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ICRI 2023 Fall Convention

Precast Double-Tee Garage Connection Failures due to Vehicular Fatigue Loading

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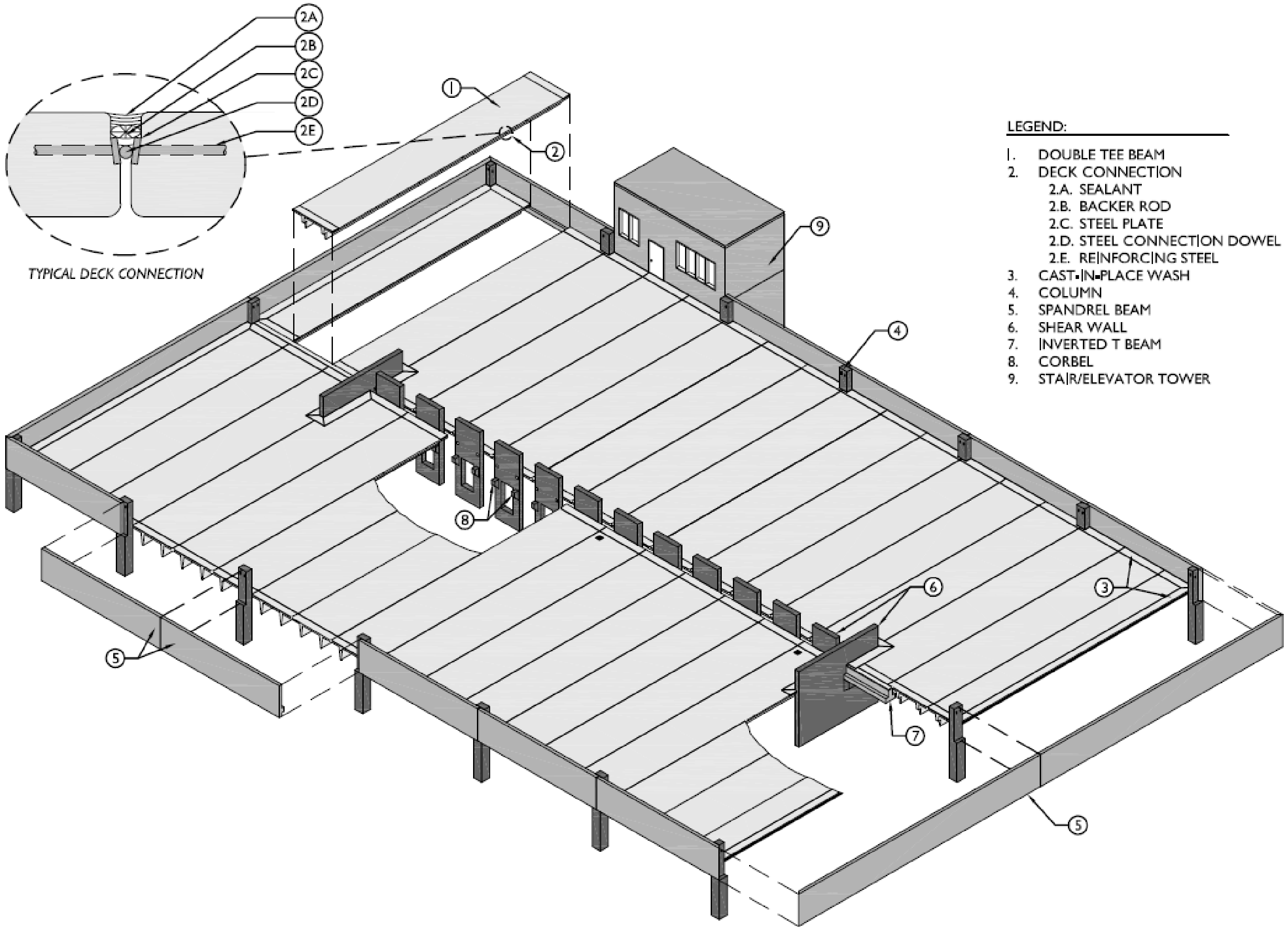
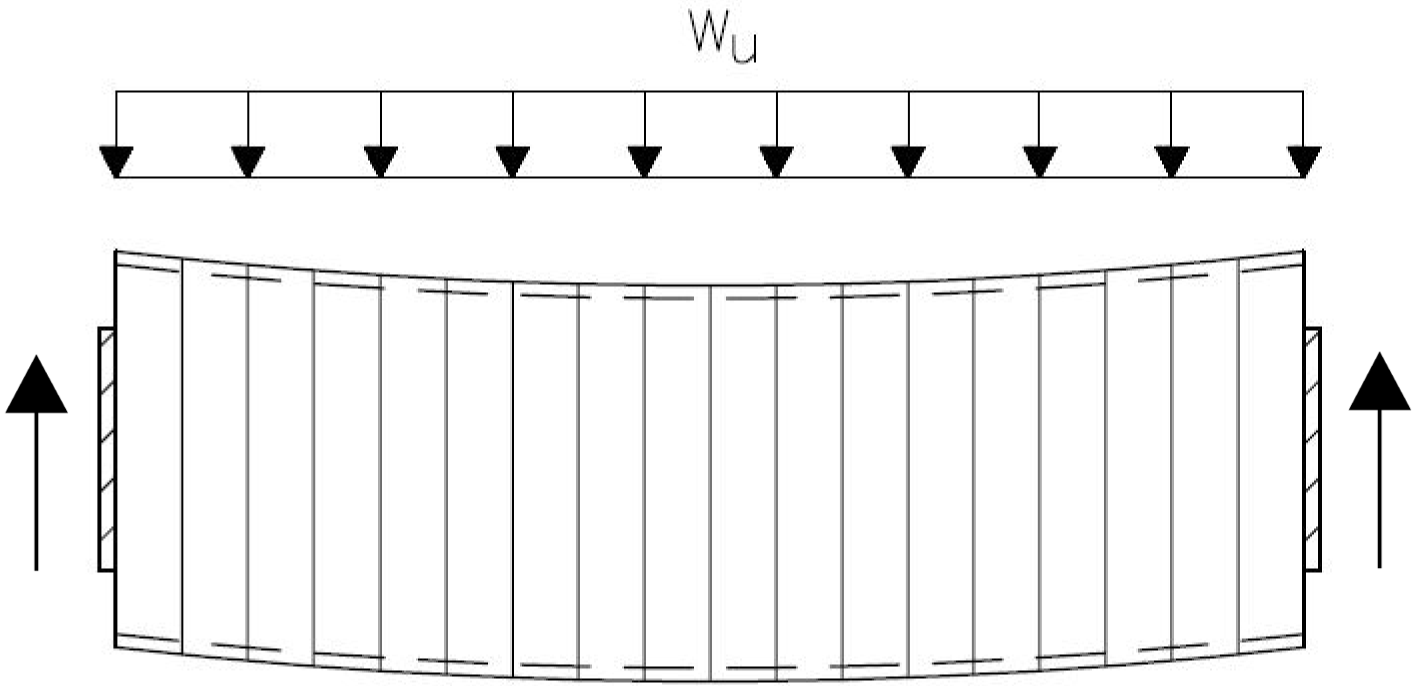
Connectco, LLC

ICRI CONCRETE REPAIR
Restore | Repurpose | Renew
35th YEAR ANNIVERSARY

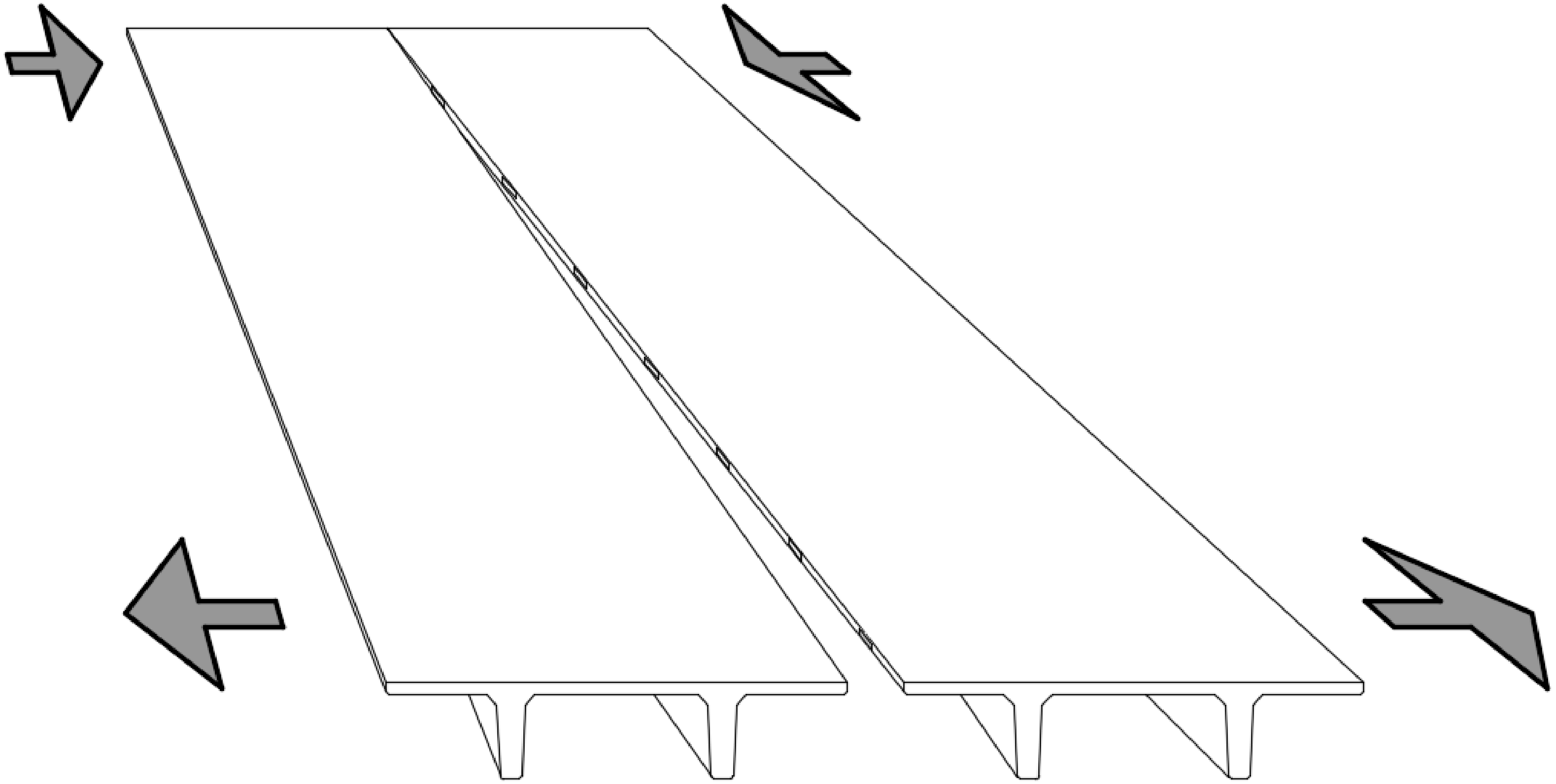
Typical Precast Double Tee Garage



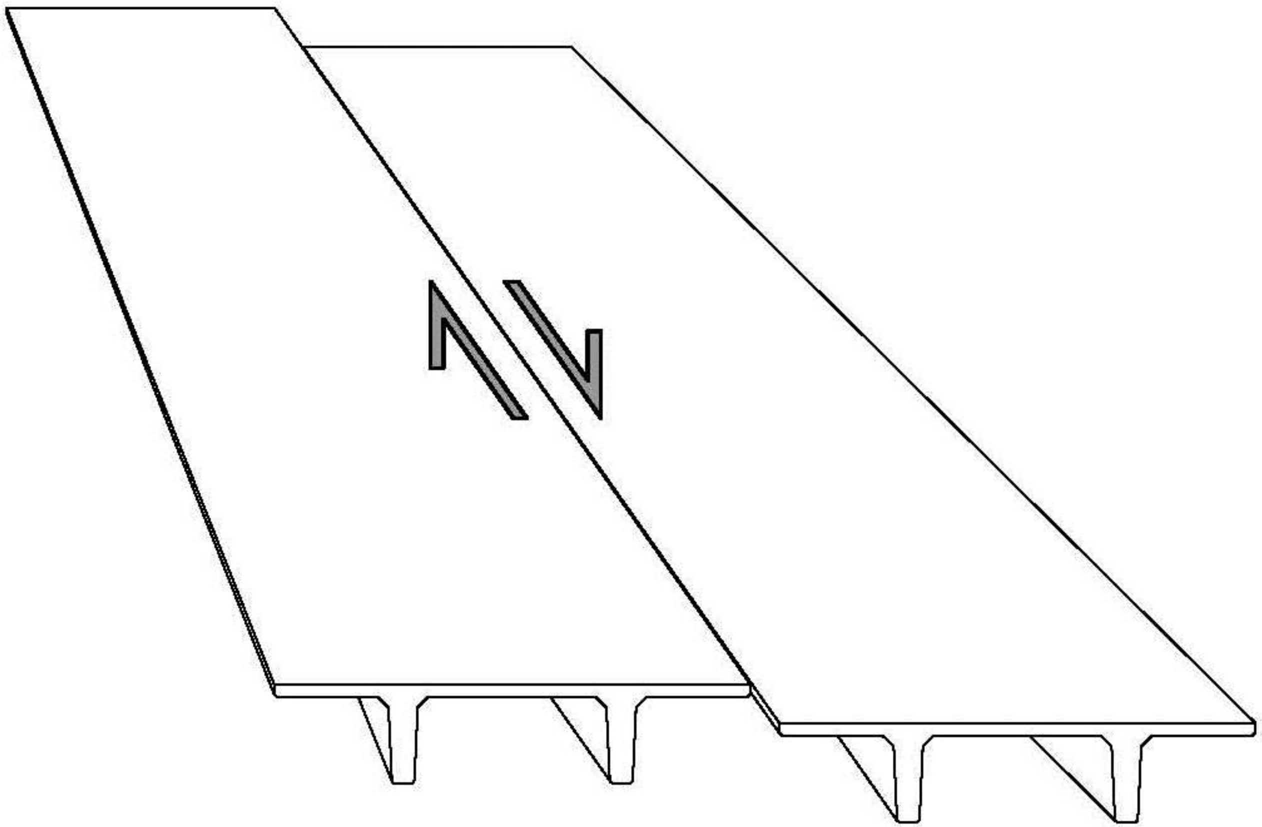
Diaphragm model



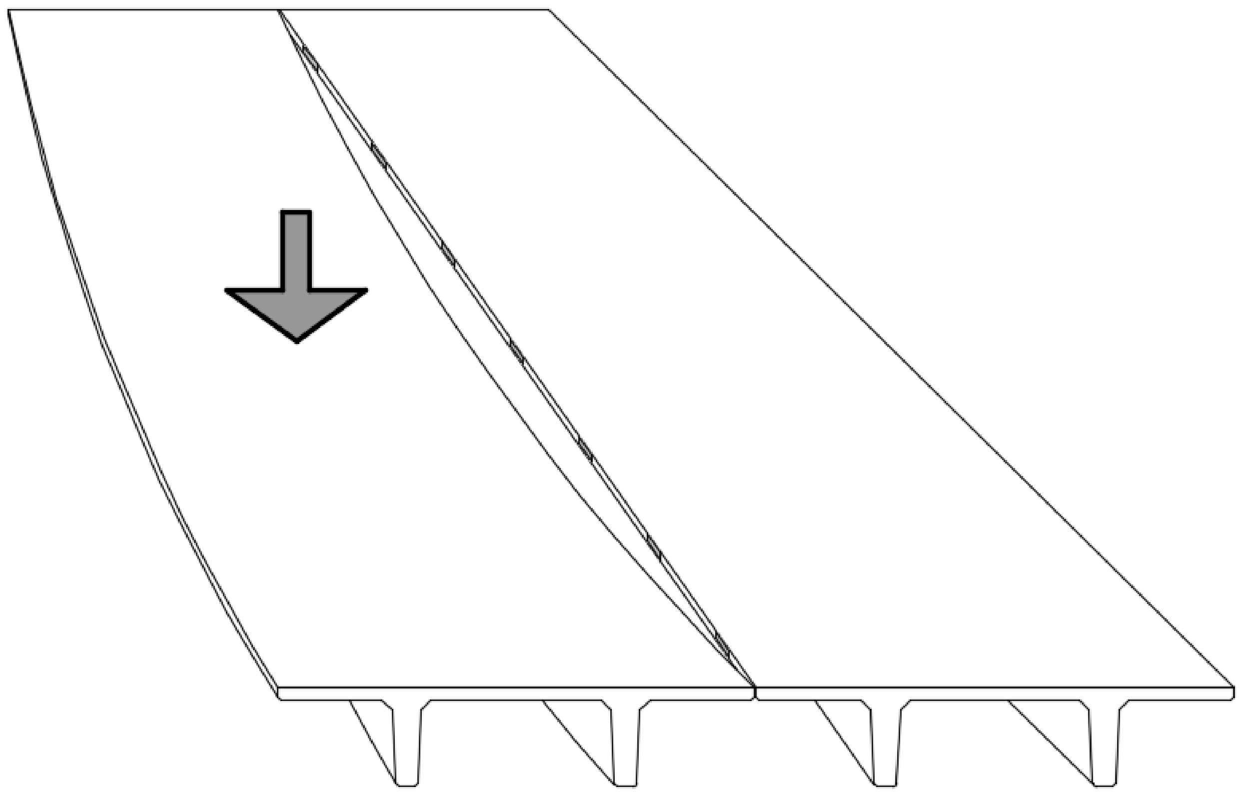
Deck Connection Forces - Chord



Deck Connection Forces - Shear



Deck Connection Forces - Gravity



Industry Standard for a “Properly Detailed Connection”:

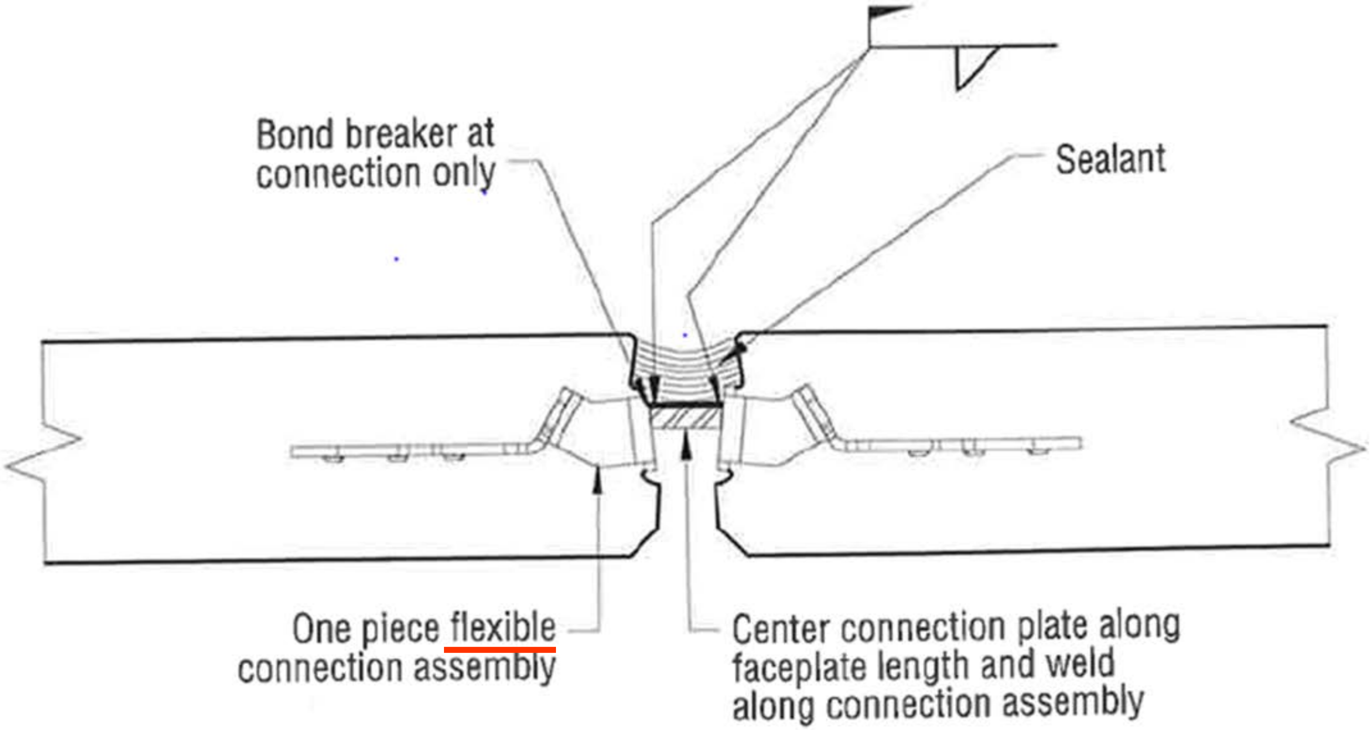


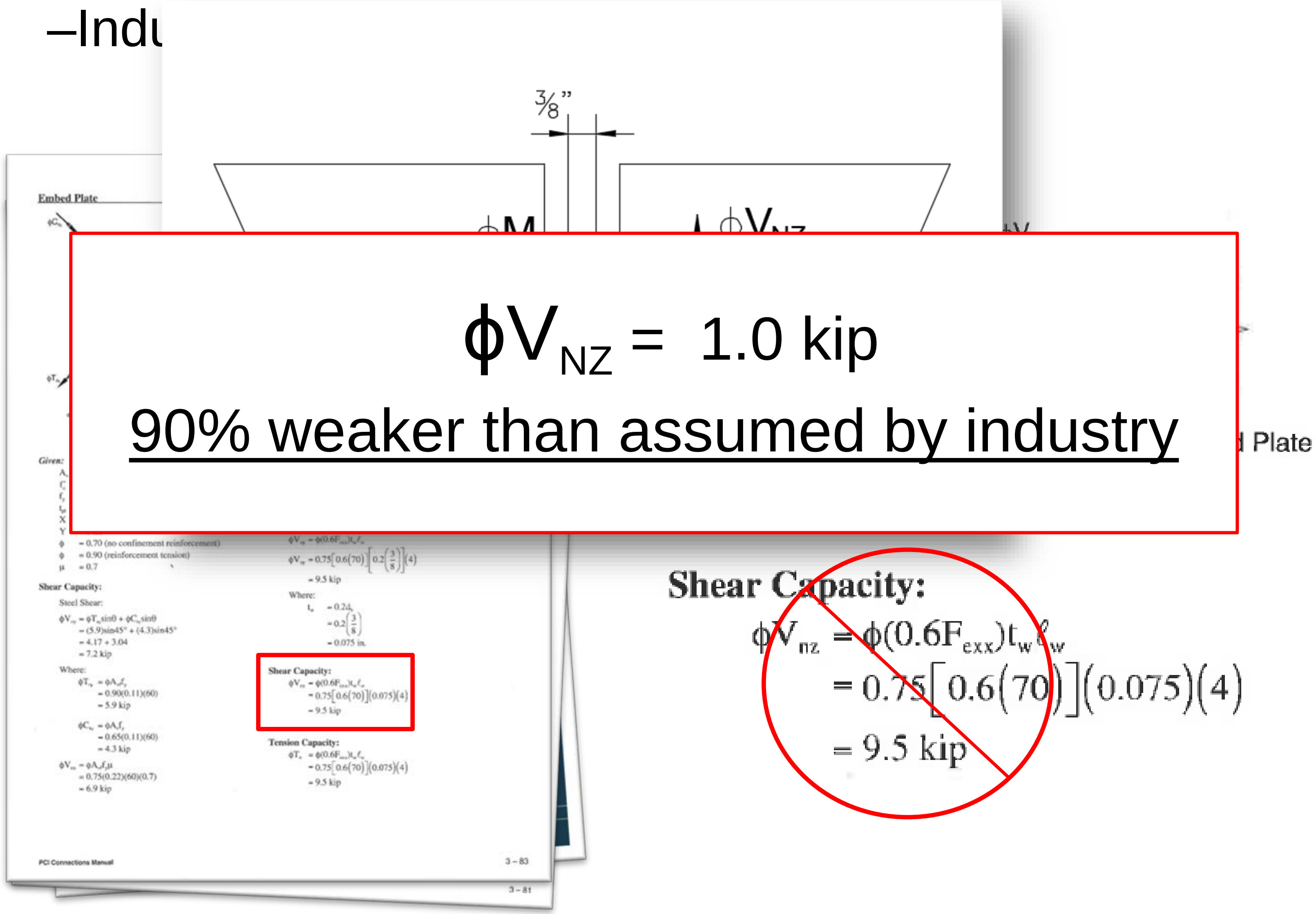
Figure 3-7 Pretopped Flange Connector

PCI, Precast Prestressed Concrete Parking Structures:
Recommended Practice for Design and Construction, Third Edition

Credit: Precast/Prestressed Concrete Institute, Cleland, Ned et all, *Precast Prestressed Concrete Parking Structures: Recommended Practice for Design and Construction, 3rd ed.*, 2015 (https://doi.org/10.15554/MNL-129-15)

How are the Connections Designed?

–Indu

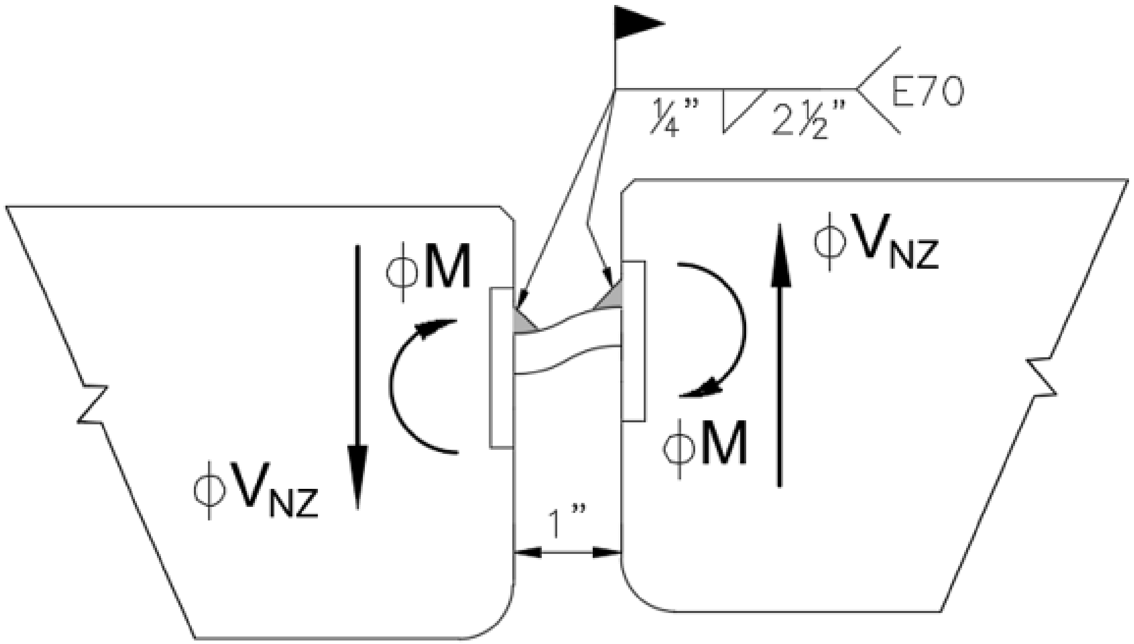


$$\phi V_{NZ} = 1.0 \text{ kip}$$

<u>90% weaker than assumed by industry</u>

–Credit: Precast/Prestressed Concrete Institute, Sennour, Larbi et all, *PCI Connections Manual for precast and prestressed concrete construction, 1st ed.*, 2008 (https://doi.org/10.15554/MNL-138-08)

Comparison with Common Connection…



When Bending in weld is considered

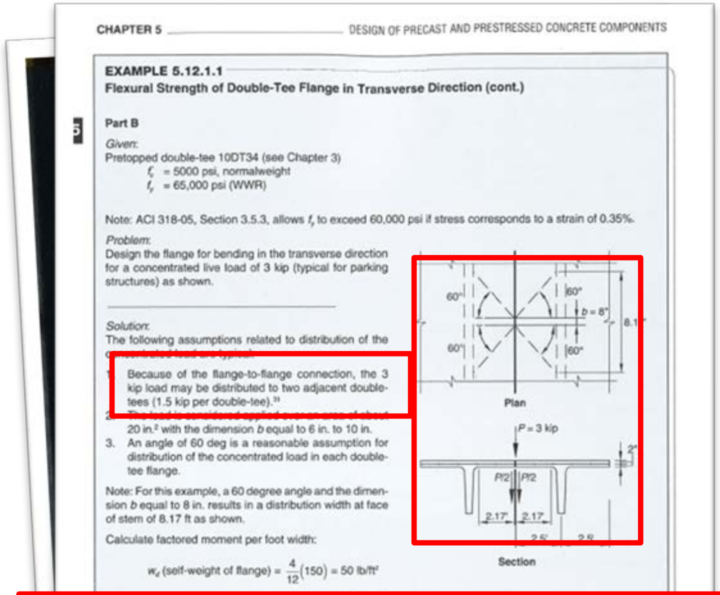
ϕV_{NZ} = 1.25 kips* <<<13.9 kips

90% weaker

* Static strength using E70xx and $0.6F_{exx}$; ϕ = 0.75

What Load is Required?

–Industry Standard…



CHAPTER 5 DESIGN OF PRECAST AND PRESTRESSED CONCRETE COMPONENTS

EXAMPLE 5.12.1.1
Flexural Strength of Double-Tee Flange in Transverse Direction (cont.)

Part B

Given:
Pretopped double-tee 10DT34 (see Chapter 3)
f'_c = 5000 psi, normalweight
f_y = 65,000 psi (WWR)

Note: ACI 318-05, Section 3.5.3, allows f_y to exceed 60,000 psi if stress corresponds to a strain of 0.35%.

Problem:
Design the flange for bending in the transverse direction for a concentrated live load of 3 kip (typical for parking structures) as shown.

Solution:
The following assumptions related to distribution of the [illegible]

1. Because of the flange-to-flange connection, the 3 kip load may be distributed to two adjacent double-tees (1.5 kip per double-tee).[31]
2. [illegible] 20 in.^{2} with the dimension b equal to 6 in. to 10 in.
3. An angle of 60 deg is a reasonable assumption for distribution of the concentrated load in each double-tee flange.

Note: For this example, a 60 degree angle and the dimension b equal to 8 in. results in a distribution width at face of stem of 8.17 ft as shown.

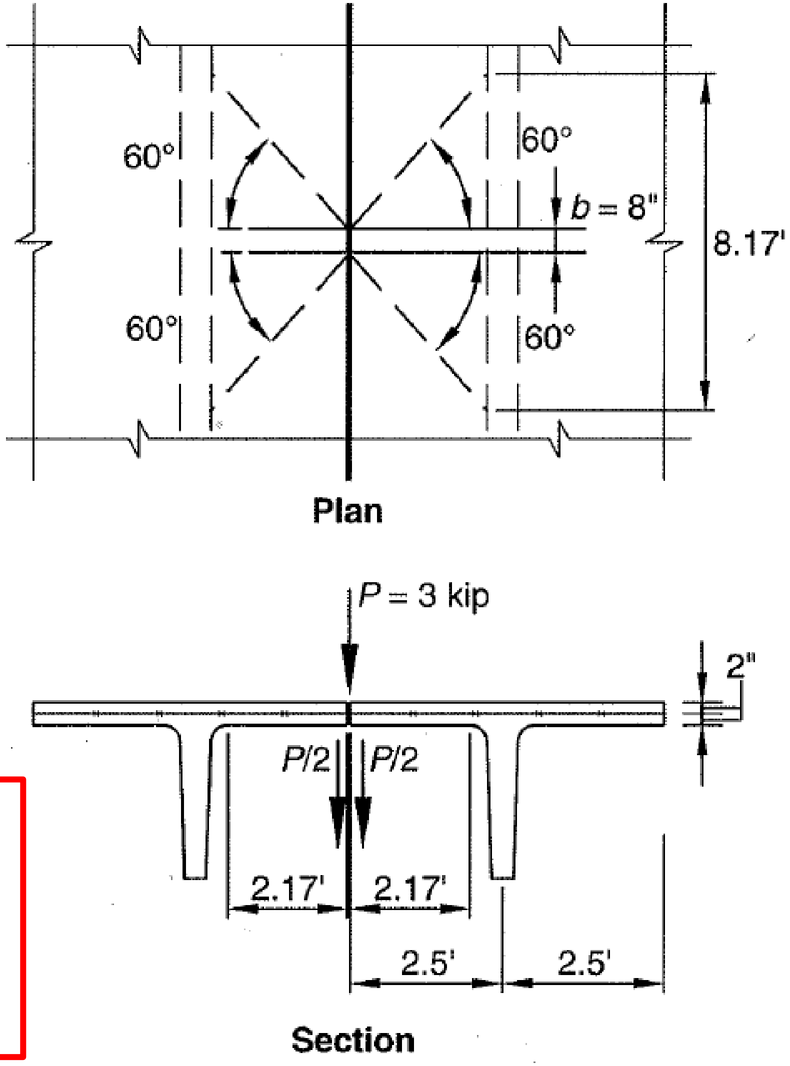
Calculate factored moment per foot width:

$$w_d \text{ (self-weight of flange)} = \frac{4}{12}(150) = 50 \text{ lb/ft}^2$$

Plan

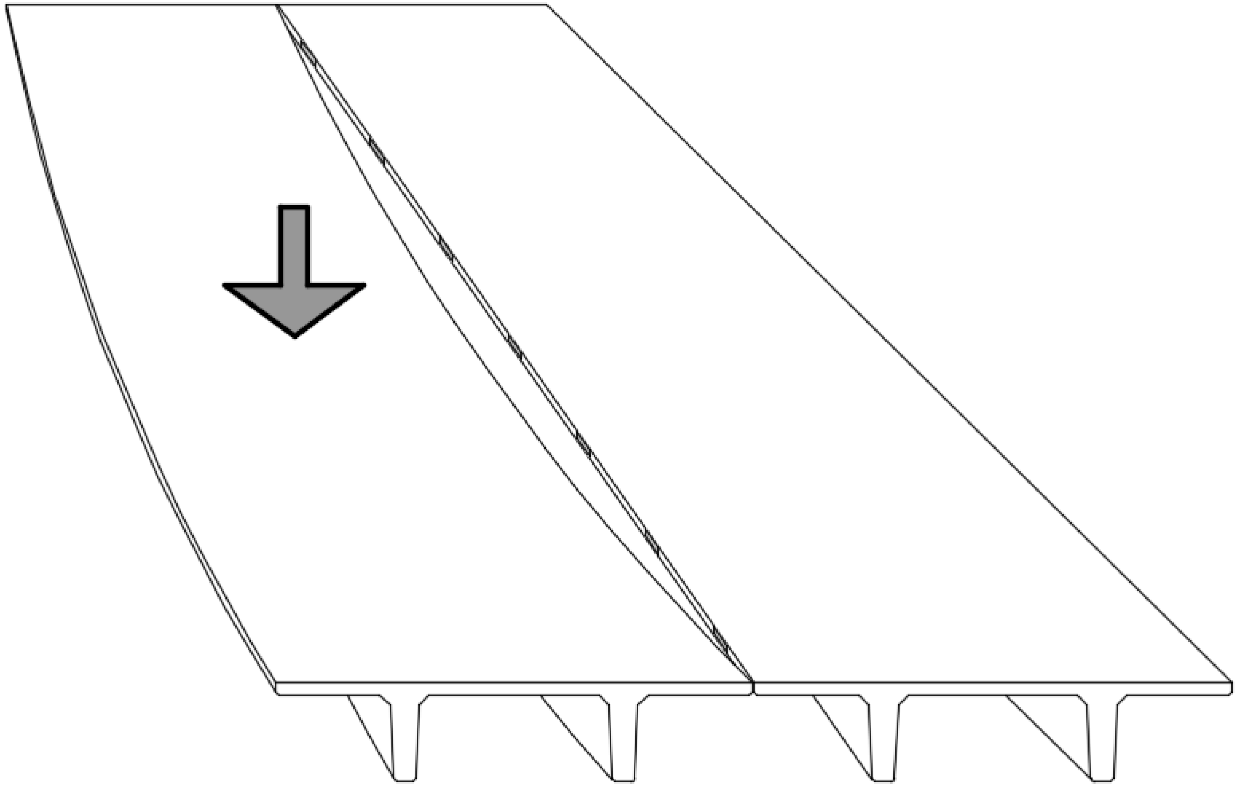
Section

“Because of the flange-to-flange connection, the 3-kip load may be distributed to two adjacent double tees (1.5 kips per double tee).”



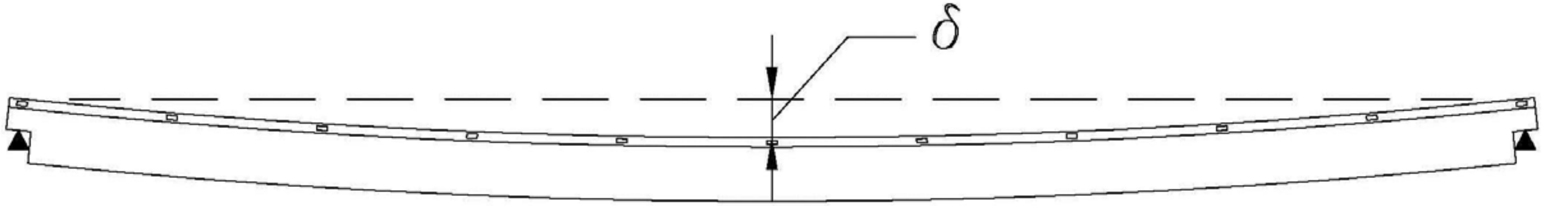
Credit: Precast/Prestressed Concrete Institute, Timothy R. Salmons, et all, *PCI Design Handbook, 8th ed.*, 2017 (https://doi.org/10.15554/MNL-120-17)

What Shear Load is Required?



What Load is Required?

–Actual Theoretical Distribution…



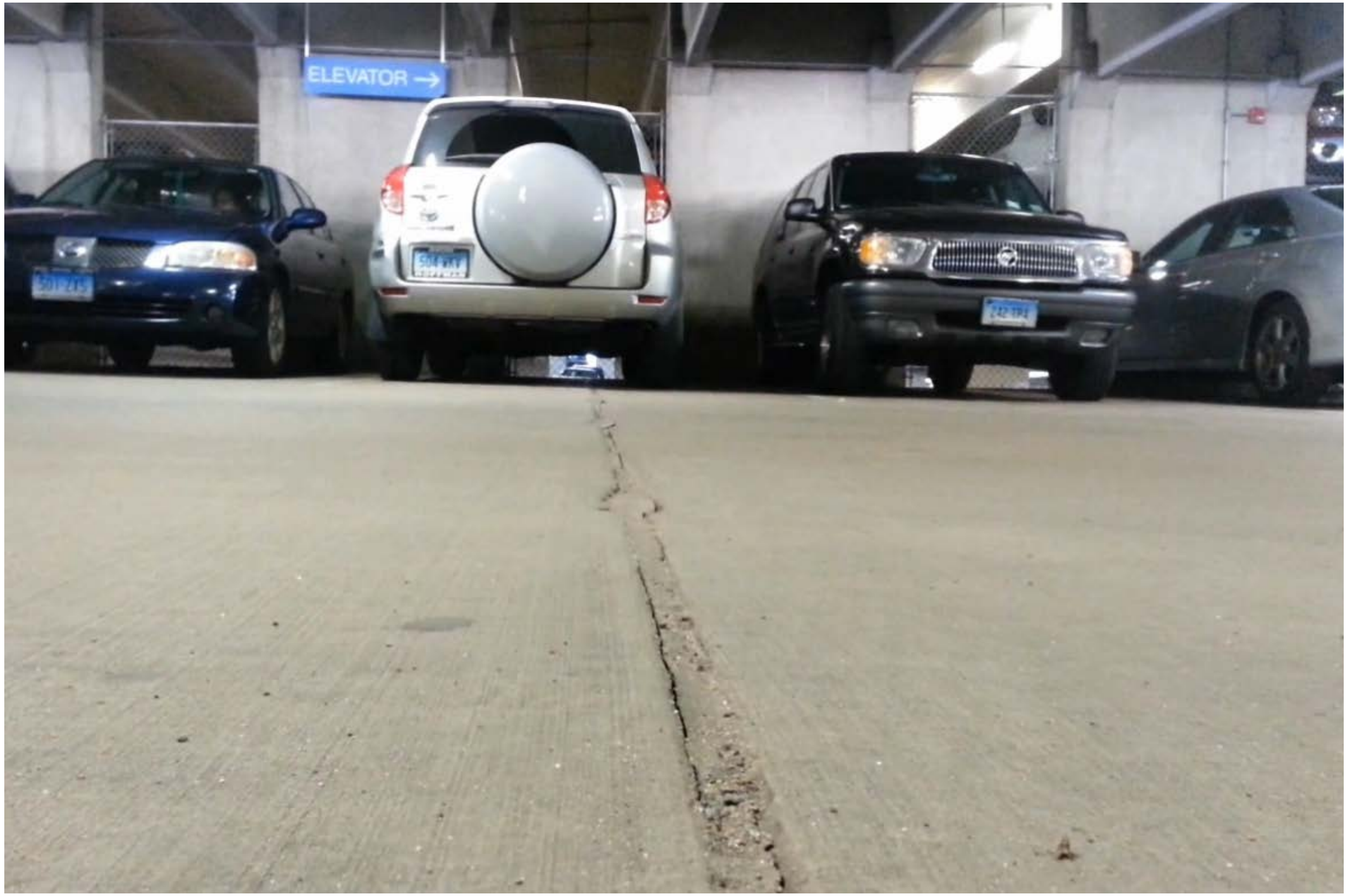
$$P_{(connection)} = P_{(axel)} \, x \, \mu \, / \, 2$$

$$\mu = \frac{\delta_x}{\sum \delta_x}$$

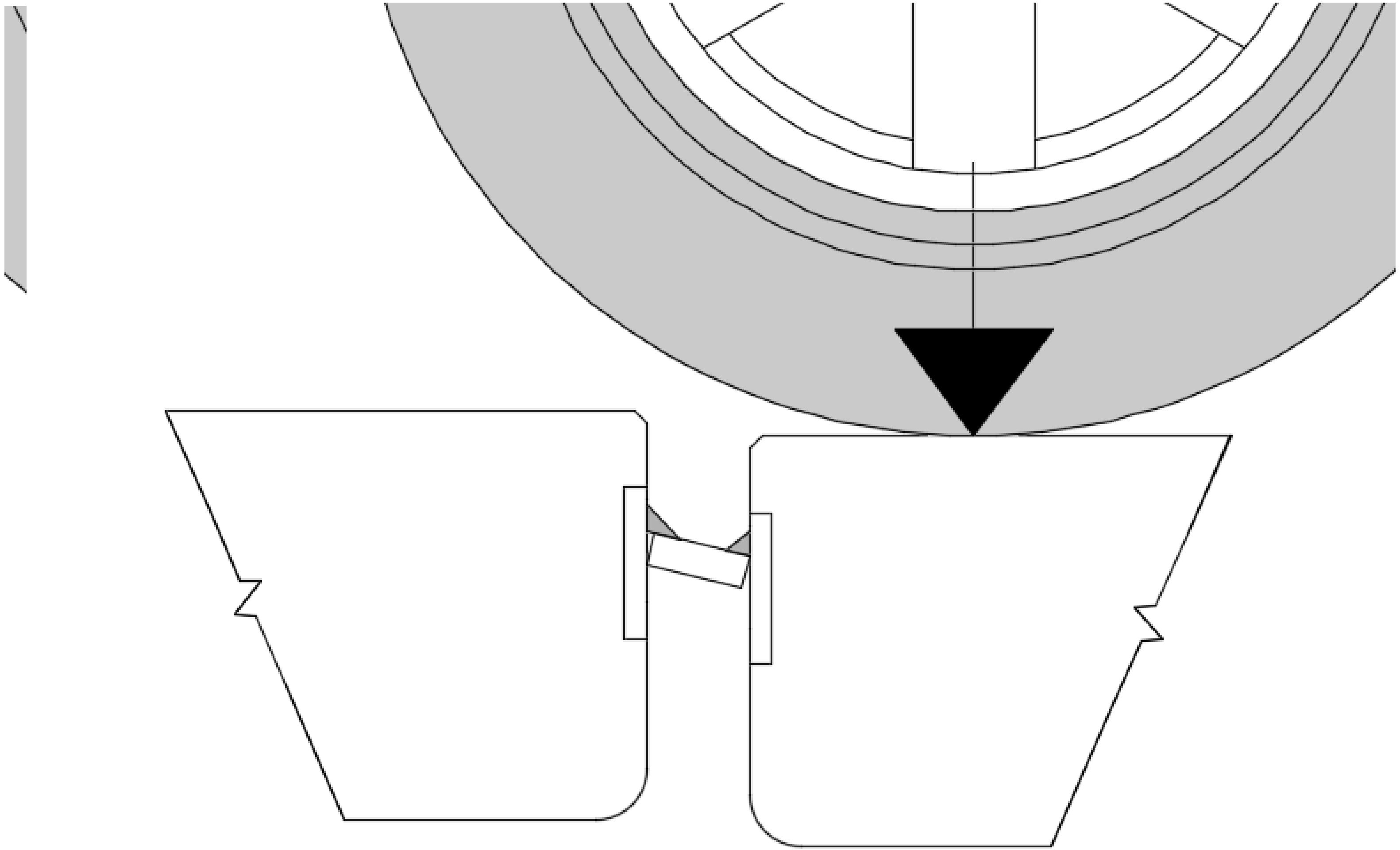
$$\delta = \frac{Px}{48EI}(3l^2 - 4x^2)$$

$$\mu = \frac{\delta_x}{\sum \delta_x} = \frac{\frac{Px}{48EI}(3l^2 - 4x^2)}{\sum[\frac{Px}{48EI}(3l^2 - 4x^2)]} = \frac{x\,(3l^2 - 4x^2)}{\sum[x\,(3l^2 - 4x^2)]}$$

…the ***Real*** Problem



Vehicular Fatigue Loading



What is Fatigue?

Fatigue - The process by which a material becomes weakened through cyclic loading

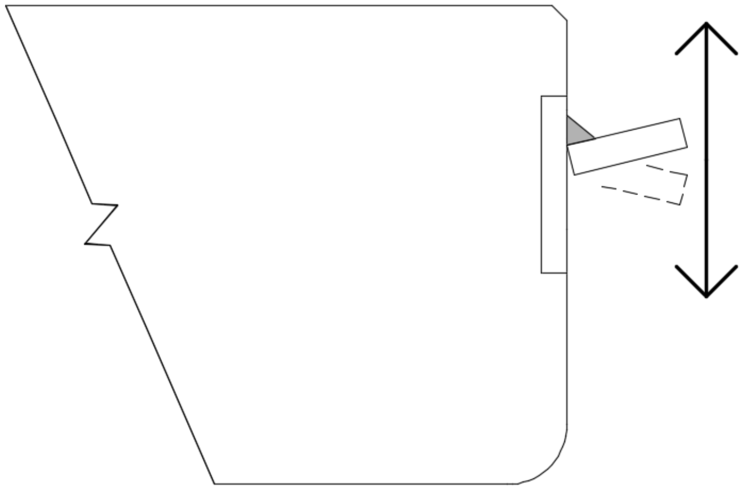
- Low Cycle Fatigue
  - Plastic deformation

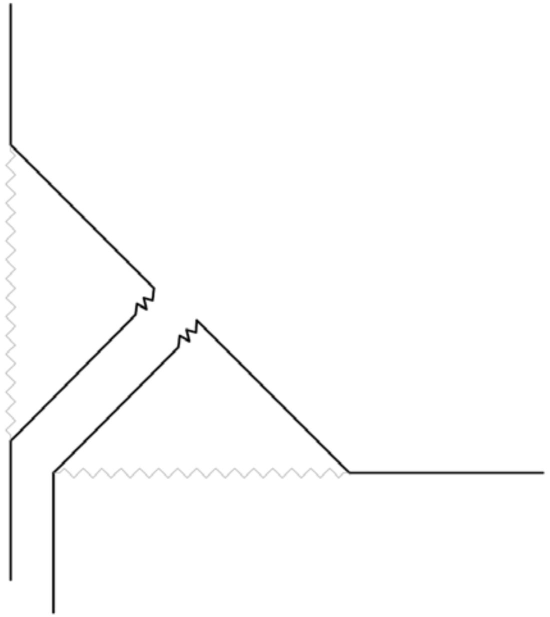
- High Cycle Fatigue
  - Elastic deformation

The Fatigue Process

Three Steps of Fatigue Failure:

1. Crack Initiation
2. Crack Propagation
3. Failure





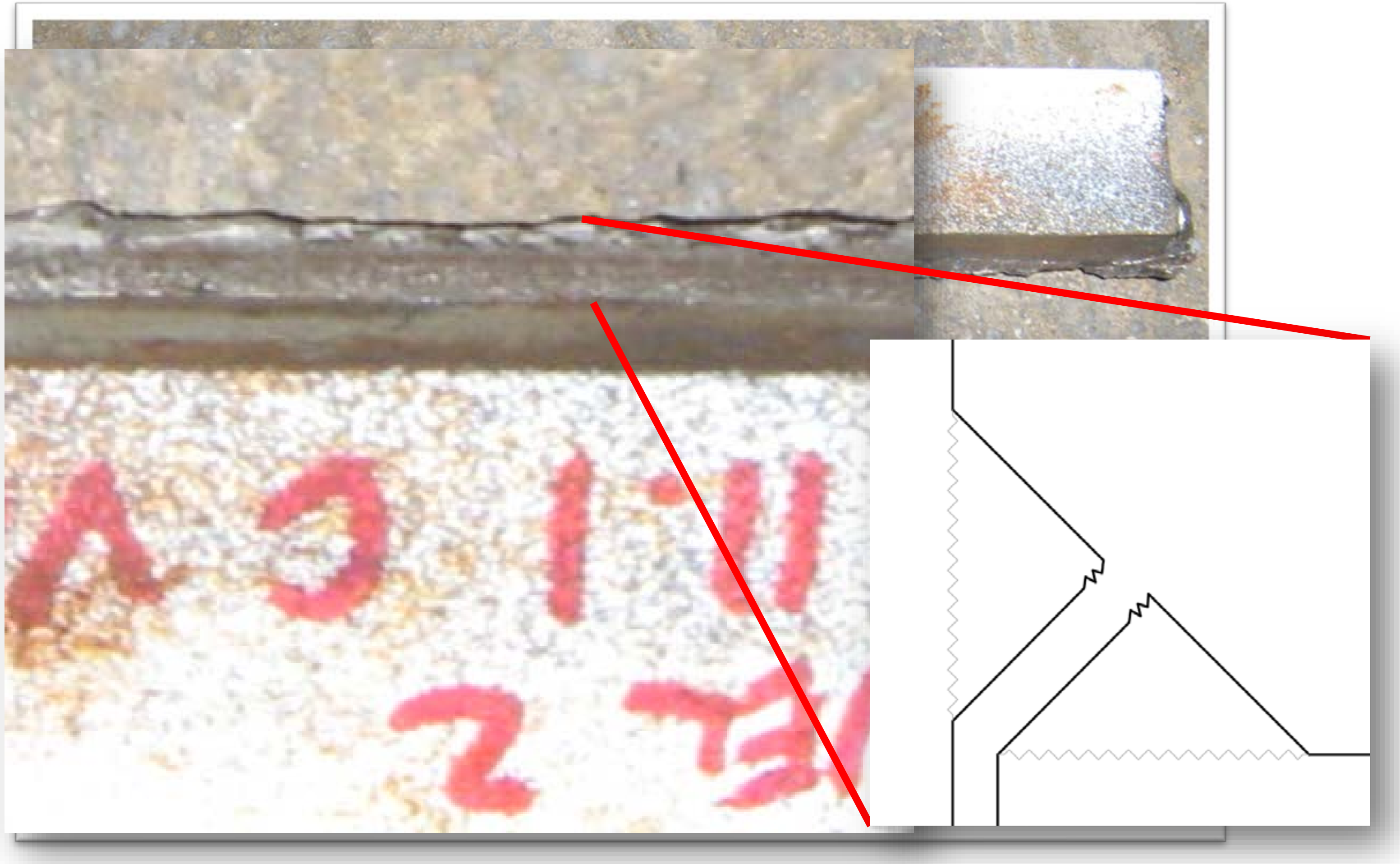
Fatigue – What to look for…

Fatigue – What not to look for…

Fractured surface jagged and wandering

Fatigue – What to look for…

Crack initiation at root, propagation at throat, and rupture at face



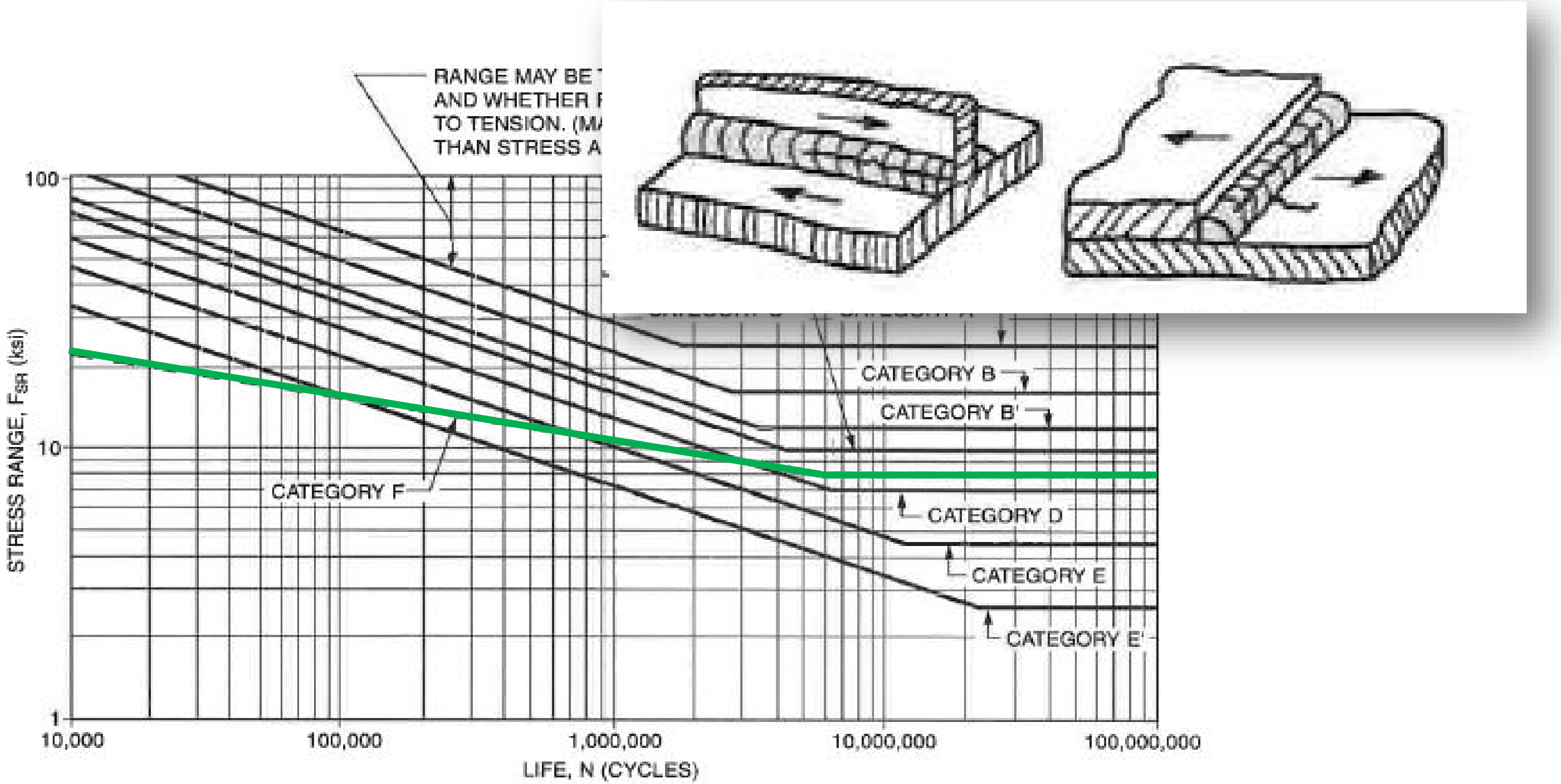
…and beach marks on weld fracture surface

…and moving / leaking joints

Designing for Fatigue

- Fatigue need not occur at high stress
- Main factors influencing fatigue are:
  - Number of cycles (2 axles/car)
  - The Stress Range (stress fluctuation)
  - Stress Category (severity of stress concentration)

S-N Curve



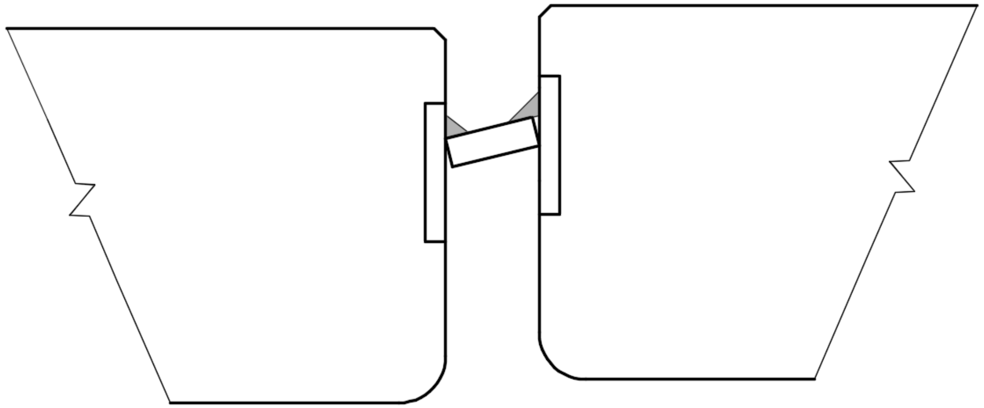
(A) U.S. CUSTOMARY UNITS

AWS D1.1 Figure 2.11 Allowable Stress Range for Cyclically Applied Load (Fatigue) in Nontubular Connections

Number of Cycles

Per AISC 360:

Fatigue analysis required if ≥ 20,000 cycles



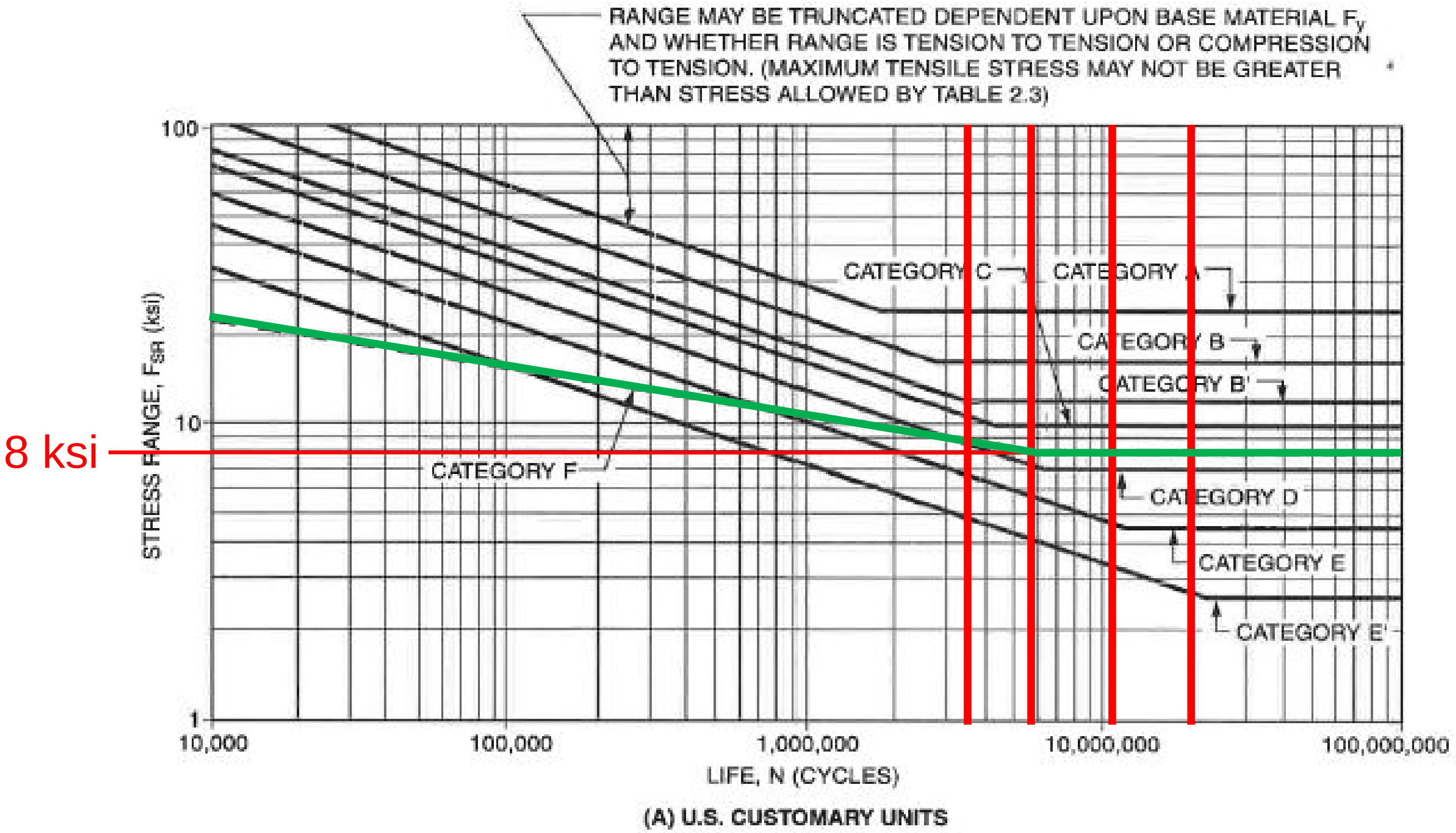
Example: 500 cars/day

X 2 axles X 2 = 2,000 cycles/day

X 365 days = 730,000 cycles/year

X 30 Years = 21.9 million cycles

S-N Curve



AWS D1.1 Figure 2.11 Allowable Stress Range for Cyclically Applied Load (Fatigue) in Nontubular Connections

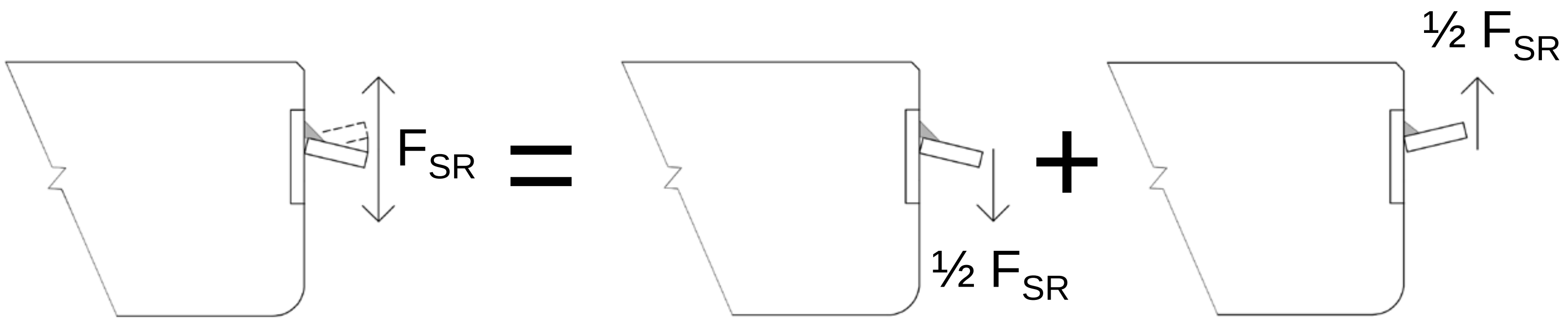
Stress Range

Per AISC and AWS Code (AWS D1.1)

Allowable stress for fatigue:

Allowable Stress Range (F_{SR})

F_{SR} = Tension + Compression Stresses

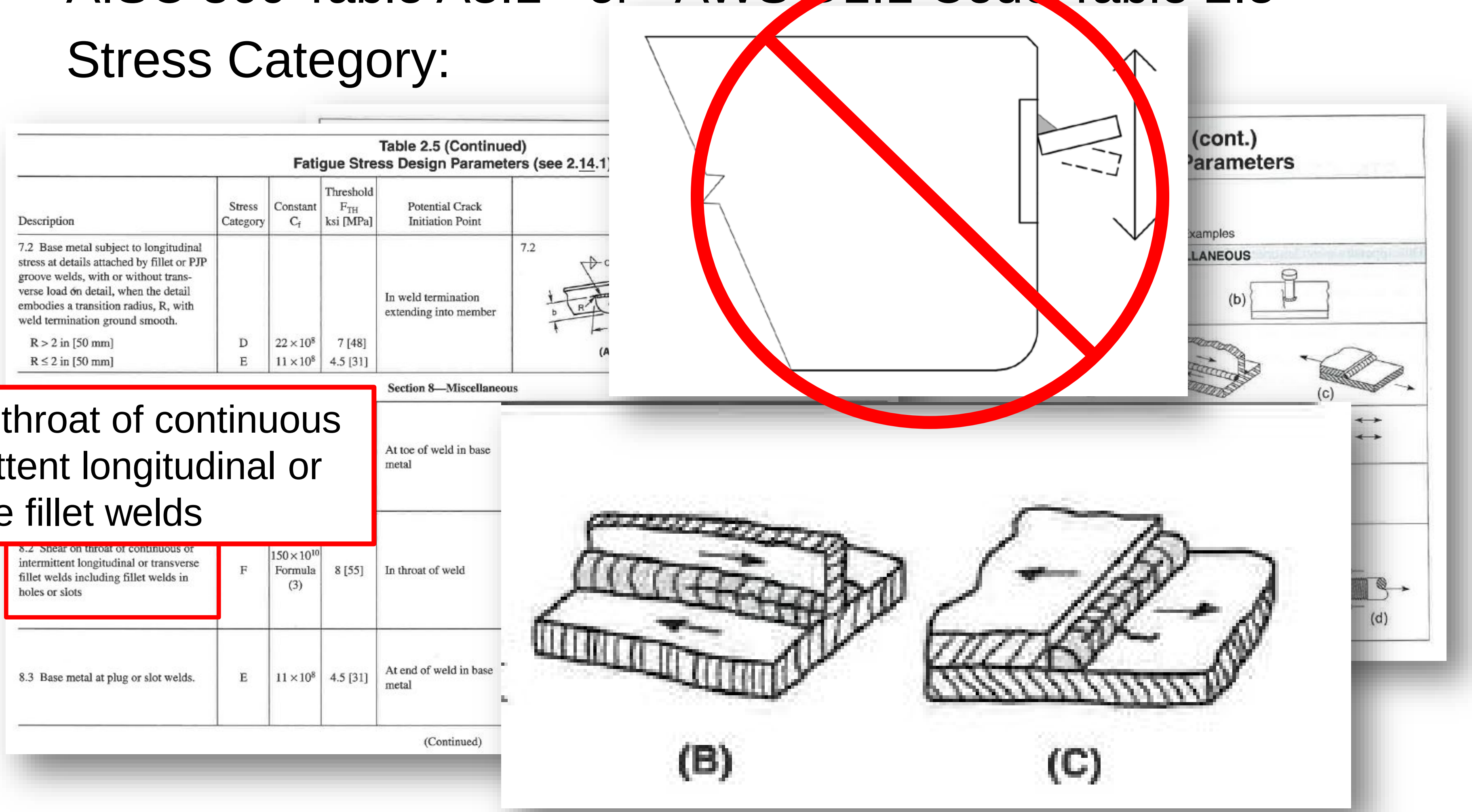


Stress Category

AISC 360 Table A3.1 <or> AWS D1.1 Code Table 2.5

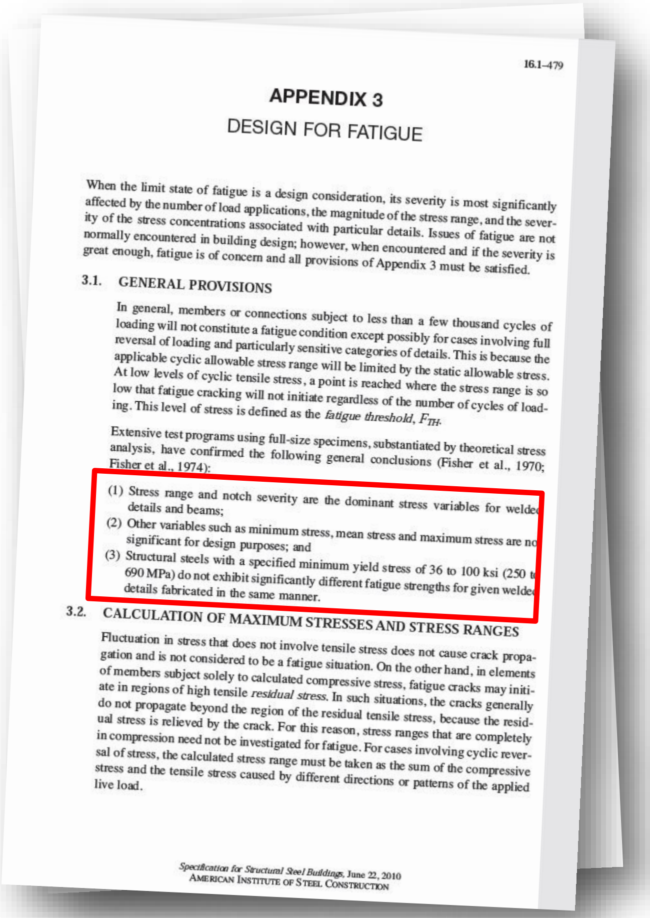
Stress Category:

Shear on throat of continuous or intermittent longitudinal or transverse fillet welds



What do Industry Experts Say?

Steel Construction Manual, American Institute of Steel Construction(AISC)


16.1–479

APPENDIX 3

DESIGN FOR FATIGUE

When the limit state of fatigue is a design consideration, its severity is most significantly affected by the number of load applications, the magnitude of the stress range, and the severity of the stress concentrations associated with particular details. Issues of fatigue are not normally encountered in building design; however, when encountered and if the severity is great enough, fatigue is of concern and all provisions of Appendix 3 must be satisfied.

3.1. GENERAL PROVISIONS

In general, members or connections subject to less than a few thousand cycles of loading will not constitute a fatigue condition except possibly for cases involving full reversal of loading and particularly sensitive categories of details. This is because the applicable cyclic allowable stress range will be limited by the static allowable stress. At low levels of cyclic tensile stress, a point is reached where the stress range is so low that fatigue cracking will not initiate regardless of the number of cycles of loading. This level of stress is defined as the *fatigue threshold*, F_{TH}.

Extensive test programs using full-size specimens, substantiated by theoretical stress analysis, have confirmed the following general conclusions (Fisher et al., 1970; Fisher et al., 1974):

(1) Stress range and notch severity are the dominant stress variables for welde[d] details and beams;

(2) Other variables such as minimum stress, mean stress and maximum stress are no[t] significant for design purposes; and

(3) Structural steels with a specified minimum yield stress of 36 to 100 ksi (250 t[o] 690 MPa) do not exhibit significantly different fatigue strengths for given welde[d] details fabricated in the same manner.

3.2. CALCULATION OF MAXIMUM STRESSES AND STRESS RANGES

Fluctuation in stress that does not involve tensile stress does not cause crack propagation and is not considered to be a fatigue situation. On the other hand, in elements of members subject solely to calculated compressive stress, fatigue cracks may initiate in regions of high tensile *residual stress*. In such situations, the cracks generally do not propagate beyond the region of the residual tensile stress, because the residual stress is relieved by the crack. For this reason, stress ranges that are completely in compression need not be investigated for fatigue. For cases involving cyclic reversal of stress, the calculated stress range must be taken as the sum of the compressive stress and the tensile stress caused by different directions or patterns of the applied live load.

Specification for Structural Steel Buildings, June 22, 2010
AMERICAN INSTITUTE OF STEEL CONSTRUCTION

Appendix 3 Design for Fatigue

1) Stress range and <u>notch severity</u> are the dominant stress variables for welded details

What do Industry Experts Say?

Steel Construction Manual, American Institute of Steel Construction(AISC)

Part 8 - Design Consideration for Welds

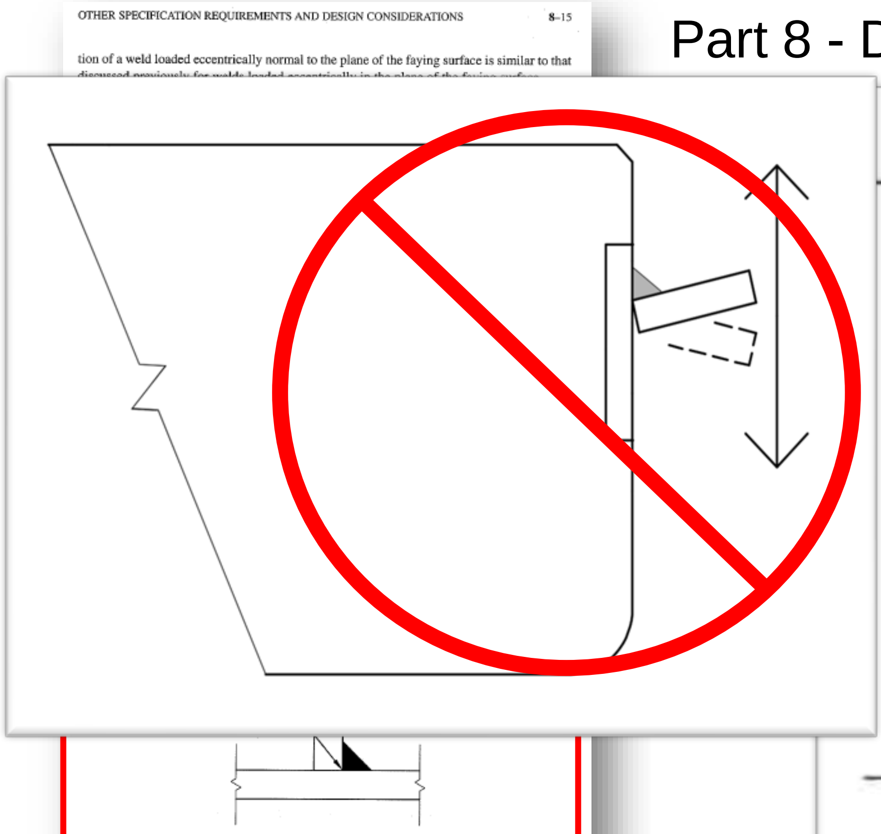
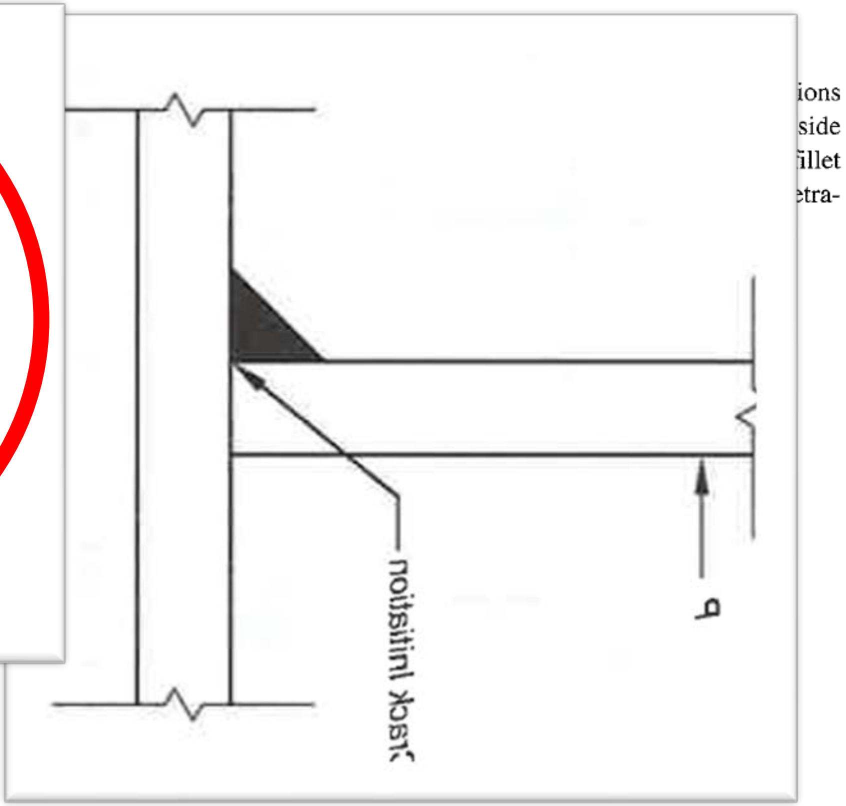


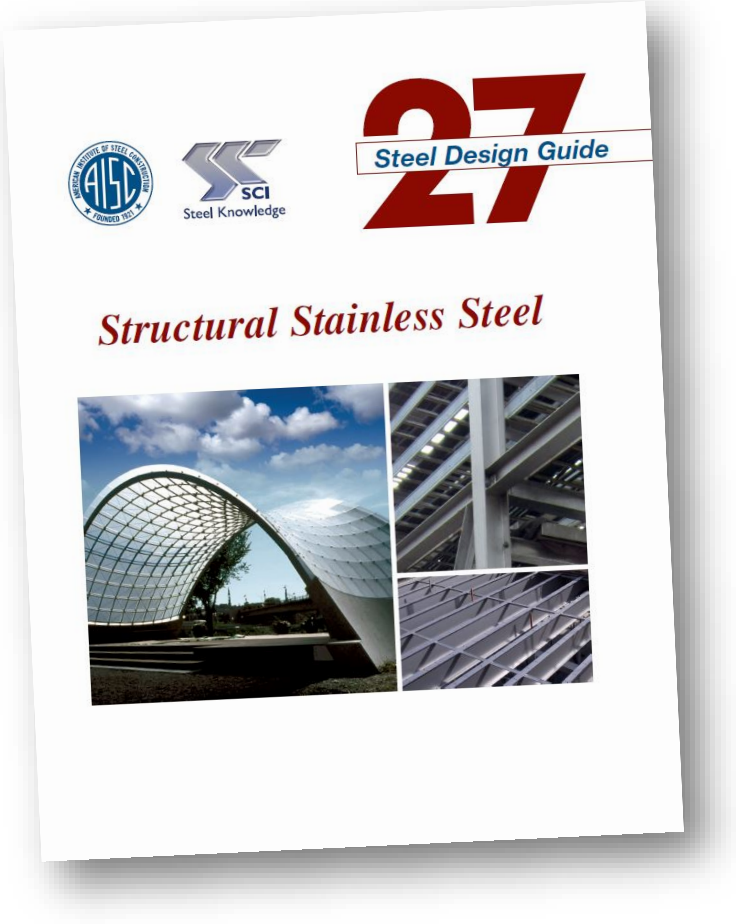
Figure 8–8. Notch effect at one-sided weld.

AMERICAN INSTITUTE OF STEEL CONSTRUCTION, INC.



What do Industry Experts Say?

Steel Design Guide 27, Structural Stainless Steel
American Institute of Steel Construction (AISC)



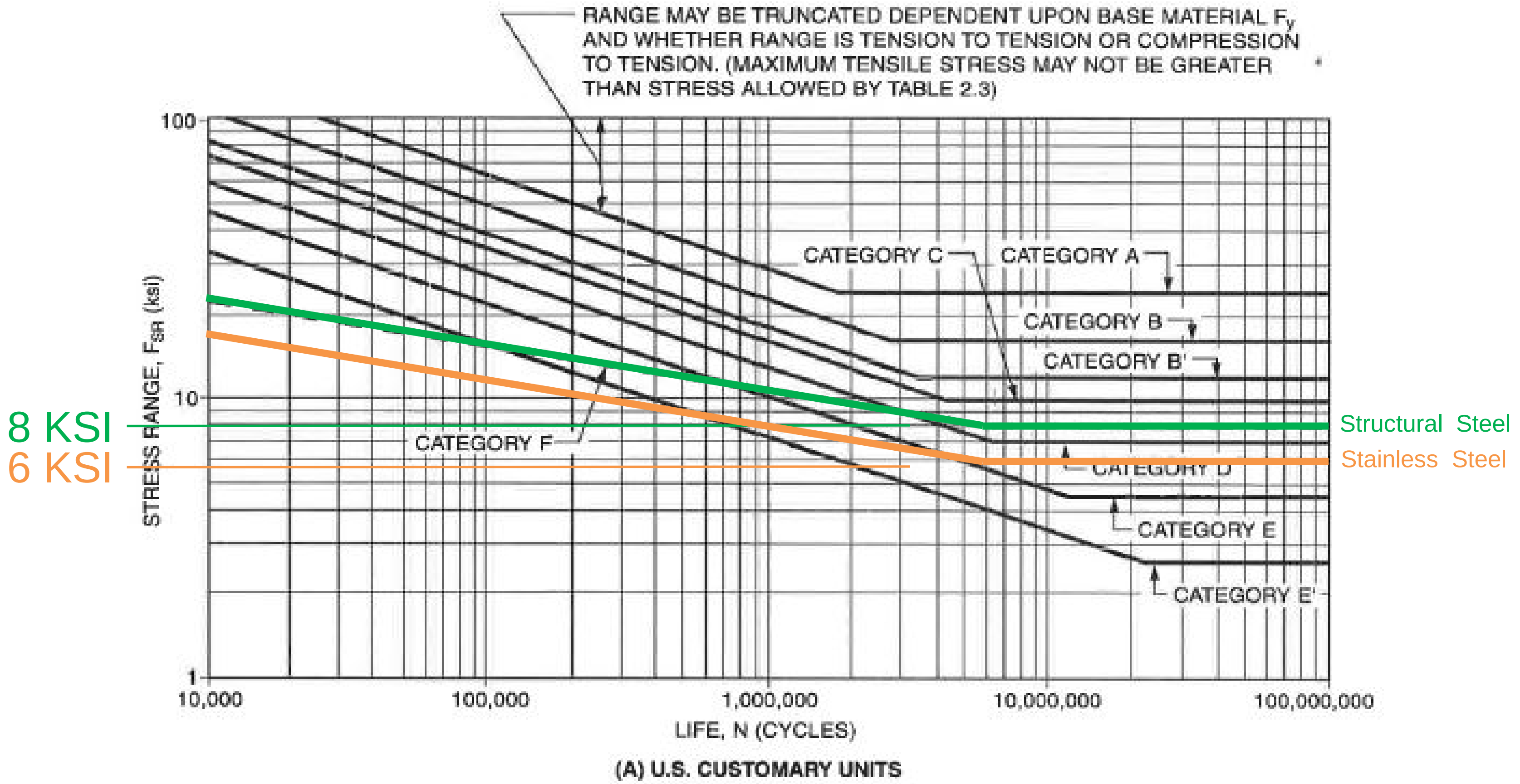
Chapter 9, Section 9.2 Design of Welded Connections

Use decreased resistance factors or increase factors of safety for stainless steel welds

$\phi = 0.55$ (LRFD) $\quad \Omega = 2.70$ (ASD)

for austenitic stainless steels

AWS S-N Curve

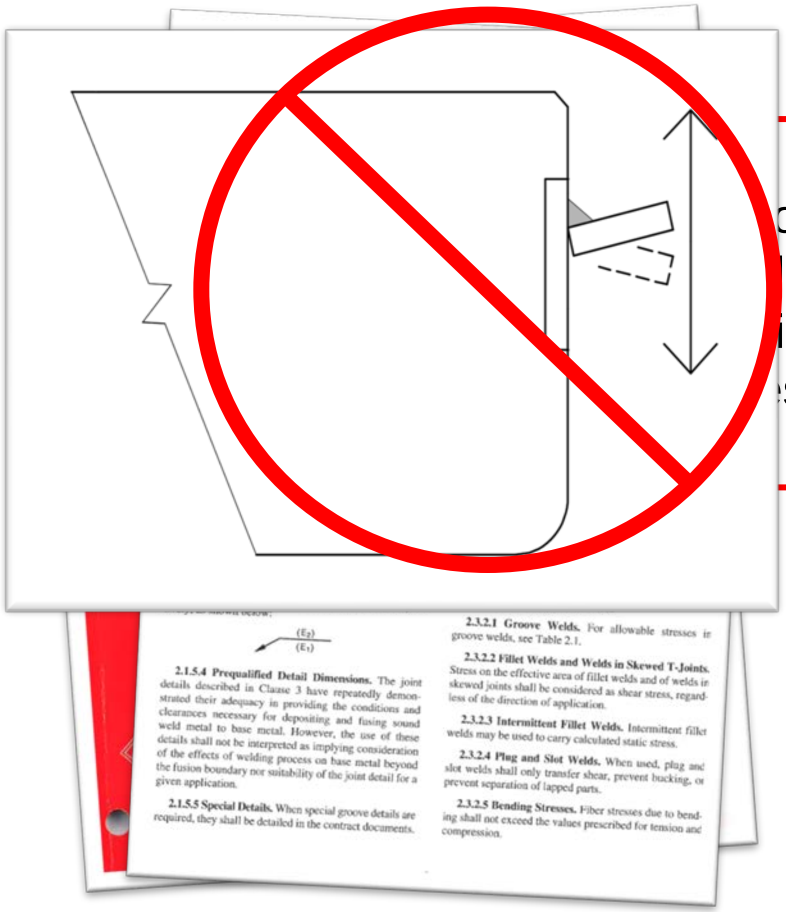


AWS D1.1 Figure 2.11 Allowable Stress Range for Cyclically Applied Load (Fatigue) in Nontubular Connections

What do Industry Experts Say?

AWS D1.6, Structural Welding Code – Stainless Steel
American Welding Society (AWS)

Section 2, Part A 2.2.2 – Bending Stresses



2.1.5.4 Prequalified Detail Dimensions. The joint details described in Clause 3 have repeatedly demonstrated their adequacy in providing the conditions and clearances necessary for depositing and fusing sound weld metal to base metal. However, the use of these details shall not be interpreted as implying consideration of the effects of welding process on base metal beyond the fusion boundary nor suitability of the joint detail for a given application.

2.1.5.5 Special Details. When special groove details are required, they shall be detailed in the contract documents.

2.3.2.1 Groove Welds. For allowable stresses in groove welds, see Table 2.1.

2.3.2.2 Fillet Welds and Welds in Skewed T-Joints. Stress on the effective area of fillet welds and of welds in skewed joints shall be considered as shear stress, regardless of the direction of application.

2.3.2.3 Intermittent Fillet Welds. Intermittent fillet welds may be used to carry calculated static stress.

2.3.2.4 Plug and Slot Welds. When used, plug and slot welds shall only transfer shear, prevent buckling, or prevent separation of lapped parts.

2.3.2.5 Bending Stresses. Fiber stresses due to bending shall not exceed the values prescribed for tension and compression.

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How Did We Get Here?

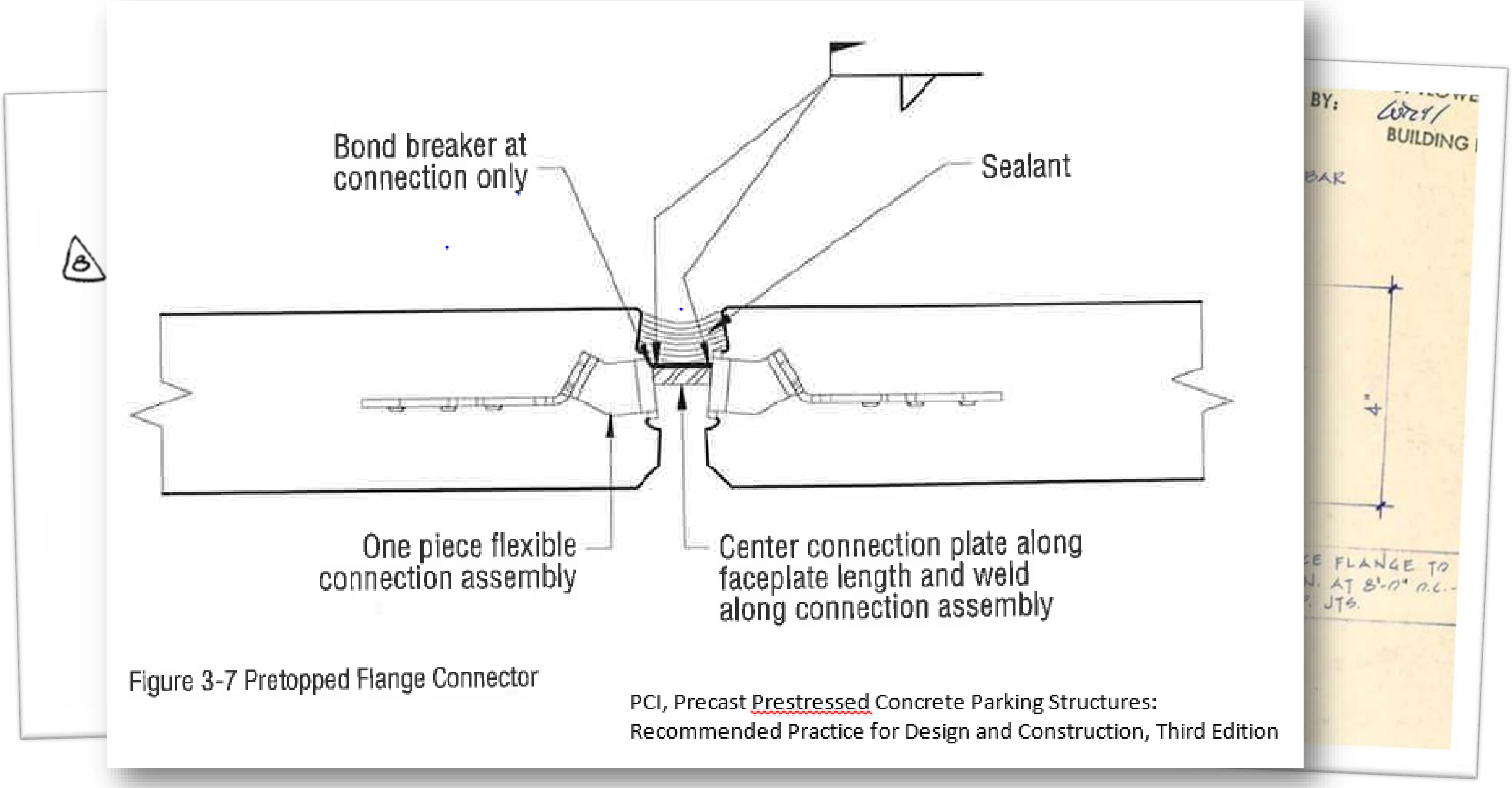
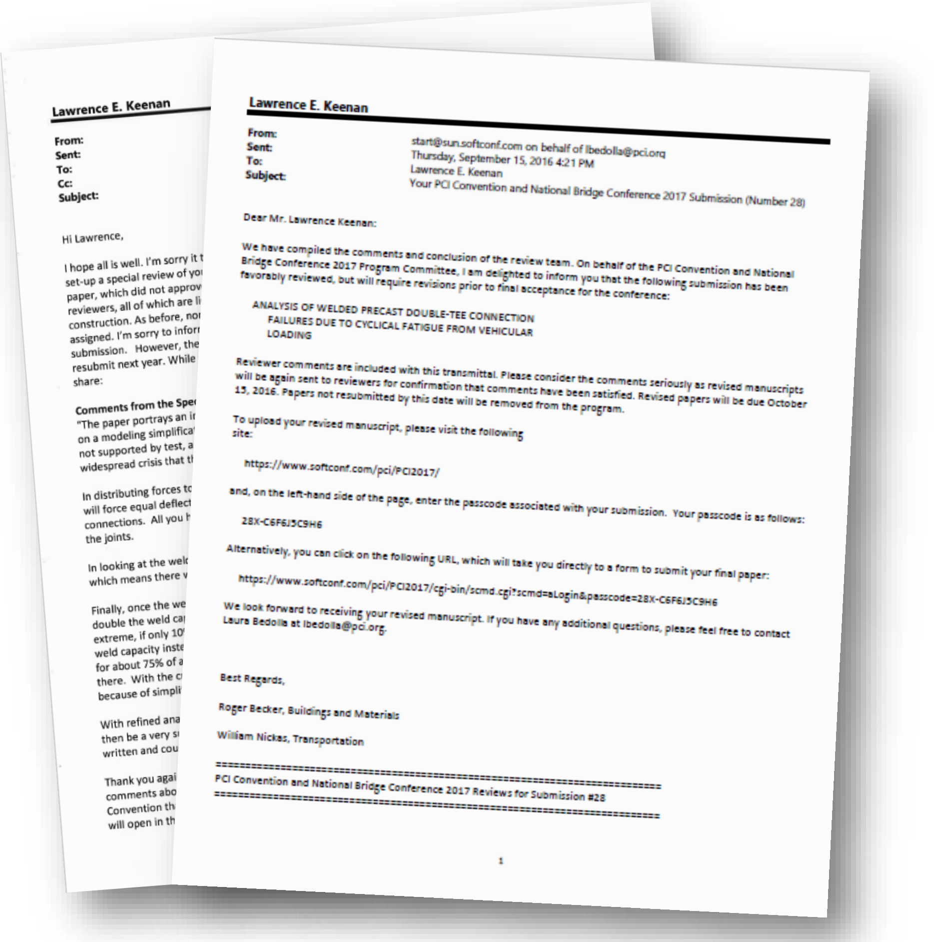


Figure 3-7 Pretopped Flange Connector

PCI, Precast Prestressed Concrete Parking Structures: Recommended Practice for Design and Construction, Third Edition

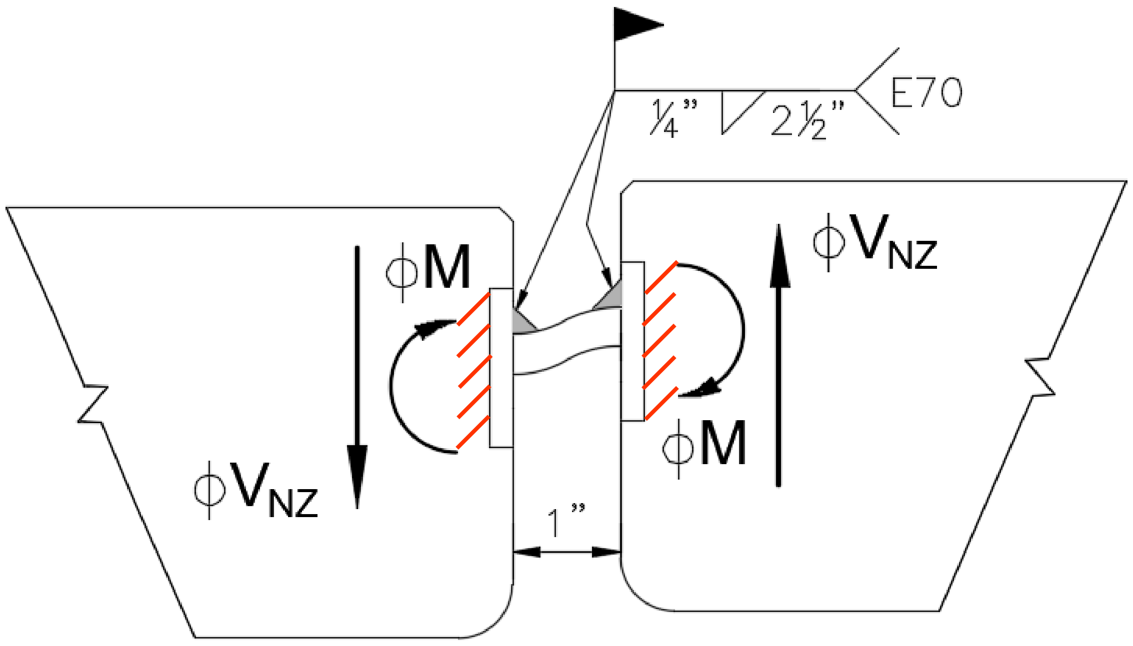
Arguments Against this Analysis

…From Review Industry Comments



Arguments Against this Analysis

…My analysis does not account for flexibility of the modern connection



Credit: Precast/Prestressed Concrete Institute, Clay Naito et al, *Double Tee Flange Connections – Analytical Evaluation*
Paper presented at the 2017 PCI Convention and National Bridge Conference, Cleveland, Ohio.

Where Are We Now?
Precast Industry Rebuttal Papers

– **Double Tee Flange Connections – Experimental Evaluation**

Credit: Precast/Prestressed Concrete Institute, Greg Lucier, Clay Naito, Andrew Osborn, Mohamed Nafadi, and Sami Rizkalla

https://www.researchgate.net/publication/316601317_Double_Tee_Flange_Connections_-_Experimental_Evaluation

– **Double Tee Flange Connections – Analytical Evaluation**

Credit: Precast/Prestressed Concrete Institute, Clay Naito, Andrew Osborn, Aisa Rahmani, and Robin Hendricks

https://www.researchgate.net/publication/316601326_Double_Tee_Flange_Connections_-_Analytical_Evaluation

– **Flange-to flange double-tee connections subjected to vehicular loading, part 1: Numerical assessment approach**

Credit: Precast/Prestressed Concrete Institute, Robin Hendricks, Clay Naito, and Andrew Osborn

https://doi.org/10.15554/pcij63.4-02

– **Flange-to flange double-tee connections subjected to vehicular loading, part 2: Fatigue life assessment**

Credit: Precast/Prestressed Concrete Institute, Clay Naito, Robin Hendricks, and Andrew Osborn

https://doi.org/10.15554/pcij64.2-05

Precast Industry Rebuttal Papers

–Experimental Evaluation

Figure 11: Test Setup with Loading and Instrumentation Frames 7.5 ft from End of Double Tees

Credit: Precast/Prestressed Concrete Institute, Greg Lucier et all, *Double Tee Flange Connections – Experimental Evaluation*
Paper presented at the 2017 PCI Convention and National Bridge Conference, Cleveland, Ohio.

Precast Industry Rebuttal Papers

–Analytical Evaluation:

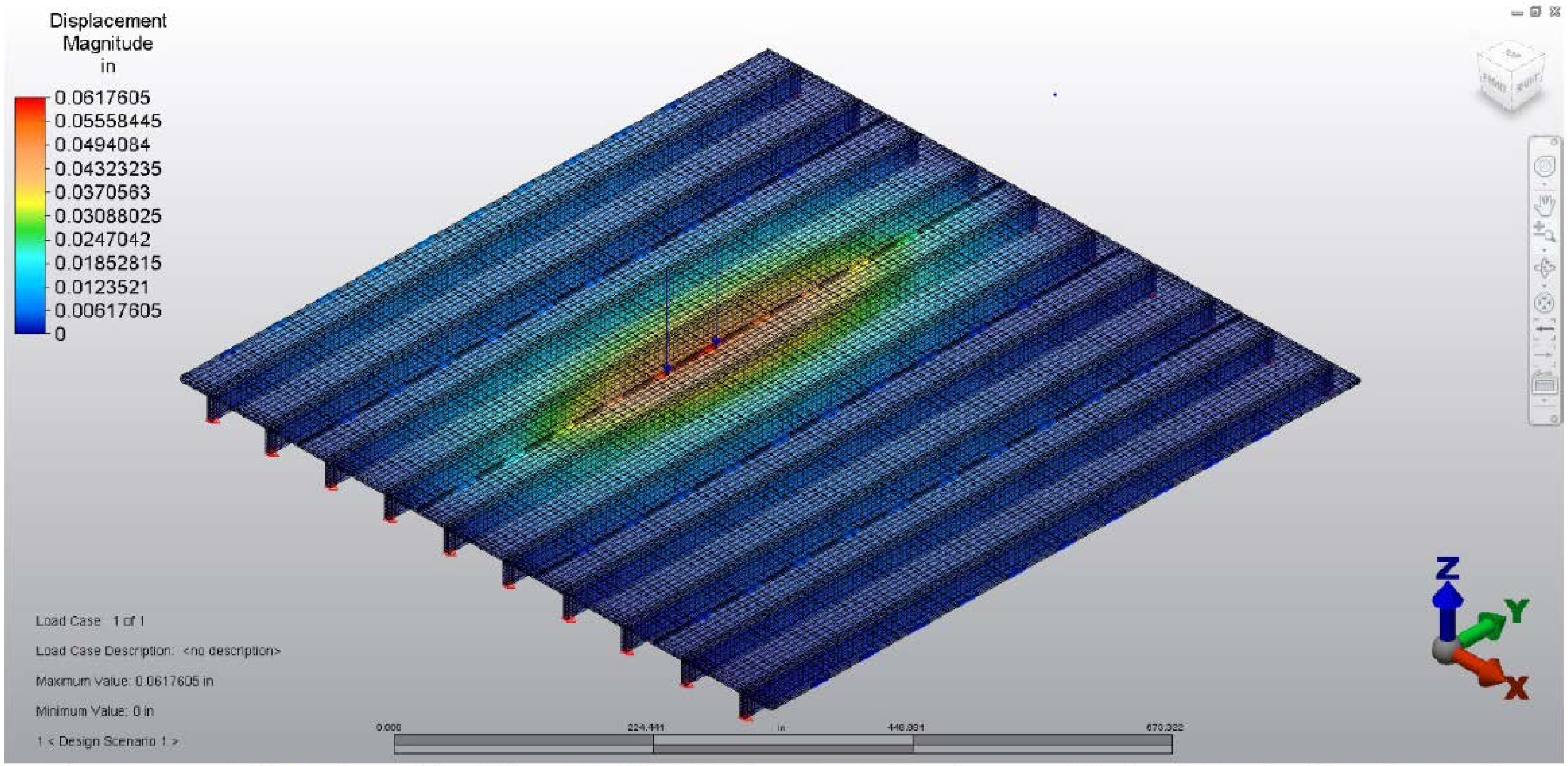


Figure 15: Deflected model of five Double Tee beams supporting an axle load (2 wheels) of 2125 lbs

Credit: Precast/Prestressed Concrete Institute, Clay Naito et al, *Double Tee Flange Connections – Analytical Evaluation*
Paper presented at the 2017 PCI Convention and National Bridge Conference, Cleveland, Ohio.

Where Are We Now?
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  https://www.researchgate.net/publication/316601317_Double_Tee_Flange_Connections_-_Experimental_Evaluation

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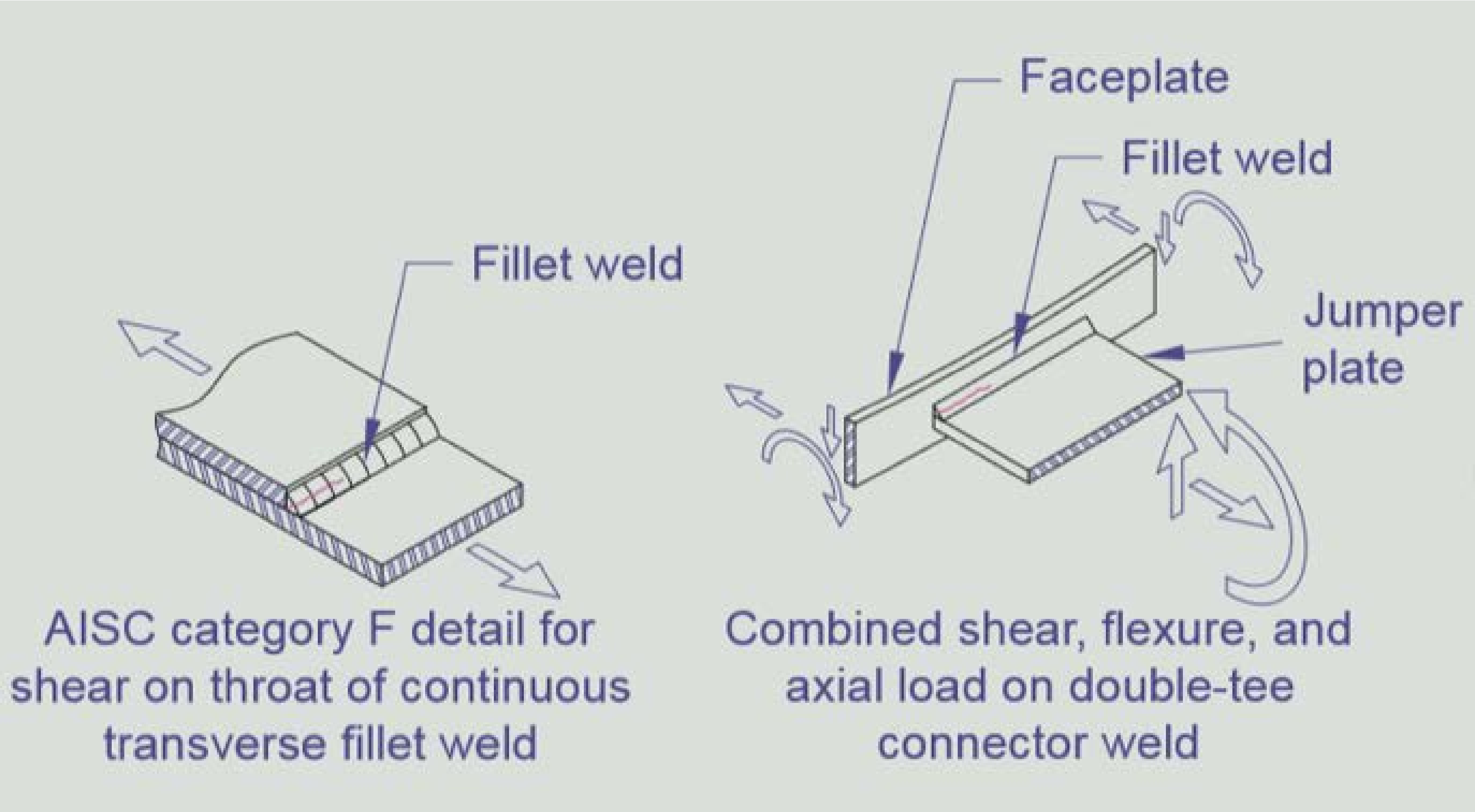
  https://doi.org/10.15554/pcij64.2-05

Precast Industry Rebuttal Papers

–Fatigue Life Assessment: Fatigue Assessment Category

Paper Comments:



Precast Industry Rebuttal Papers

–Fatigue Life Assessment: Experimental Study

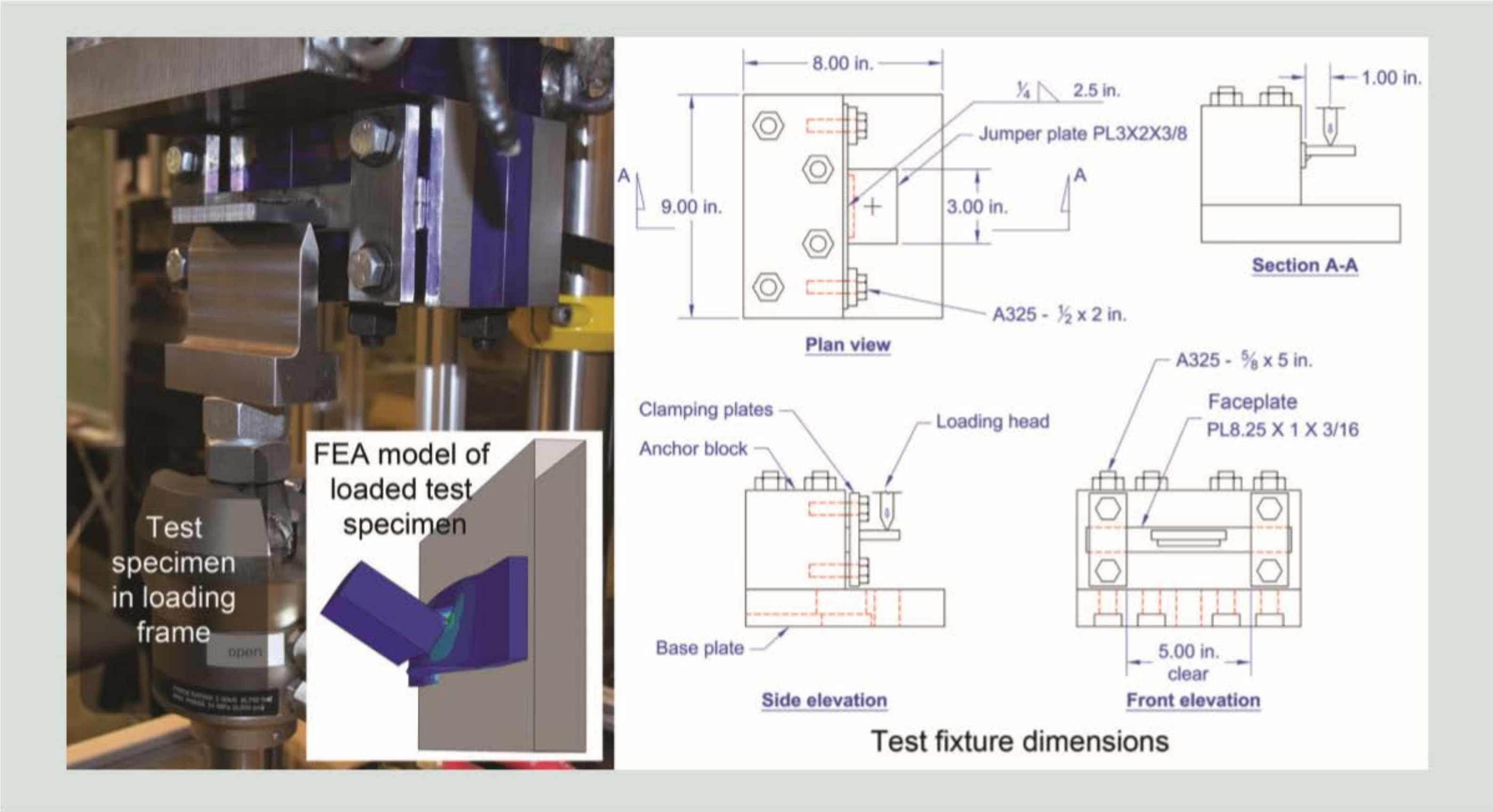
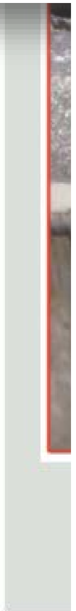


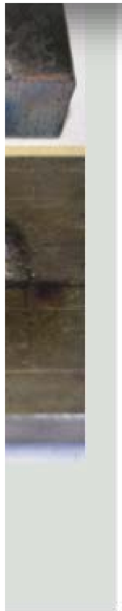
Figure 5. Fatigue loading setup. Note: FEA = finite element analysis. 1 in. = 25.4 mm.

Credit: Precast/Prestressed Concrete Institute, Clay Naito, Robin Hendricks, and Andrew Osborn, *Flange-to flange double-tee connections subjected to vehicular loading, part 2: Fatigue life assessment* (https://doi.org/10.15554/pcij64.2-05)

Precast Industry Rebuttal Papers

"…the fatigue failure surfaces started at the ends of the weld and propagated toward the middle. The failure surface was also greater at the ends and smaller at the middle of the weld due to the elevated stress generated from the flexibility of the faceplate (Fig. 6)."





Fig

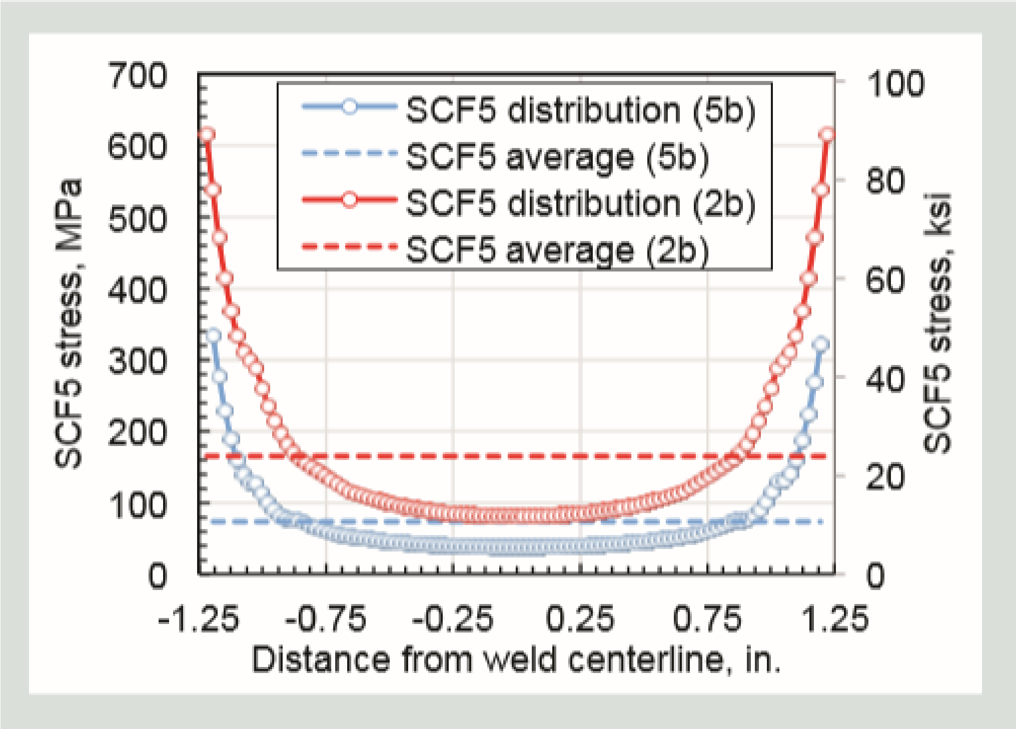


Figure 6. SCF5 stress in welds. Note: SCF5 = stress concentration factor. 1 in. = 25.4 mm.

Credit: Preca … ble-tee connections
subjected to

Precast Industry Rebuttal Papers

S-N Curve – PCI Funded Research Effort

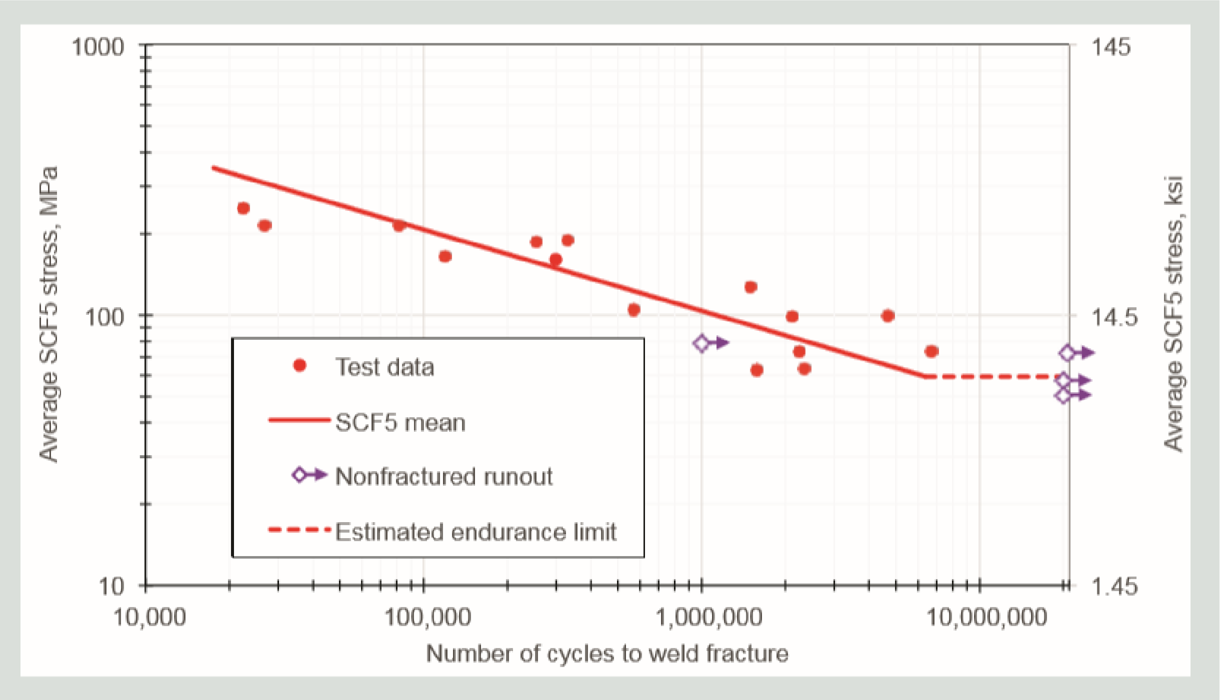
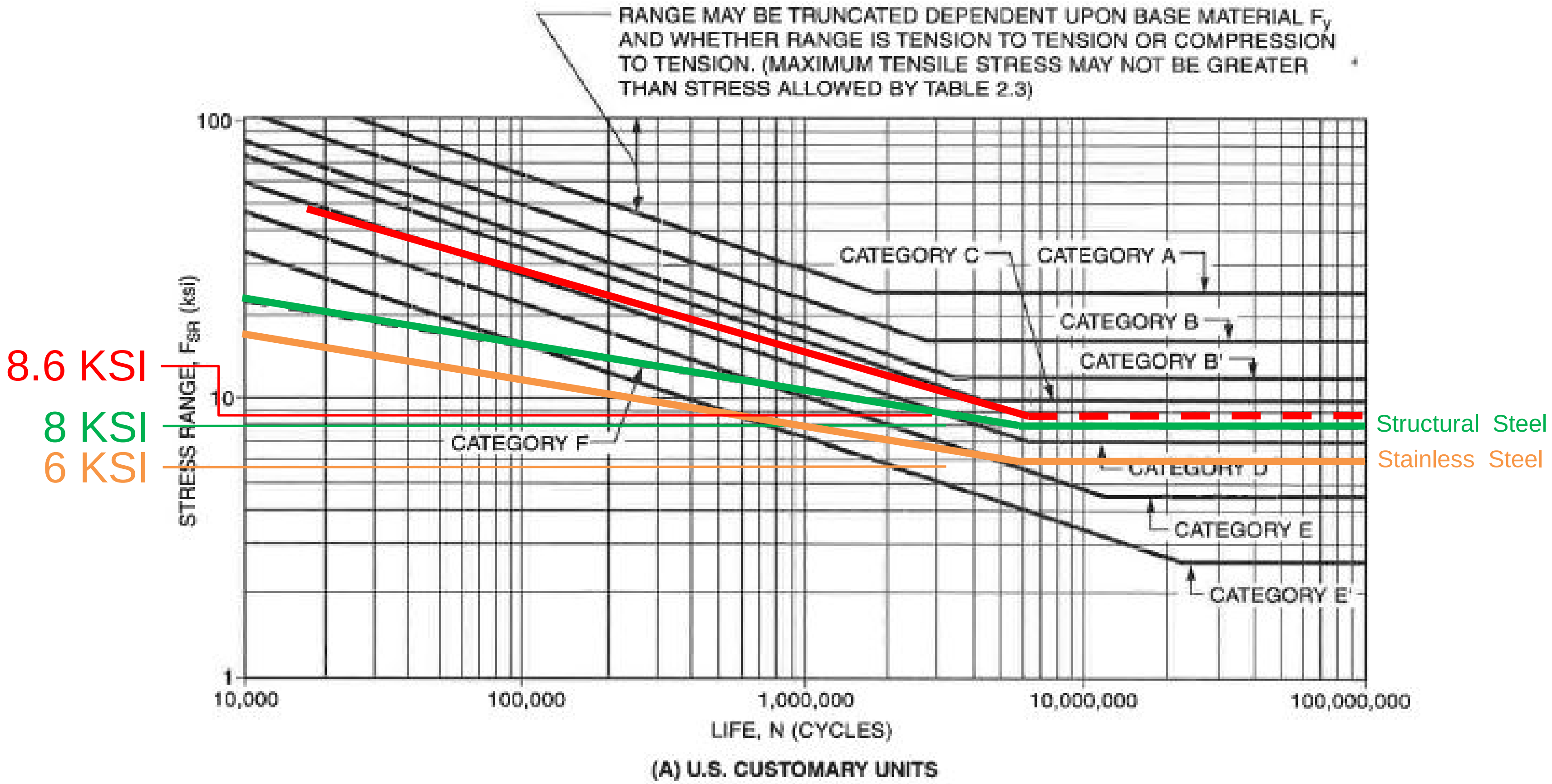


Figure 8. Fillet weld S-N curve. Note: SCF5 = stress concentration factor.

Figure 8, Flange-to flange double-tee connections subjected to vehicular loading, part 2: Fatigue life assessment

Credit: Precast/Prestressed Concrete Institute, Clay Naito, Robin Hendricks, and Andrew Osborn, *Flange-to flange double-tee connections subjected to vehicular loading, part 2: Fatigue life assessment*

AWS S-N Curve



AWS D1.1 Figure 2.11 Allowable Stress Range for Cyclically Applied Load (Fatigue) in Nontubular Connections

Precast Industry Rebuttal Papers

–Fatigue Life Assessment: Principal Conclusion

"A simulated garage shows a heavily used parking structures, with 500 cars per day, would theoretically reach **52 to 62 years** before fatigue-induced fracture would be expected to occur."

52 to 62 years

Credit: Precast/Prestressed Concrete Institute, Clay Naito, Robin Hendricks, and Andrew Osborn, *Flange-to flange double-tee connections subjected to vehicular loading, part 2: Fatigue life assessment* (https://doi.org/10.15554/pcij64.2-05)

"It is not our abilities that show what we truly are.

How is this possible?

It is our choices"

- Albus Dumbledore

Vehicle Weight

Vehicle Weight

–**Fatigue Life Assessment: Vehicle Weight**

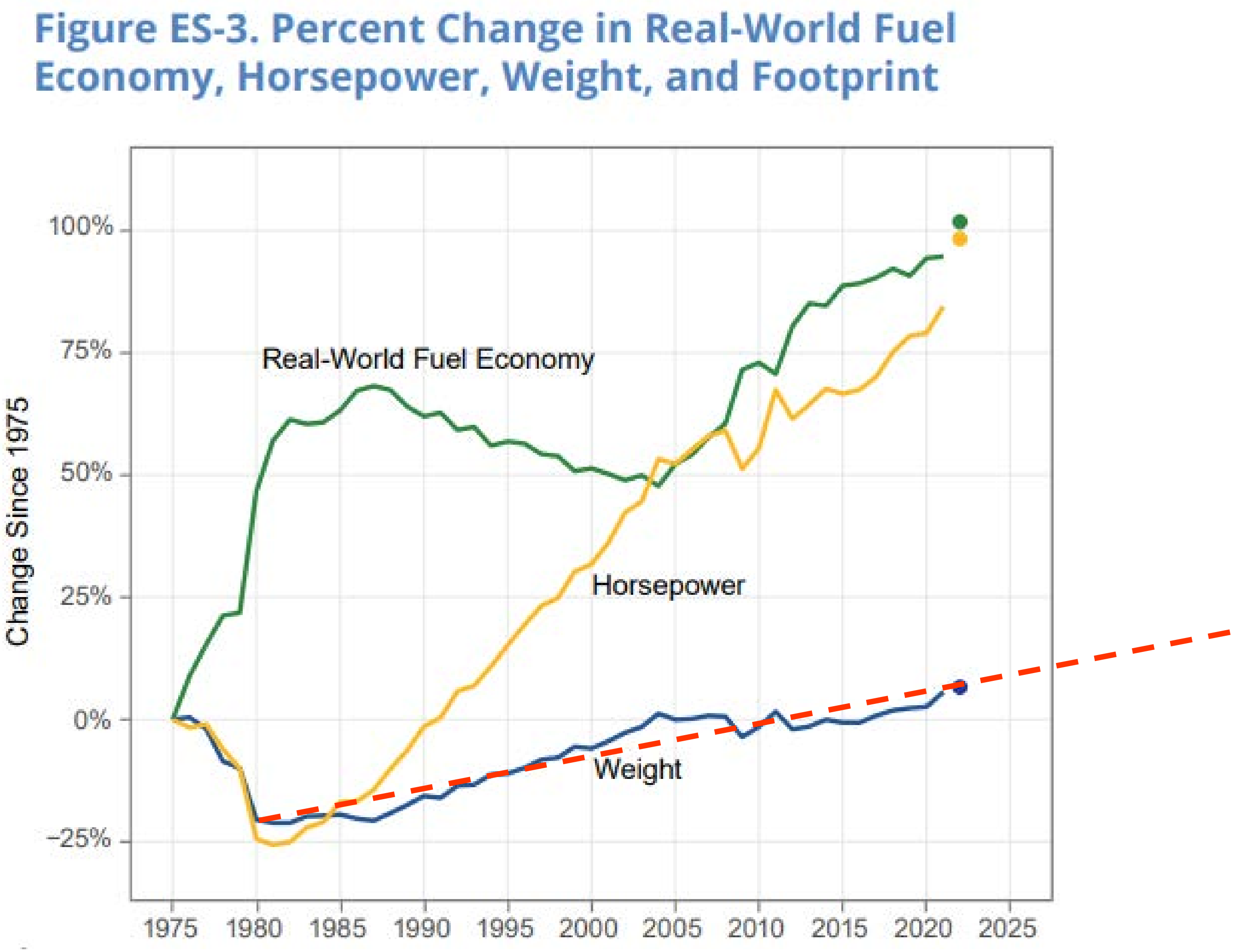
This study used average vehicle weight of **3,547 lbs** from a 2001 study of nine garages (increased 4% per 2015 data).

- Per 2015 EPA study, average vehicle weight (trucks and cars) was **3,735 lbs (190 lbs higher)**

- Per 2020 EPA study, average vehicle weight was highest on record at **4,156 lbs (600 lbs higher!)**

Vehicle Weight

Per 2022 EPA study weight continues to increase



Where were Vehicles Placed?

Where the Weight was Placed

–**Fatigue Life Assessment: Car Loading Distribution**

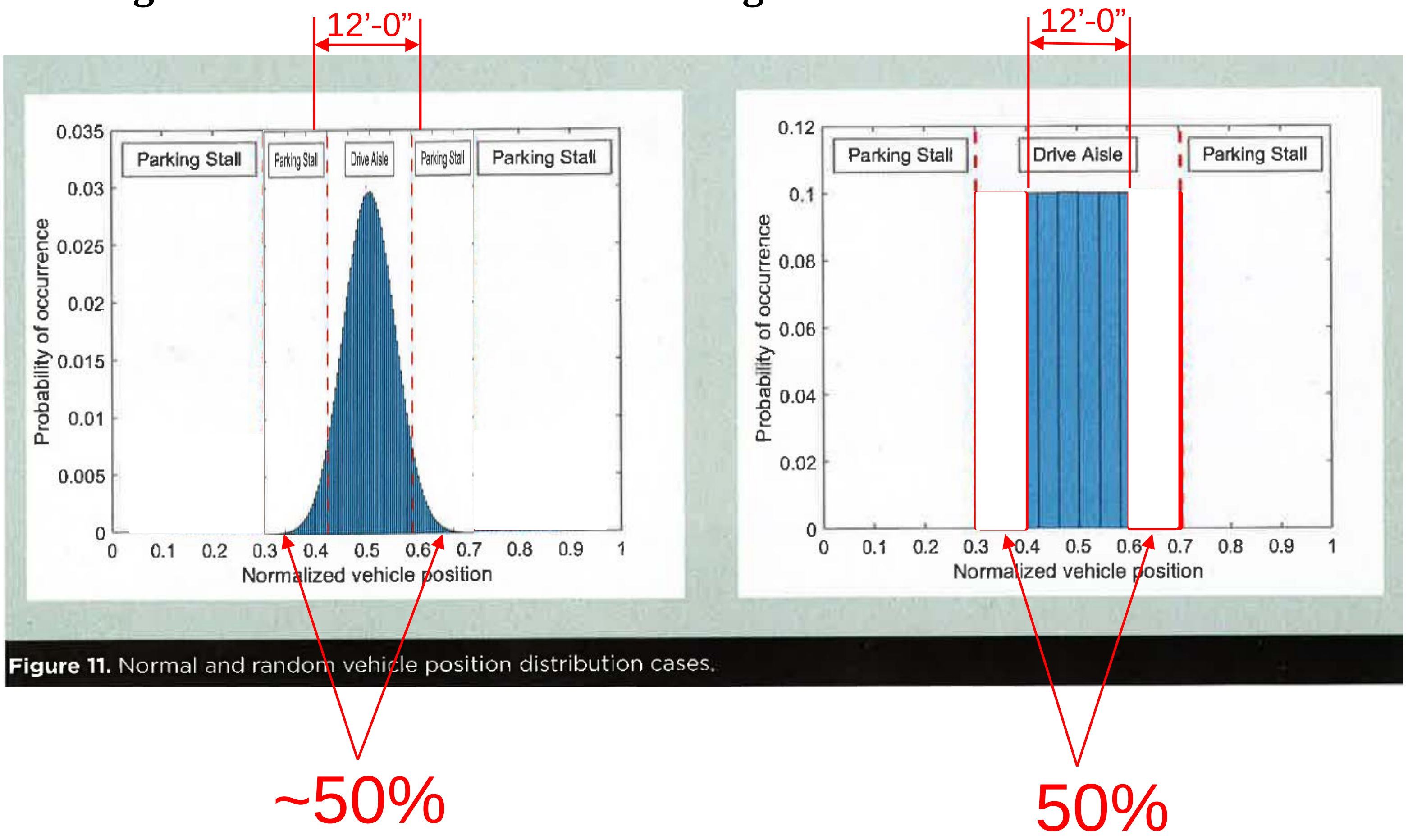


Figure 11. Normal and random vehicle position distribution cases.

Credit: Precast/Prestressed Concrete Institute, Clay Naito, Robin Hendricks, and Andrew Osborn, *Flange-to flange double-tee connections subjected to vehicular loading, part 2: Fatigue life assessment* (https://doi.org/10.15554/pcij64.2-05)

Where would you drive?

Where the Weight was Placed

–Fatigue Life Assessment: Influence Lines

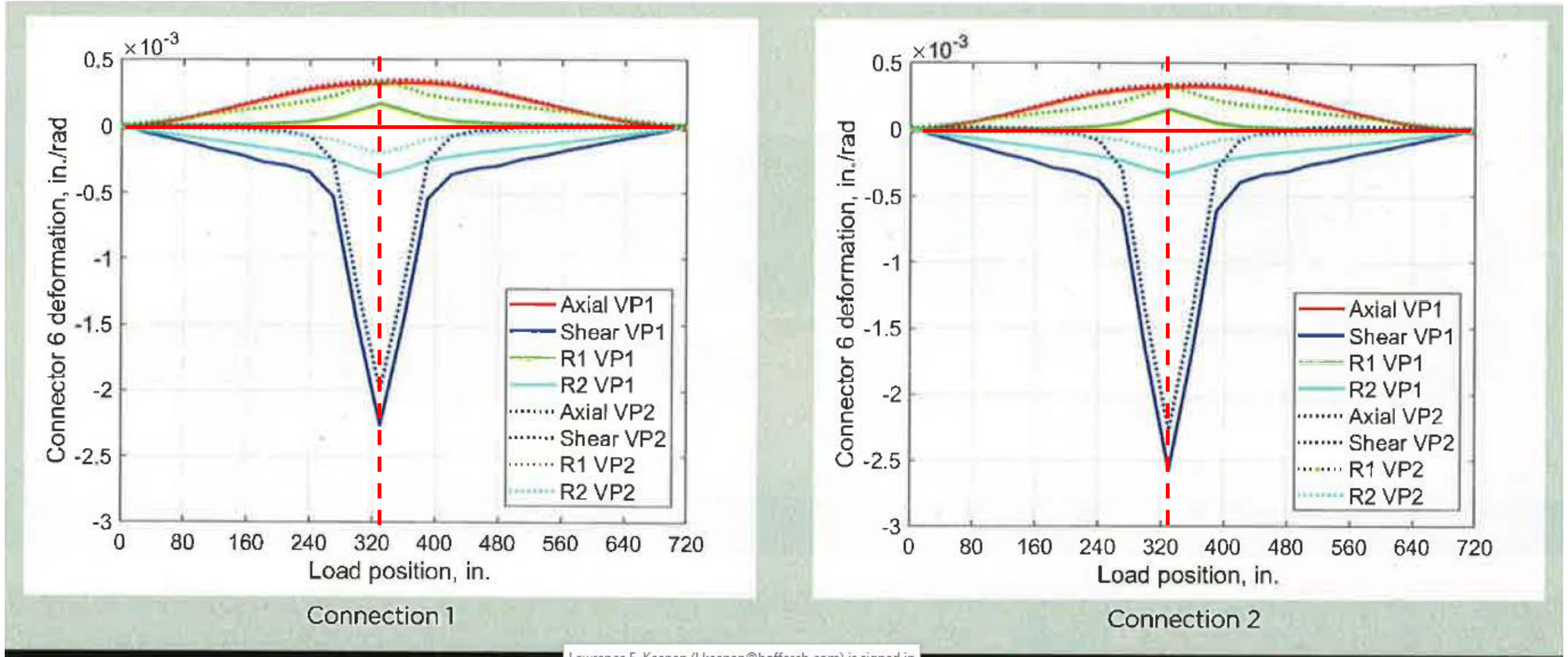
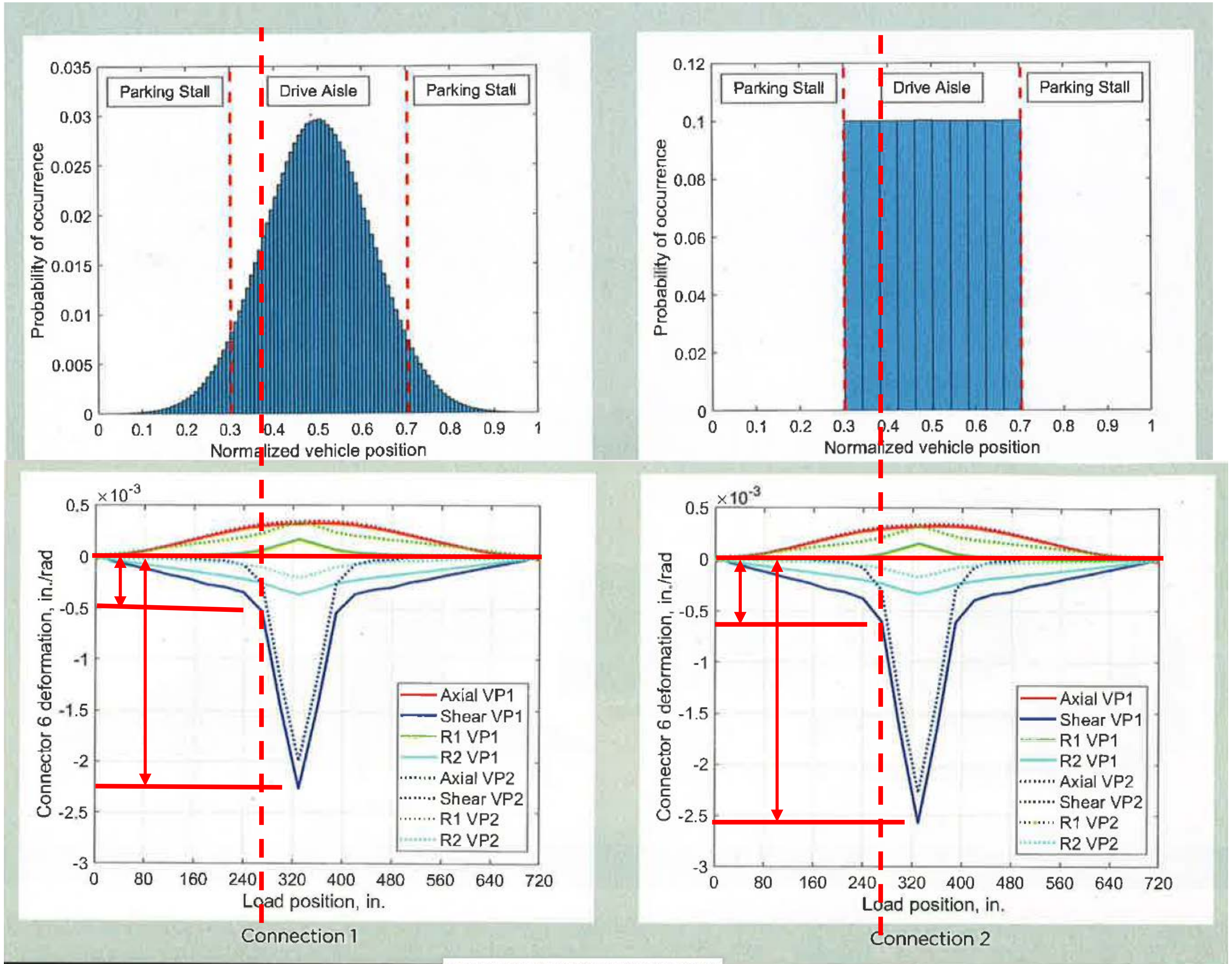


Figure 15. Connection 6 influence lines uniform spacing configuration. Note: 1 in. = 25.4 mm.

Credit: Precast/Prestressed Concrete Institute, Clay Naito, Robin Hendricks, and Andrew Osborn, *Flange-to flange double-tee connections subjected to vehicular loading, part 2: Fatigue life assessment* (https://doi.org/10.15554/pcij64.2-05)



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Why it matters

S-N Curve – PCI Funded Research Effort

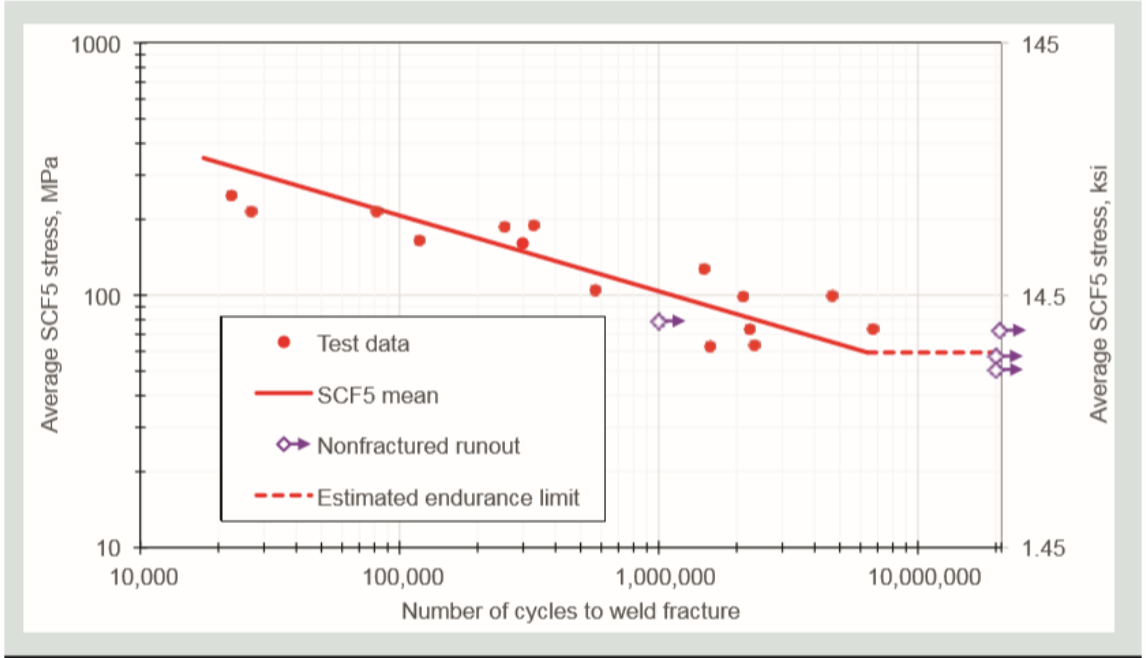


Figure 8. Fillet weld S-N curve. Note: SCF5 = stress concentration factor.

Figure 8, Flange-to flange double-tee connections subjected to vehicular loading, part 2: Fatigue life assessment

Credit: Precast/Prestressed Concrete Institute, Clay Naito, Robin Hendricks, and Andrew Osborn, *Flange-to flange double-tee connections subjected to vehicular loading, part 2: Fatigue life assessment*

What Model was Used?

“Hard Frictionless Contact”

–All PCI Papers Assume Hard Contact

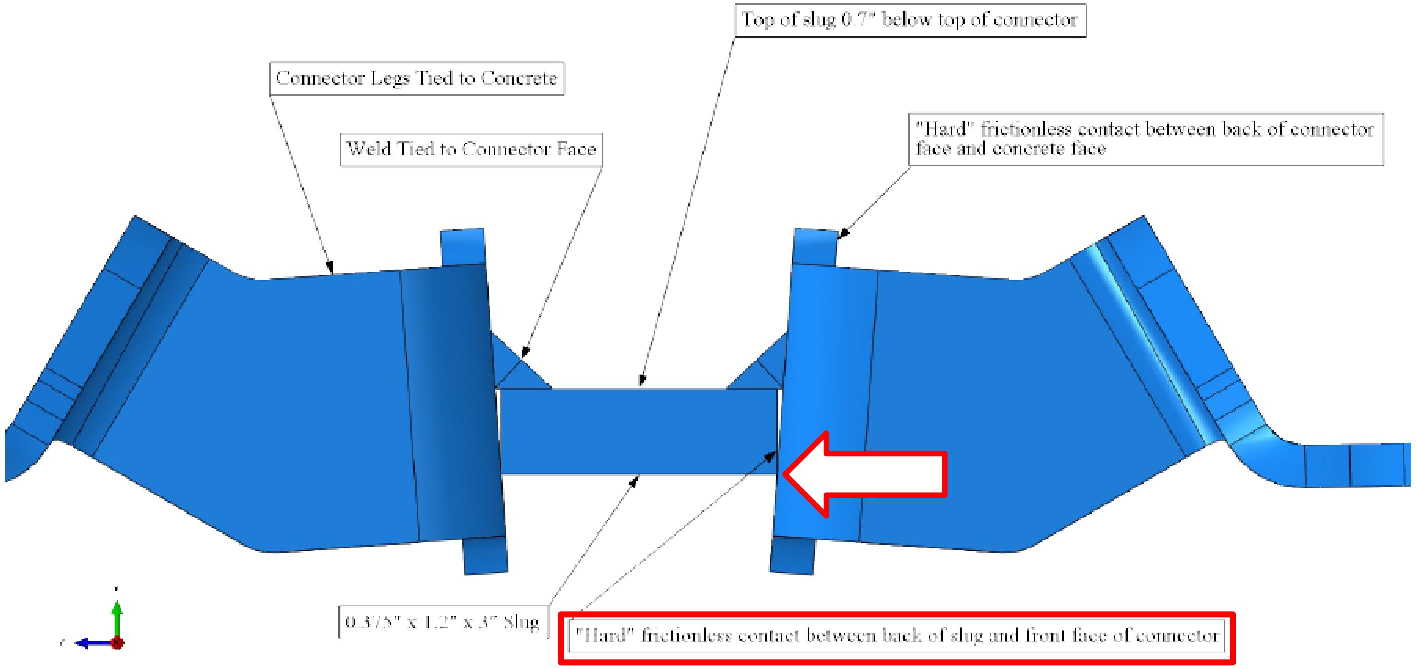
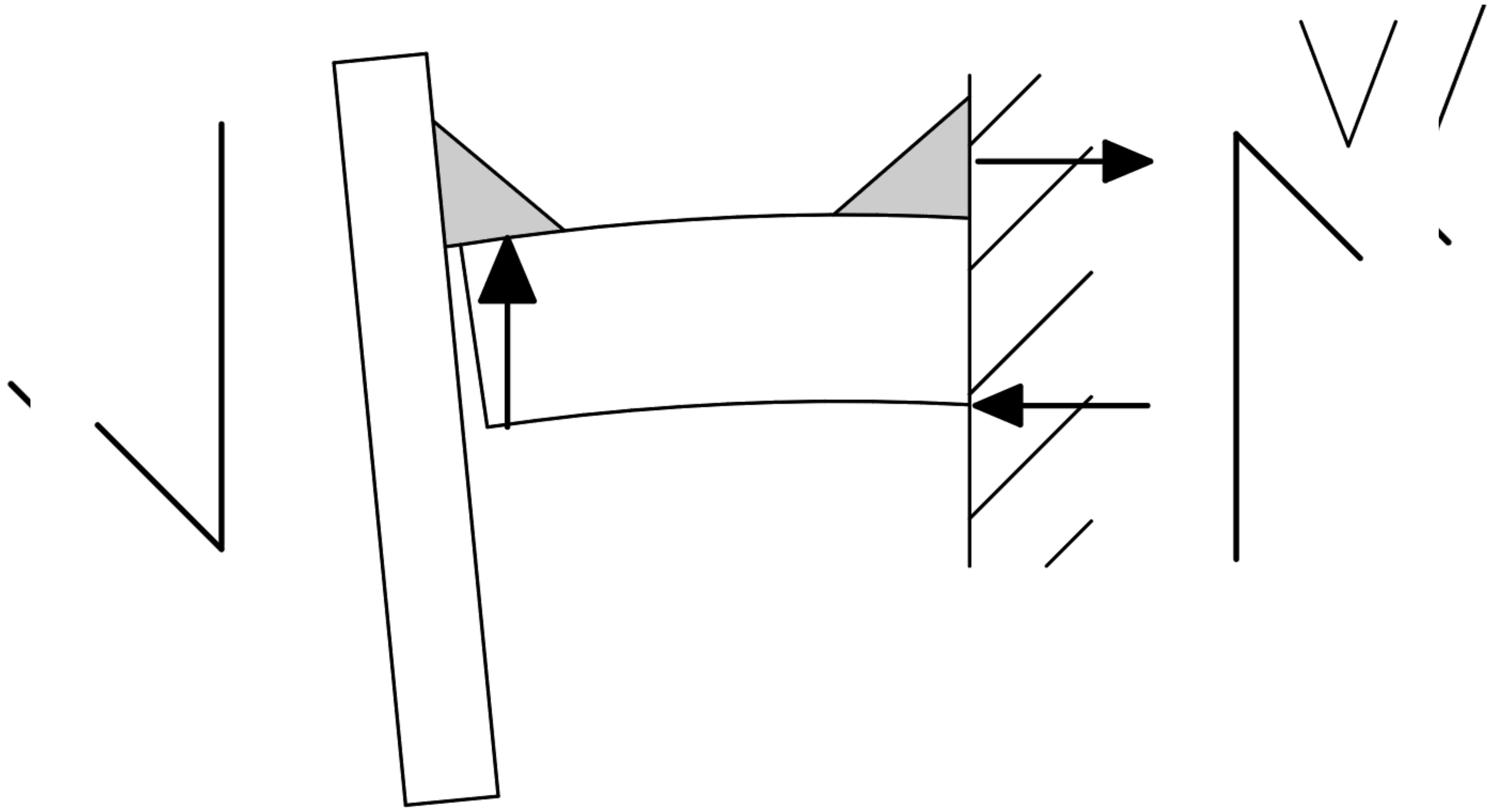


Figure 39: Details of Combined Assembly for Manufacturer 1

“Hard Frictionless contact between back of slug and front face of connector”

Credit: Precast/Prestressed Concrete Institute, Clay Naito et al, *Double Tee Flange Connections – Analytical Evaluation*
Paper presented at the 2017 PCI Convention and National Bridge Conference, Cleveland, Ohio.



Keenan Paper

– Models considered by Keenan:

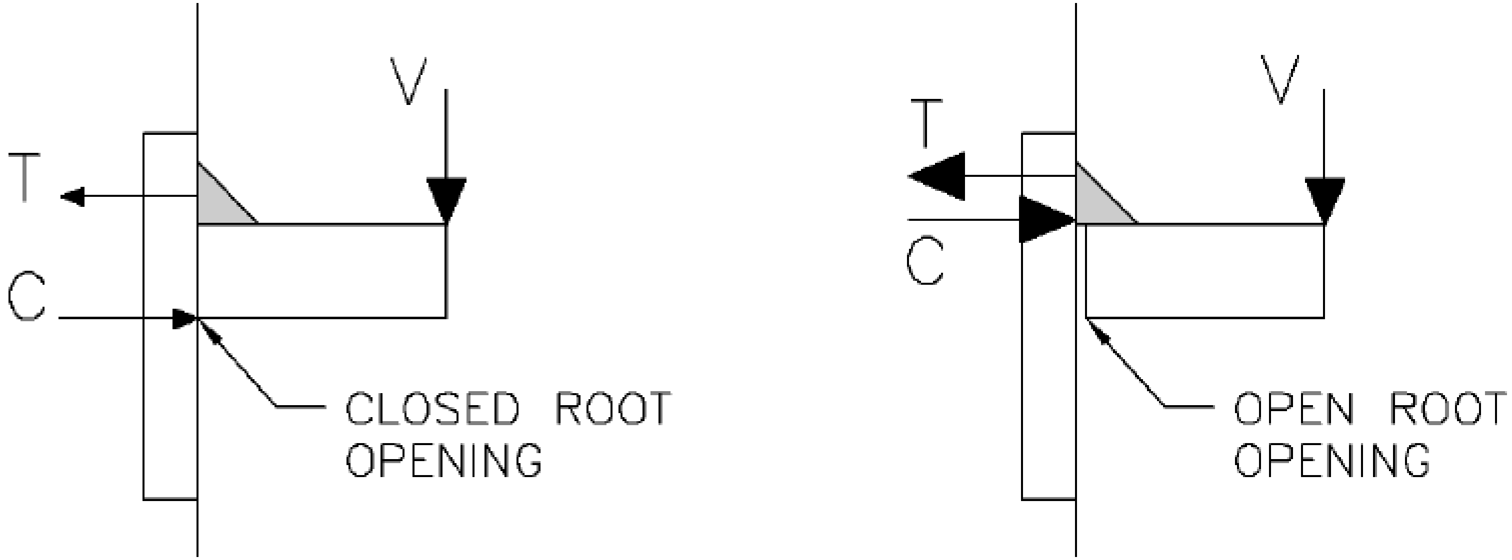


Figure 25 Comparison of forces for open versus closed root openings.

Credit: Precast/Prestressed Concrete Institute, Lawrence Keenan, *ANALYSIS AND DESIGN OF WELDED PRECAST DOUBLE-TEE CONNECTIONS FOR CYCLICAL FATIGUE FROM VEHICULAR LOADING*

Keenan Paper

– Calculation by Keenan:

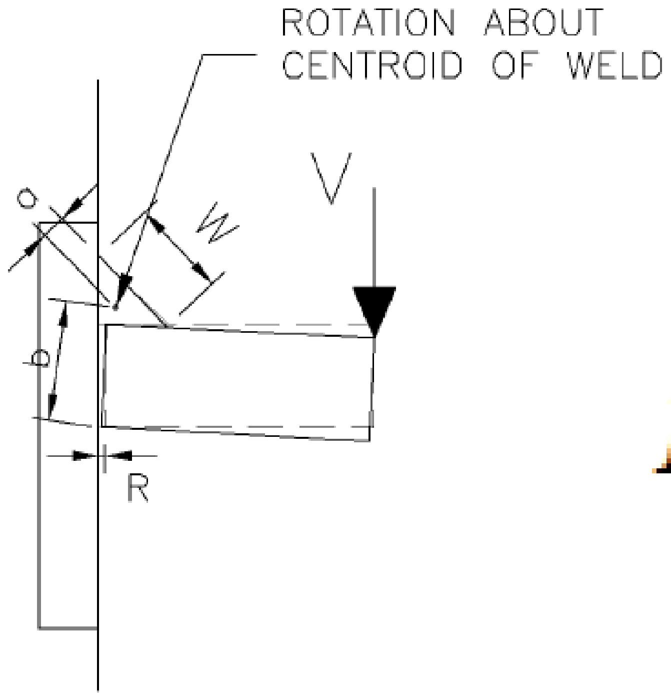


Figure 26 The weld forms a hinge under loading, with rotation about the centroid.

$$R \approx \frac{1}{3{,}000}\text{"}$$

Credit: Precast/Prestressed Concrete Institute, Lawrence Keenan, *ANALYSIS AND DESIGN OF WELDED PRECAST DOUBLE-TEE CONNECTIONS FOR CYCLICAL FATIGUE FROM VEHICULAR LOADING*

Per AISC

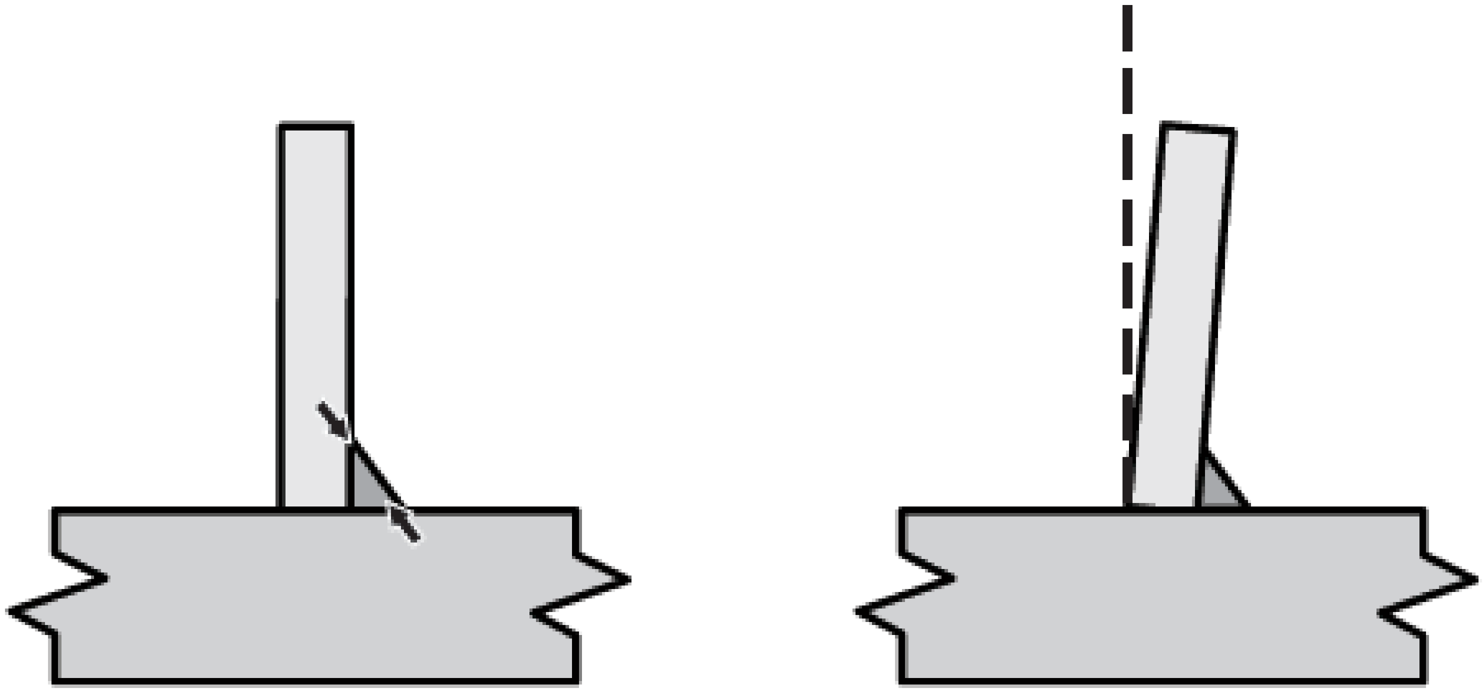
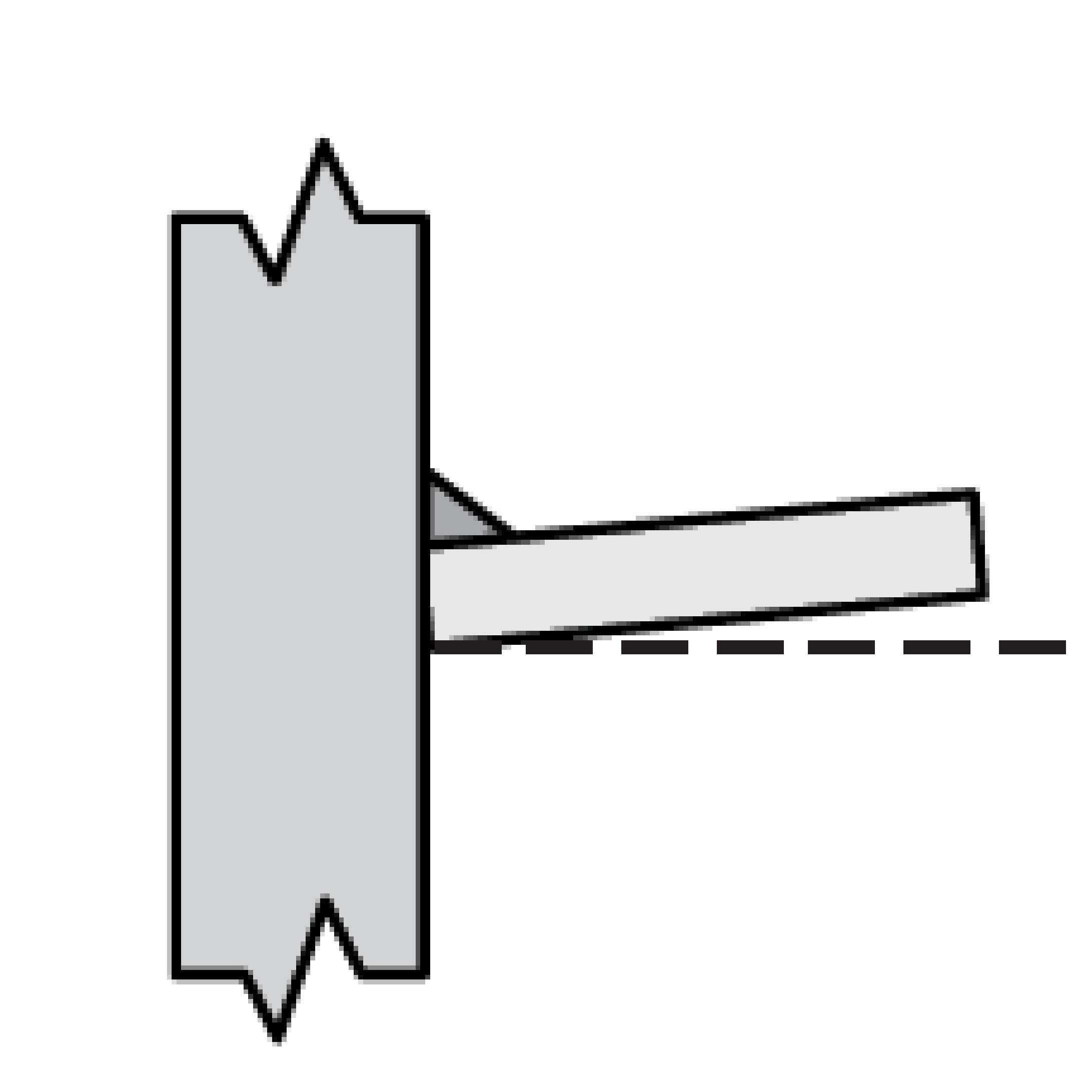


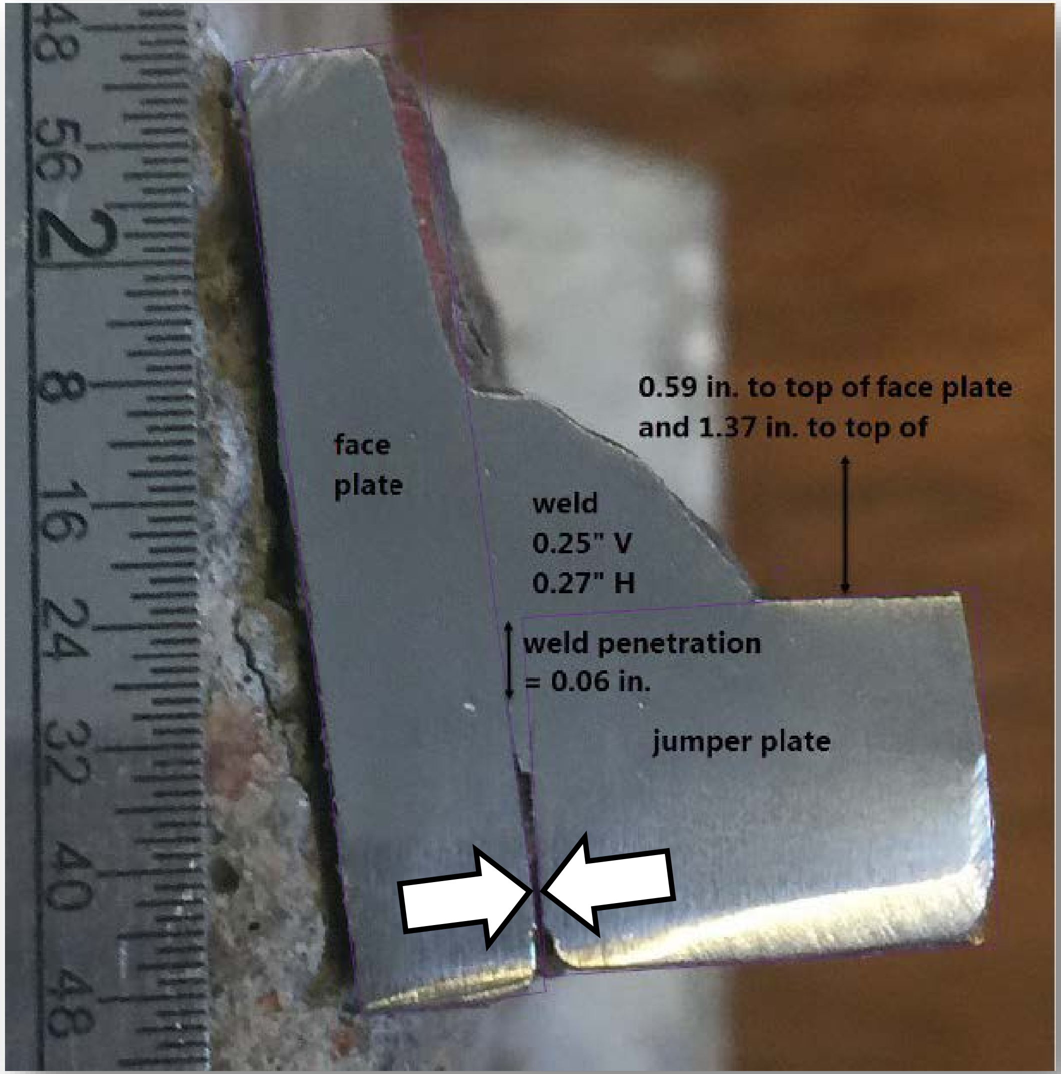
Figure 6–3. Angular distortion.

Credit: American Institute of Steel Construction, Duane Miller, *Steel Design Guide 21, Welded Connections – A Primer for Engineers*

Hard Frictionless Contact ?

Hard Frictionless Contact ?





Credit: American Institute of Steel Construction, Duane Miller, *Steel Design Guide 21, Welded Connections – A Primer for Engineers*

What Steel was Used?

Stainless Steel was not Used in These Tests

– **A36 structural steel was used to create PCI’s S-N Curve**

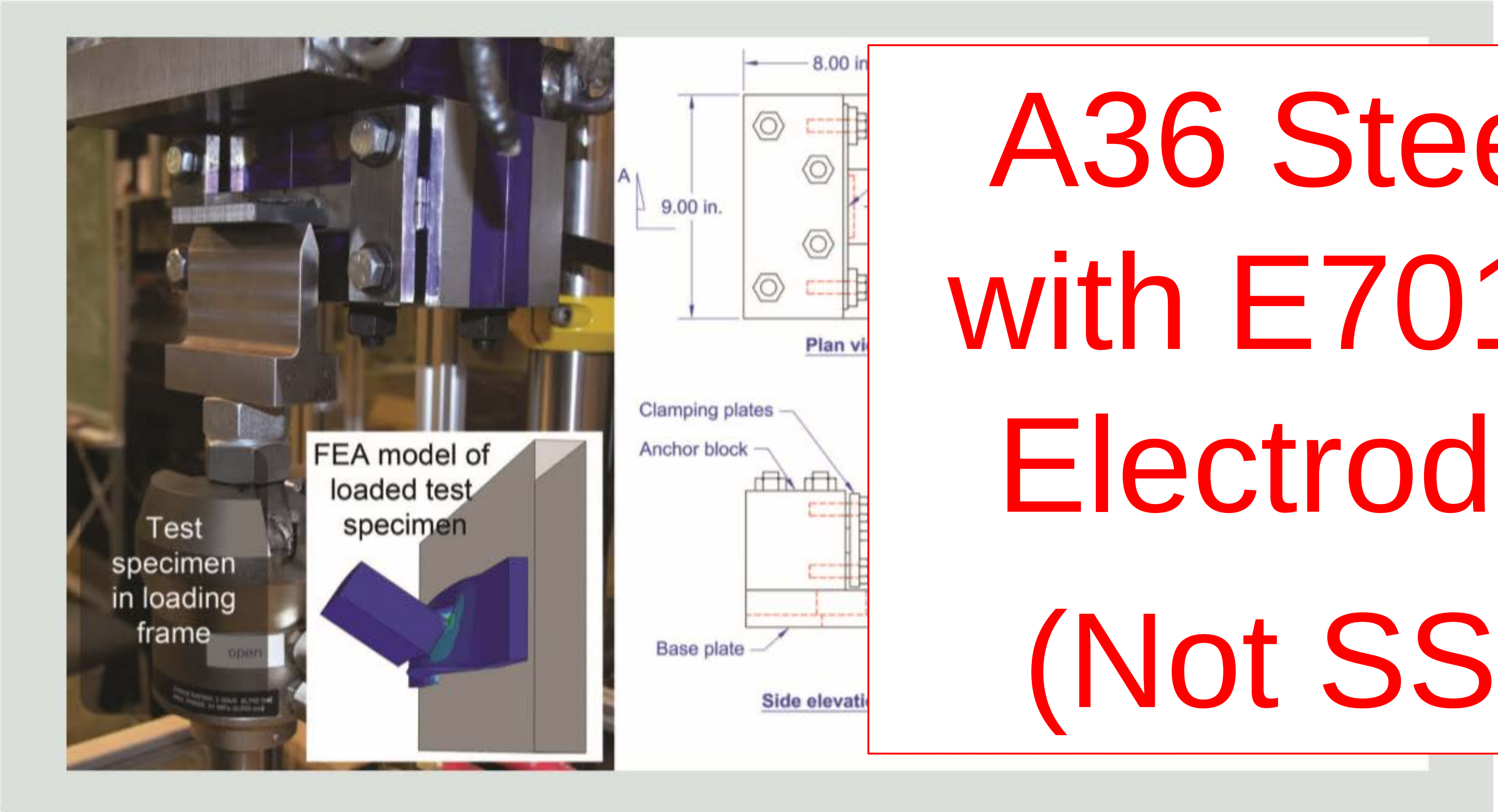


Figure 5. Fatigue loading setup. Note: FEA = finite element analysis. 1 in. = 25.4 mm.

A36 Steel with E7018 Electrode (Not SS)

Credit: Precast/Prestressed Concrete Institute, Clay Naito, Robin Hendricks, and Andrew Osborn, *Flange-to flange double-tee connections subjected to vehicular loading, part 2: Fatigue life assessment* (https://doi.org/10.15554/pcij64.2-05)

Average Stress or Maximum?

Maximum Stress or Average Stress?

–**Fatigue life assessment: Stress in Welds**

Cracks Initiate Here

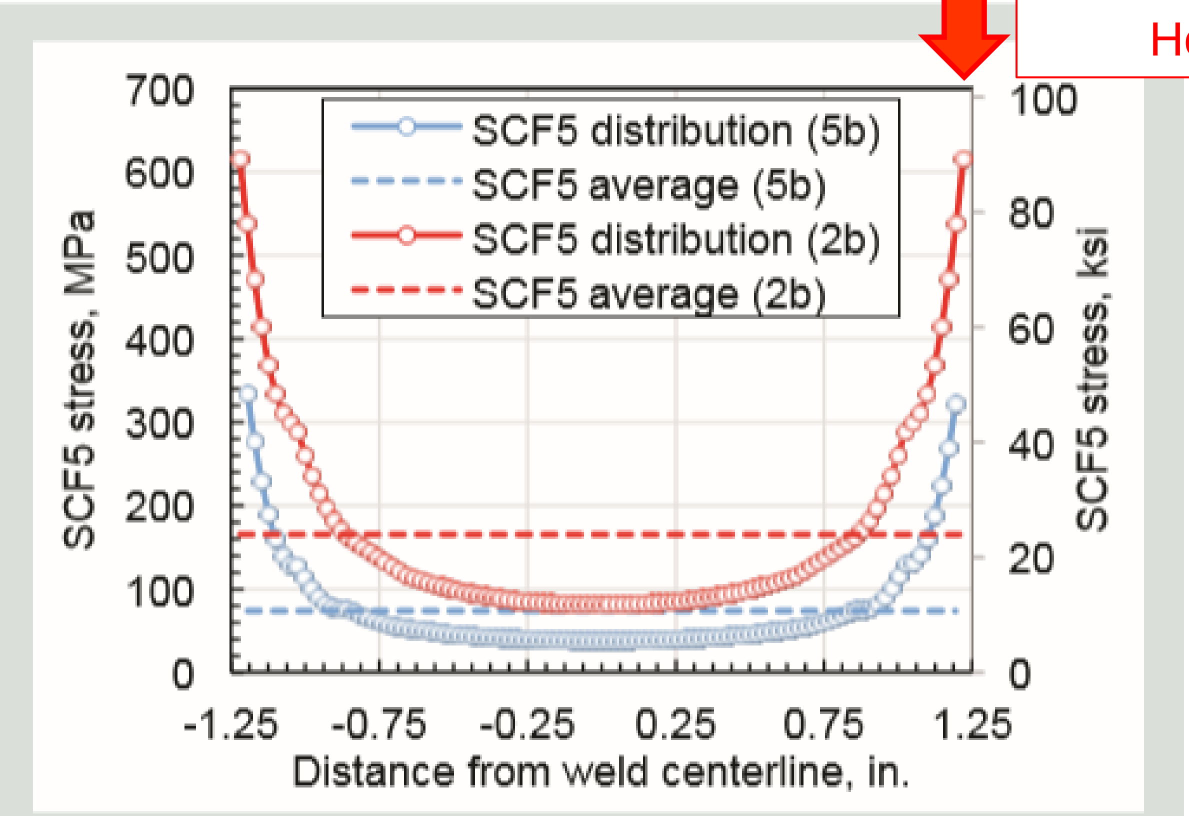


Figure 6. SCF5 stress in welds. Note: SCF5 = stress concentration factor. 1 in. = 25.4 mm.

Credit: Precast/Prestressed Concrete Institute, Clay Naito, Robin Hendricks, and Andrew Osborn, *Flange-to flange double-tee connections subjected to vehicular loading, part 2: Fatigue life assessment*

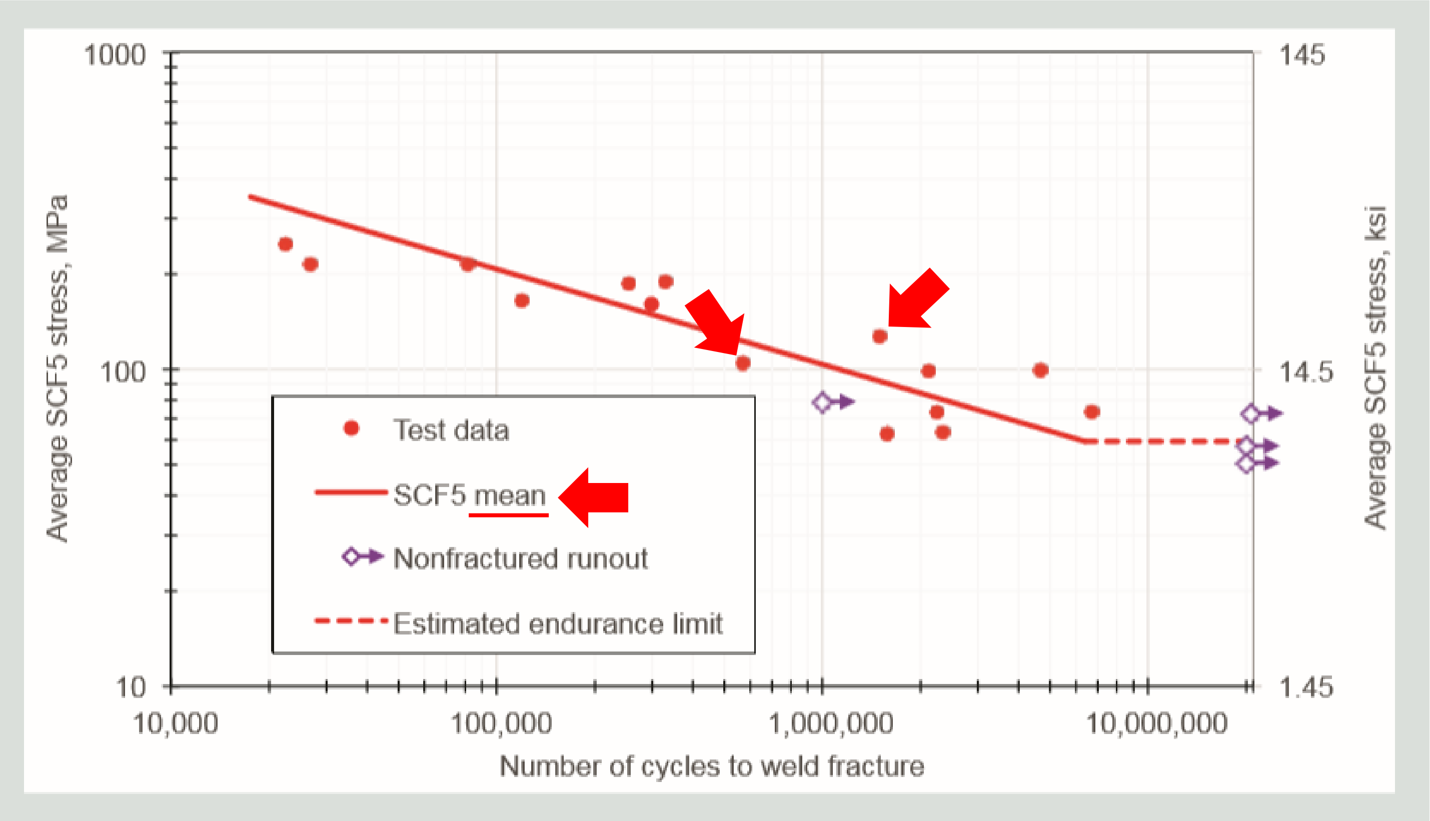
The Most Important Factor

The S-N Curve and “Endurance Limit” they used for analysis includes….

NO FACTOR OF SAFETY

Precast Industry Rebuttal Papers

S-N Curve – PCI Funded Research Effort



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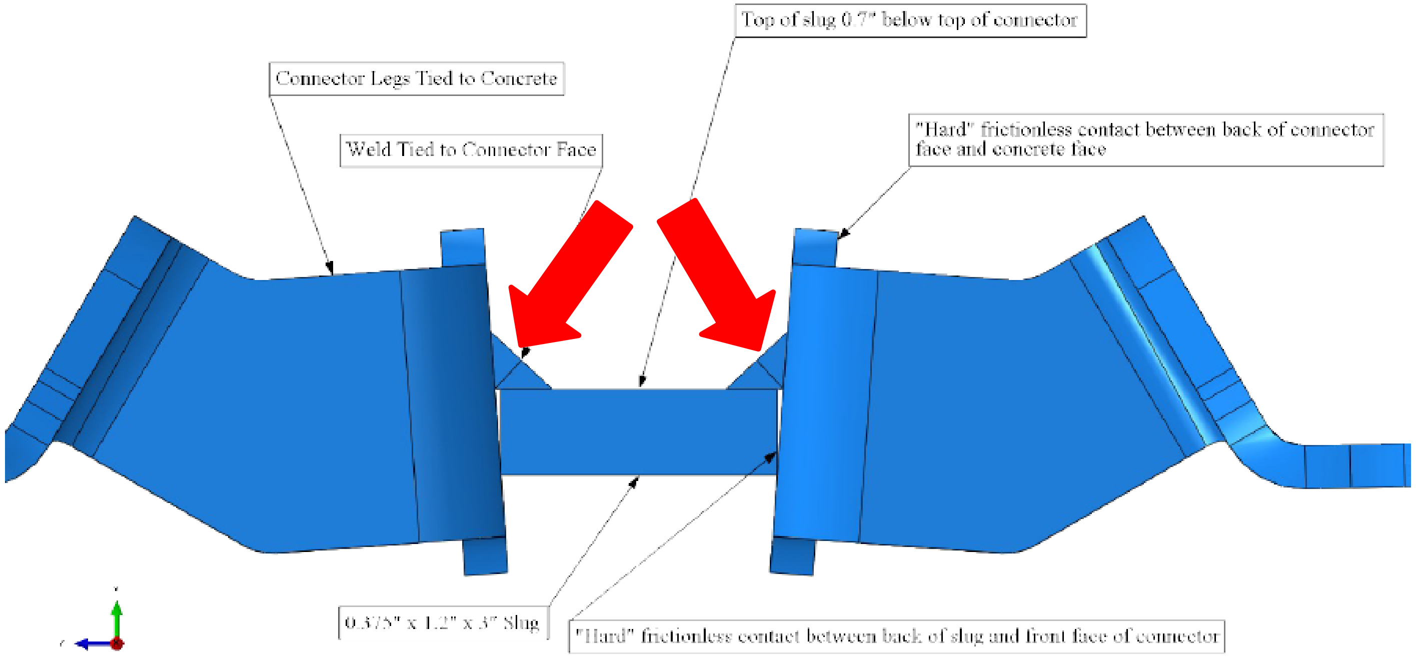
Per PCI method, half of welds are designed to fail…
…and there are two welds per connection



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Credit: Precast/Prestressed Concrete Institute, Clay Naito et al, *Double Tee Flange Connections – Analytical Evaluation*
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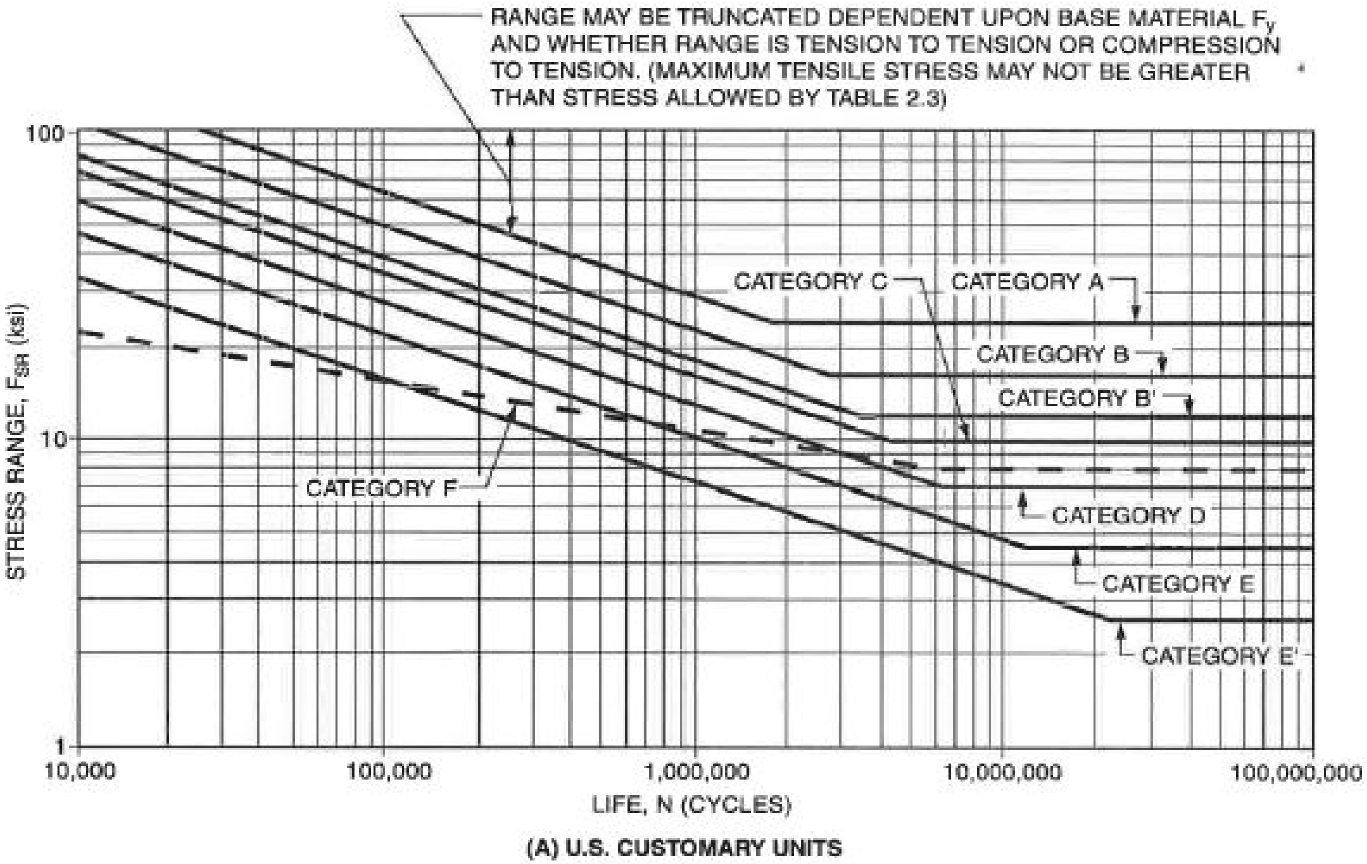
AWS S-N Curve



AWS D1.1 Figure 2.11 Allowable Stress Range for Cyclically Applied Load (Fatigue) in Nontubular Connections

Code and Industry Requirements

–Per the American Welding Society

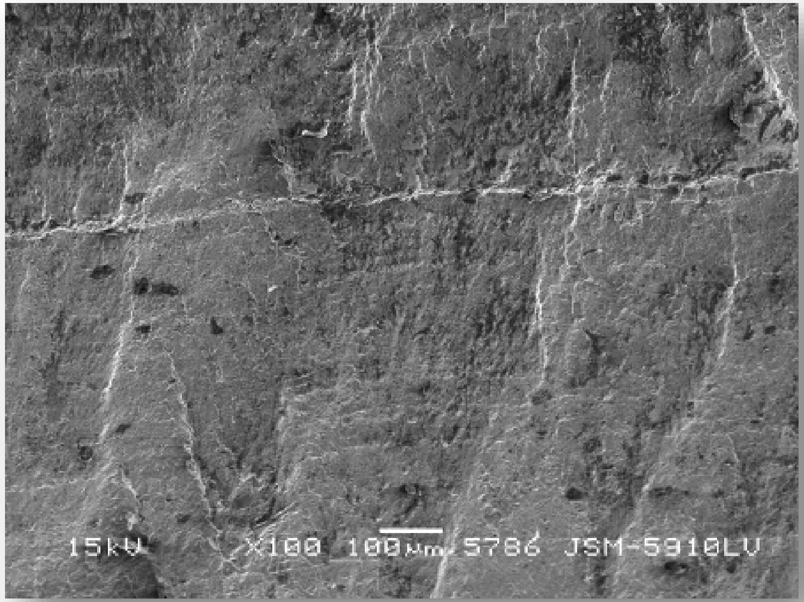
"The data contained in the chart started as experimental results with experimental variations. The mean was reduced two sigma, so 97.7% of the experimental data lies above the design curve."

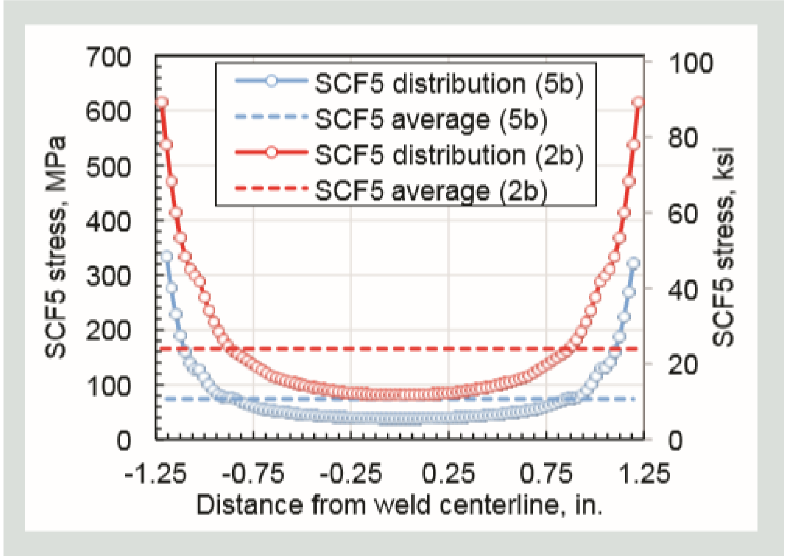
Conclusions

Conclusions

1. The common double-tee connection is
   - Poorly configured and inappropriate
   - Does not meet Code requirements for fatigue resistance
   - Prone to fatigue failure

2. The current “flexible” connection greatly increases fatigue induced stresses, making it even less suitable than the previous “inflexible” connection





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Questions?

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