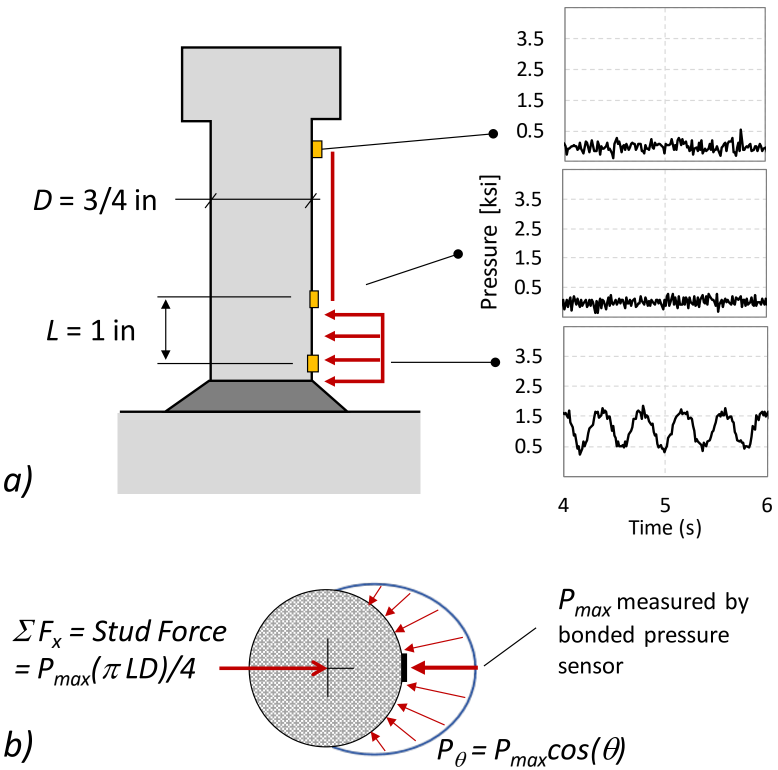
Specimen 3 – Clean Mill Scale

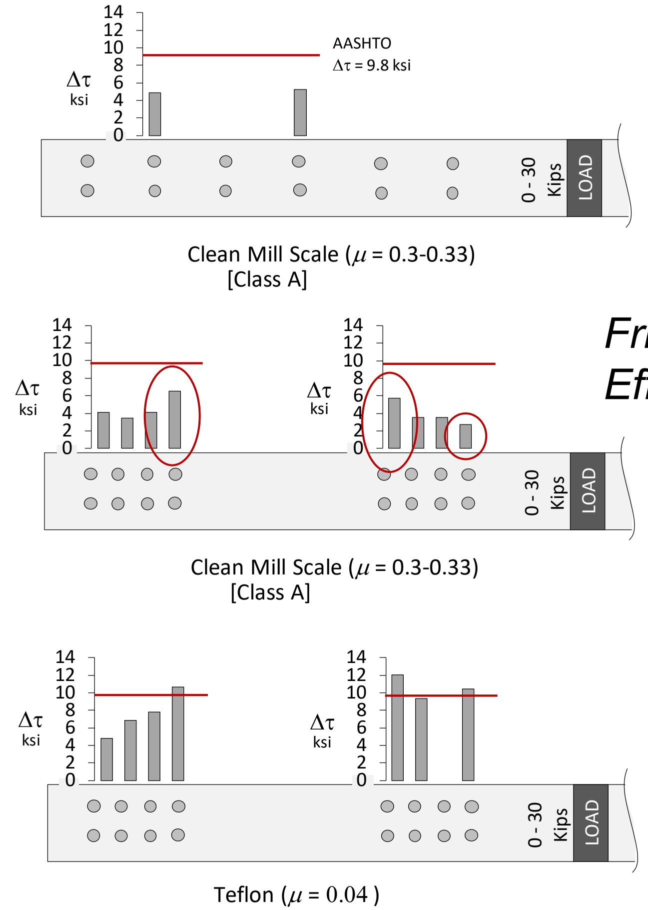


Specimen 4 – Teflon Separation



Stud Force Measurement

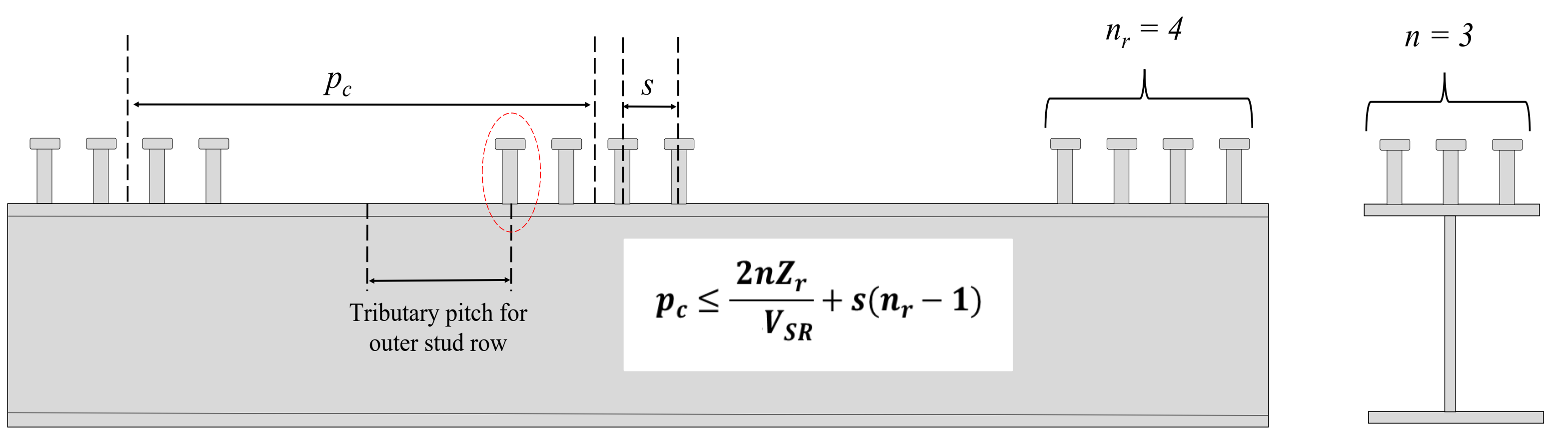




Friction Effects?

Conclusions / Recommendations

- Modify Stud Finite Life Capacity (Log-Log Synergy with Existing Details)
  - m > 3   CAFL = 7
- Further Investigation of Friction Demand Reductions (ongoing NCHRP investigation)
- Include Guidance for Clustered Stud Demand Calculations



AASHTO Updates to Shear Stud Design

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TRB Webinar: Steel Bridge Shear Stud—Research and Design Provisions

22 June 2023

FHWA Resource Center

Office of Innovation Implementation

U.S. Department of Transportation
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Acronyms

AASHTO	American Association of State Highway and Transportation Officials
$ADTT_{SL}$	average daily truck traffic in a single lane
BDS	bridge design specifications
CAFT	constant amplitude fatigue threshold
FHWA	Federal Highway Administration
LRFD	load and resistance factor design
TRB	Transportation Research Board

Symbology

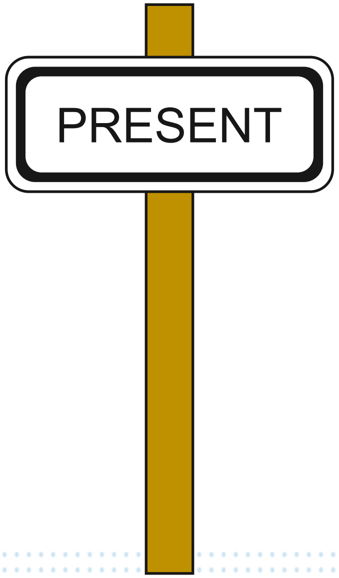
A	fatigue detail category constant
A_{sc}	area of shear connector
d	diameter of shear connector
E_c	concrete elastic modulus
f'_c	concrete compressive strength
F_u	tensile strength of shear connector
H	height of shear connector
m	fatigue growth constant
N	number of cycles
n_l	longitudinal number of shear connectors in cluster
n_t	transverse number of shear connectors
p	shear connector pitch
Q_n	nominal resistance
s	center-to-center spacing of shear connectors in a cluster
V_{sr}	horizontal fatigue shear range per unit length
Z_r	shear load resistance of individual shear connector
β	LRFD reliability index
ϕ_{sc}	resistance factor of shear connector
$(\Delta F)_n$	nominal stress range

Strength of Shear Connector

$$Q_n = 0.5A_{sc}\sqrt{f_c'E_c} \leq A_{sc}F_u$$

$$\phi_{sc} = 0.85$$

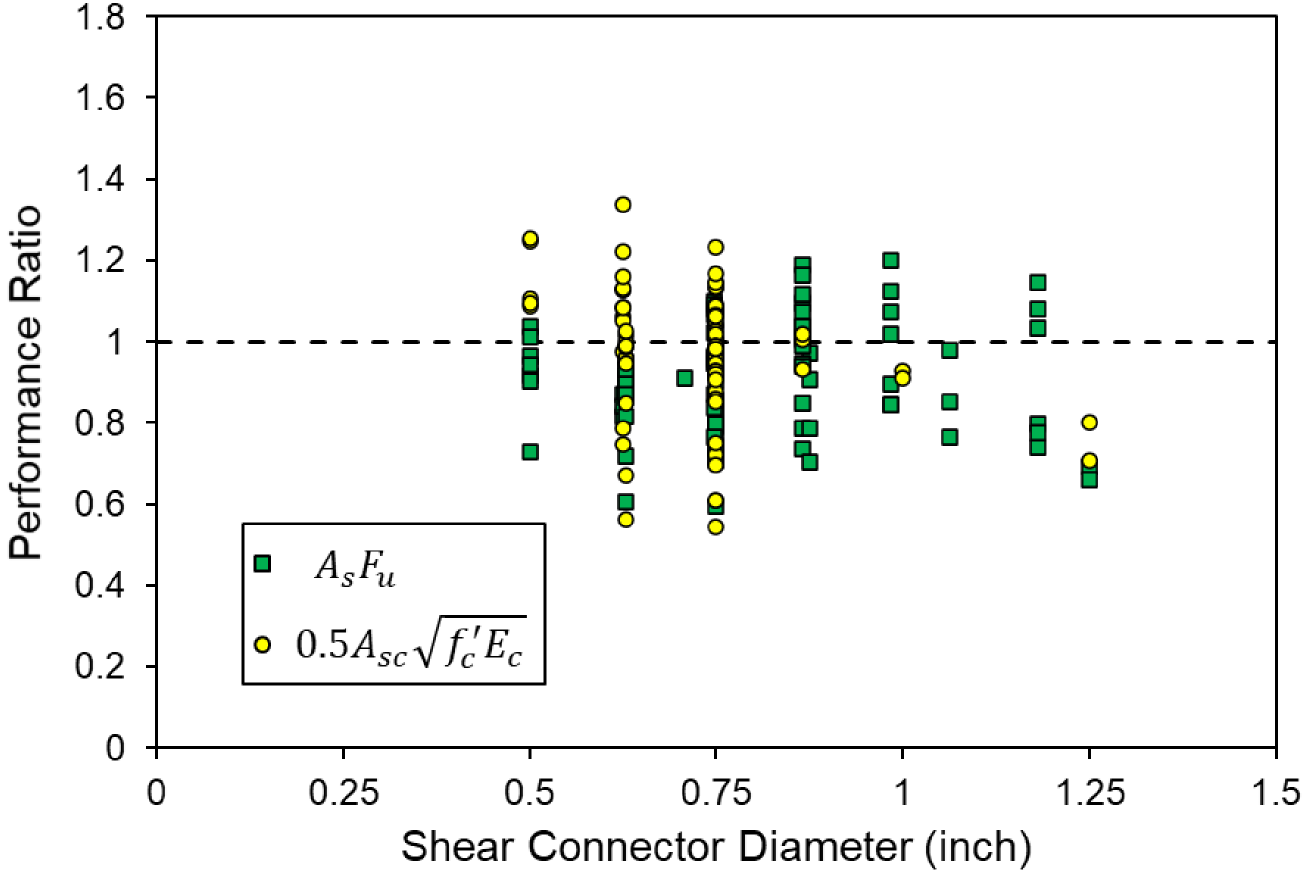
AASHTO LRFD BDS 9th Edition
Equation 6.10.10.4.3-1



Shear connector capacity based on two-part equation:

- Concrete crushing, and
- Tensile strength of shear connector.

Strength of Shear Connector



Performance ratio is experimental value divided by Equation 6.10.10.4.3-1 prediction.

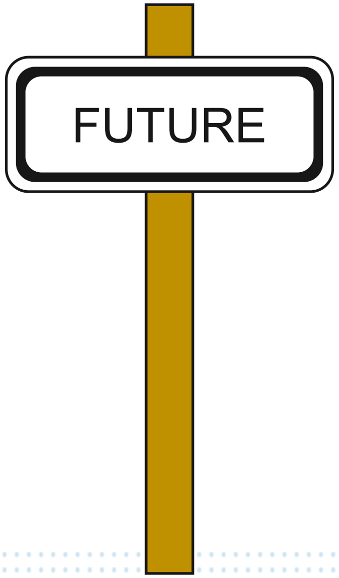
- 179 data points.
- 20 different studies between years of 1956 and 2019.
- Diameters from $^1/_2$ to $1^1/_4$ inch.

Strength of Shear Connector

$$Q_n = 0.70 A_{sc} F_u$$

$$\phi_{sc} = 1.00$$

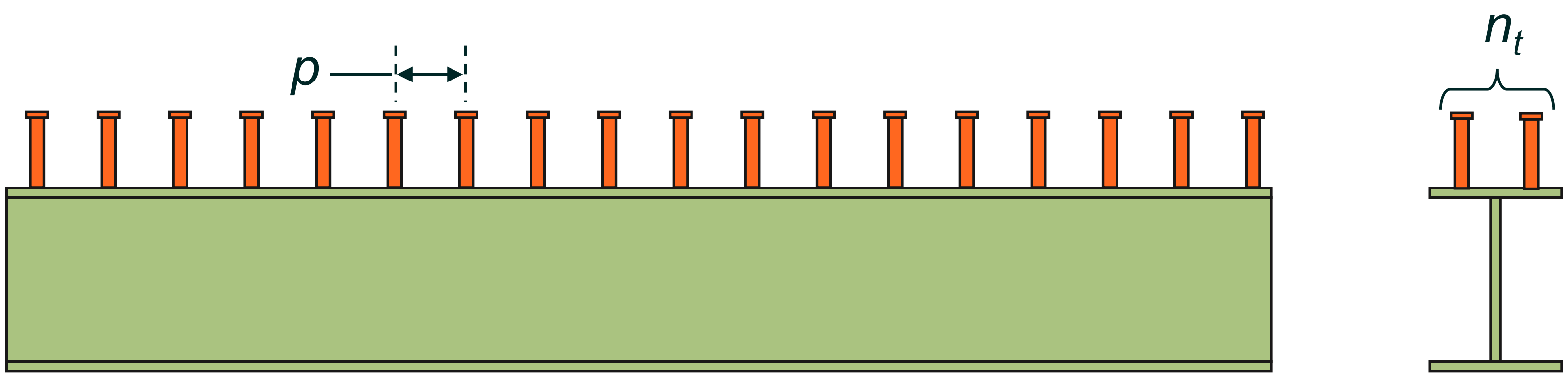
AASHTO LRFD BDS 10th Edition
Equation 6.10.10.4.3-1



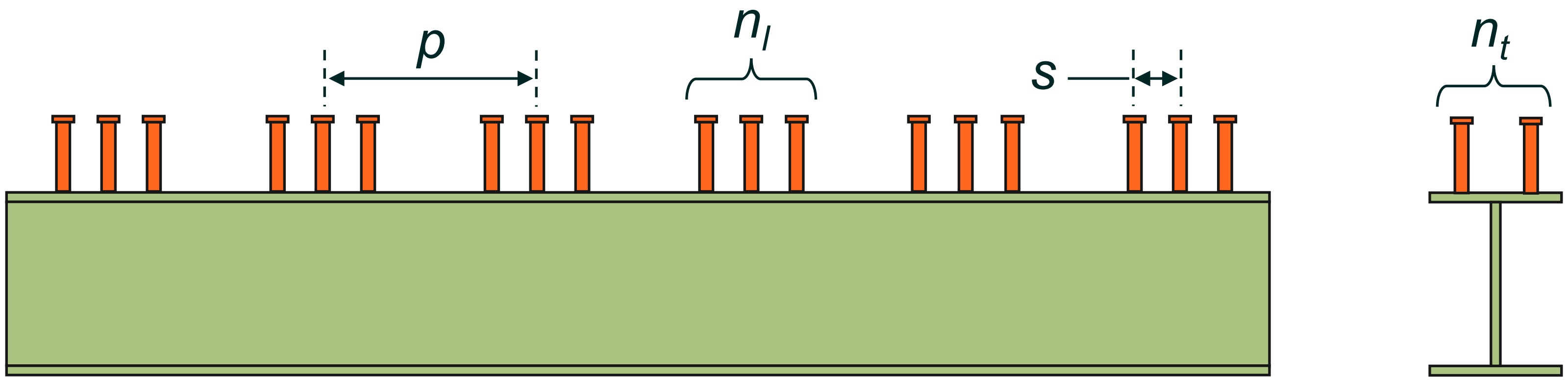
Required revising minimum stud height (*H*) to diameter (*d*) ratio,

- $H/d \geq 5.0$ for normal weight concrete,
- $H/d \geq 7.0$ for lightweight concrete,
- See Pallarés and Hajjar (2010).

Pitch of Shear Connector



$$p \leq \frac{n_t Z_r}{V_{sr}}$$



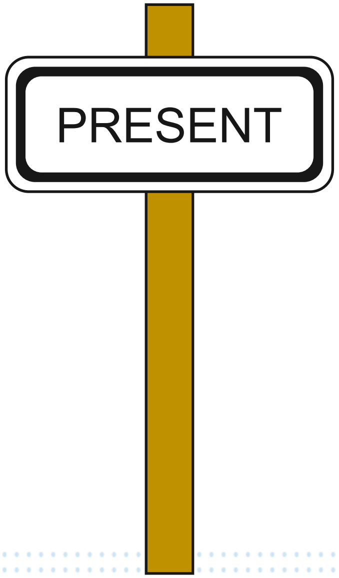
$$p \leq \frac{2n_t Z_r}{V_{sr}} + s(n_l + 1)$$

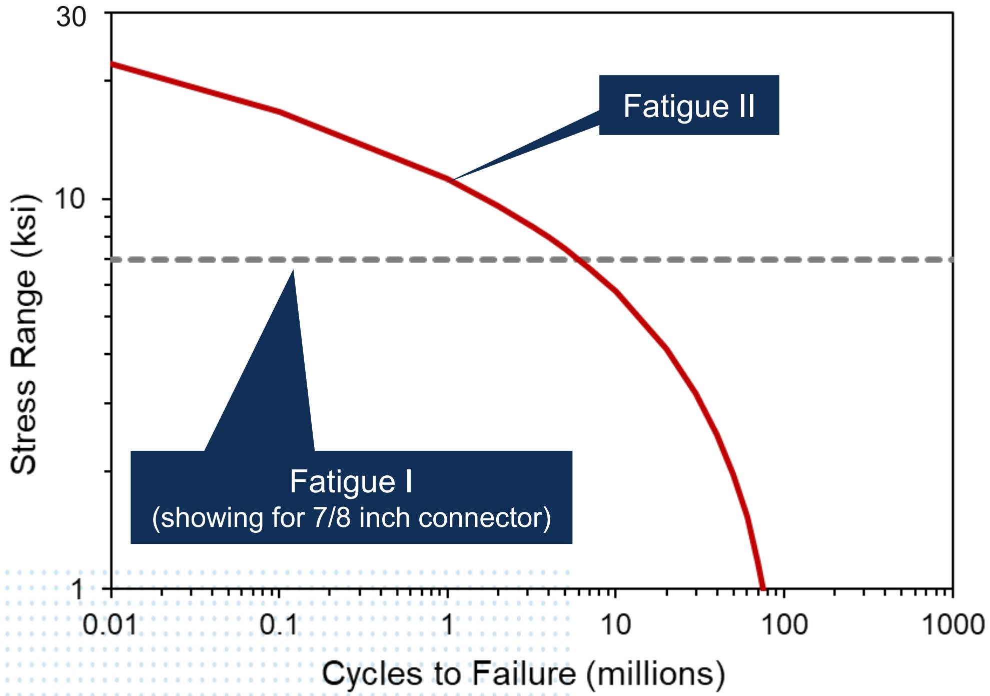
Fatigue of Shear Connector

(Fatigue I) $Z_r = 5.5d^2$

(Fatigue II) $Z_r = (34.5 - 4.28 \log N)\, d^2$

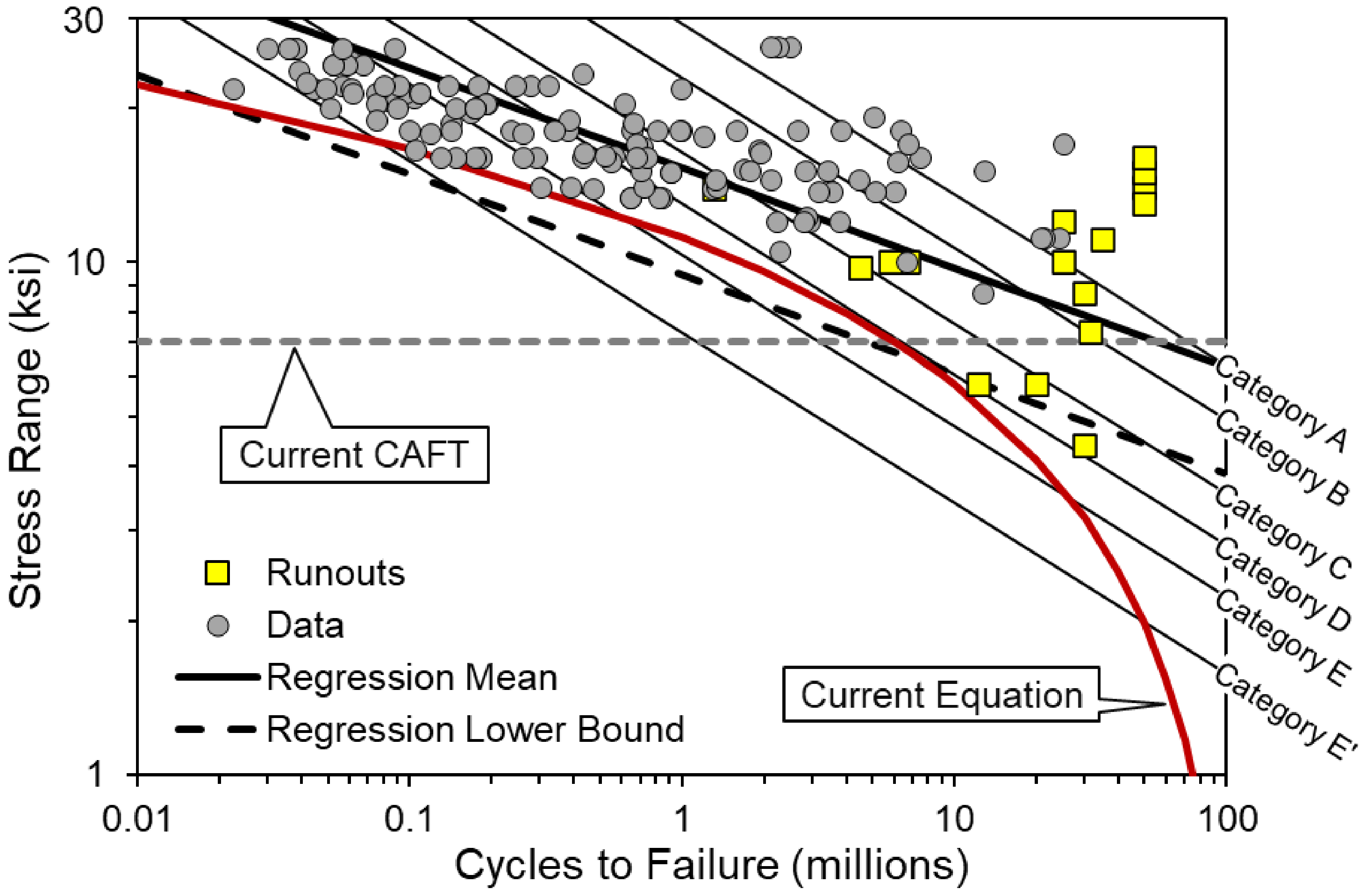
AASHTO LRFD BDS 9th Edition
Equations 6.10.10.2-1 through 6.10.10.2-3





NOTE:
This is for stud-type shear connectors, not showing requirements for channel-type shear connectors.

Fatigue of Shear Connector



130 failure points
17 runouts

- 18 references,
- 1959-2019,
- $^{3}/_{4}$ to 1-$^{1}/_{4}$ inch diameter ($^{1}/_{2}$ inch was excluded).

Slope = -5.14

Fatigue of Shear Connector

$$(\Delta F)_n = \left(\frac{A}{N}\right)^{\frac{1}{3}}$$

PRESENT

$$(\Delta F)_n = \left(\frac{A}{N}\right)^{\frac{1}{m}}$$

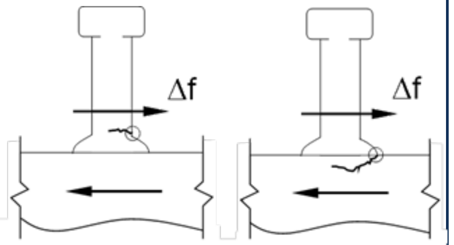
FUTURE

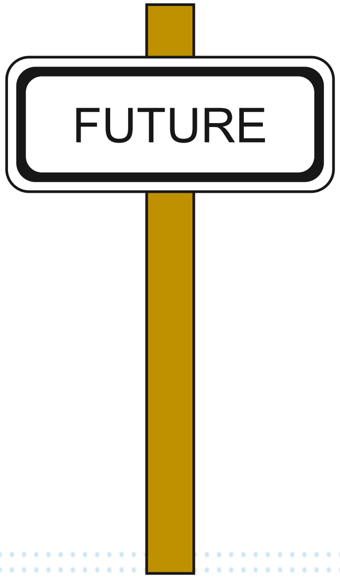
AASHTO LRFD BDS
Equation 6.6.1.2.5-2

Fatigue of Shear Connector

Column added to accommodate variable growth constants

Adding this column eliminates existing Table 6.6.1.2.3-2

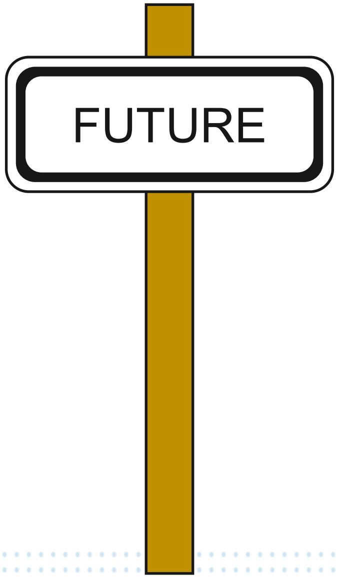
Description	Category	Constant *A* $(ksi)^3$	Growth Constant, *m*	Threshold $(\Delta F)_{TH}$ ksi	75-year $(ADTT)_{SL}$	Potential Crack Initiation Point	Illustrative Examples
Section 9—Miscellaneous							
9.2 Shear connectors or base metal at shear connectors attached by fillet or automatic stud welding (for use in the calculation of Z_r in Eq. 6.10.10.1.2-1 or 6.10.10.1.2-2). Use the horizontal fatigue shear range per unit length, V_{sr}, and Eq. 6.10.10.1.2-1 or 6.10.10.1.2-2, as applicable, to determine the pitch of the shear connectors for fatigue.	N/A	1040 x 10^8	5	7	11,320	Toe of stud growing through the stud, or into the base metal	



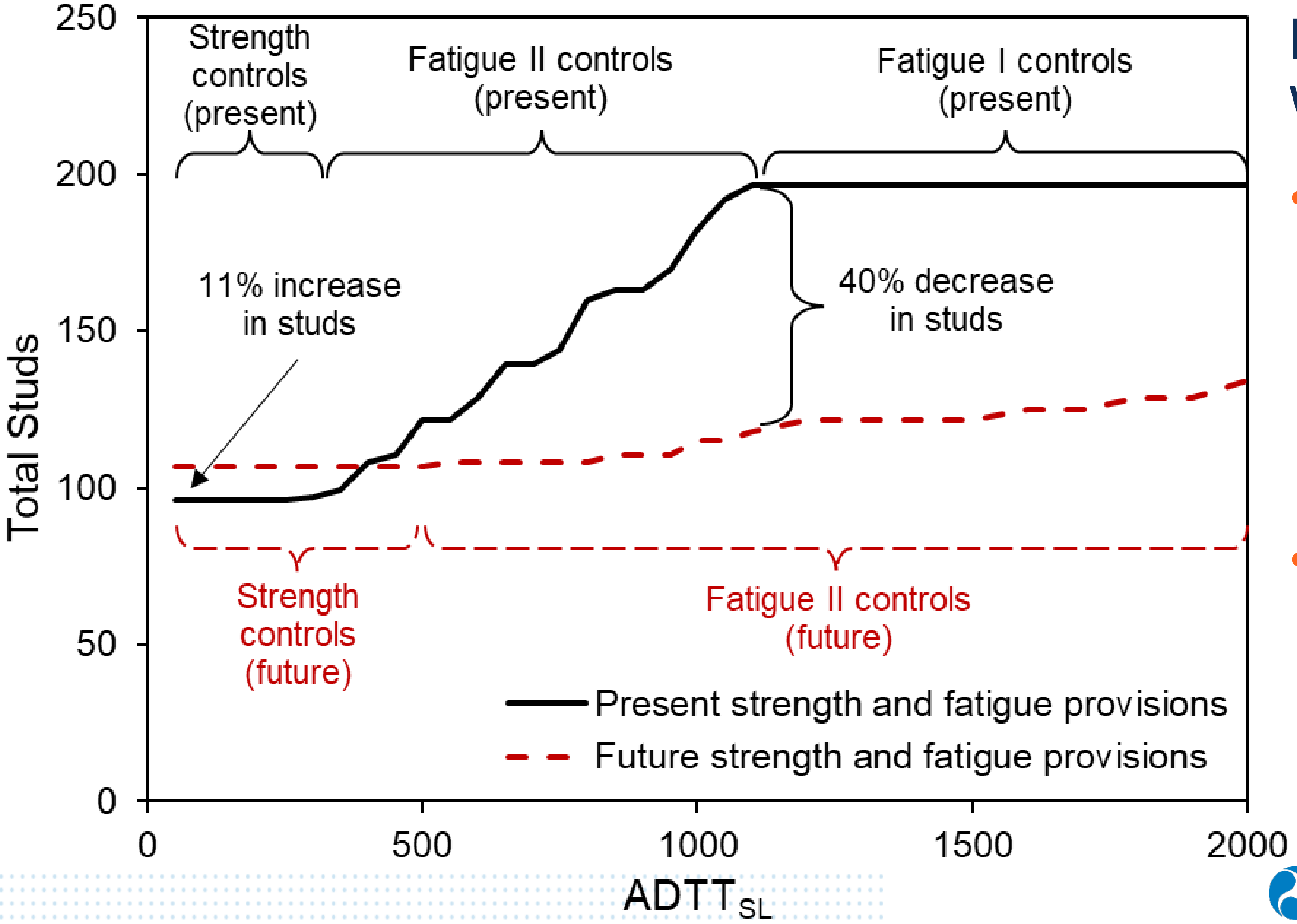
Adding this column eliminates existing Table 6.6.1.2.5-3

Other Changes

- Channel-type shear connectors were removed.
- Minimum longitudinal spacing between shear connectors reduced to 4*d* (currently at 6*d*).



Anticipated Effect



Example of 40-ft span W21x93 rolled beam bridge.

- Three other deeper, longer span girder examples showed a 4-26% reduction in shear connectors. Controlled by Fatigue II.
- Strength I will only govern on short spans.

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