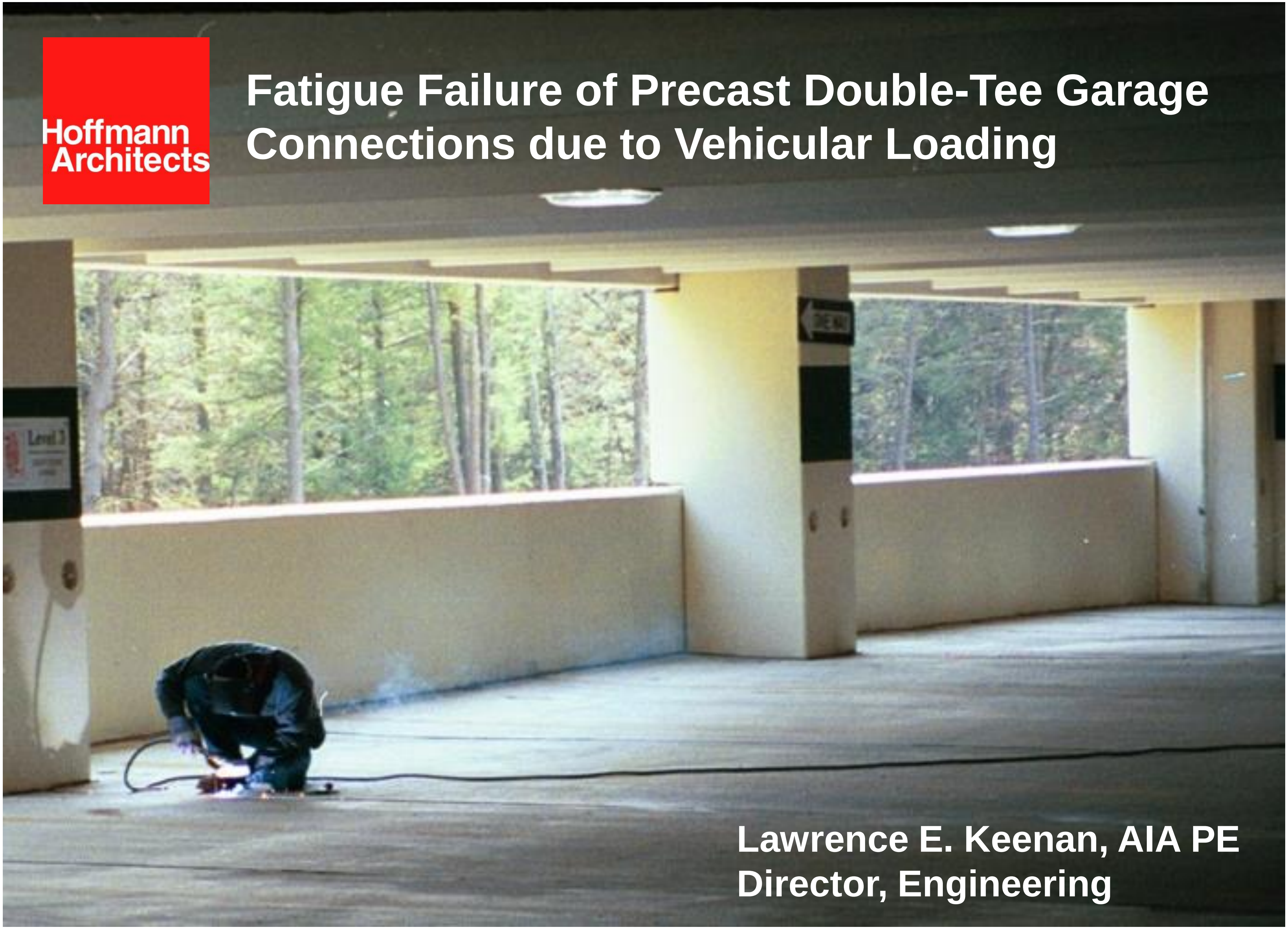
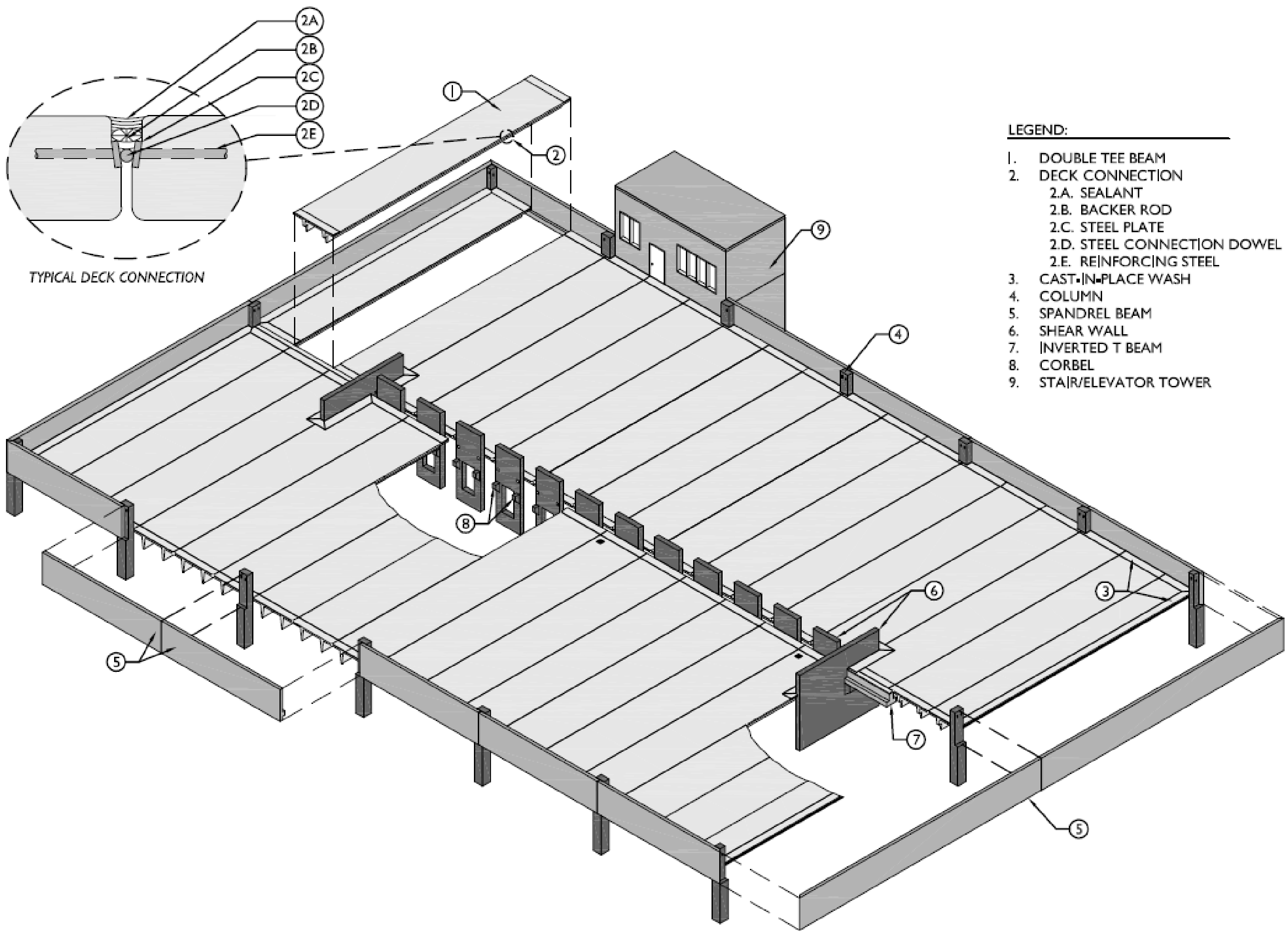
Hoffmann Architects

Fatigue Failure of Precast Double-Tee Garage Connections due to Vehicular Loading



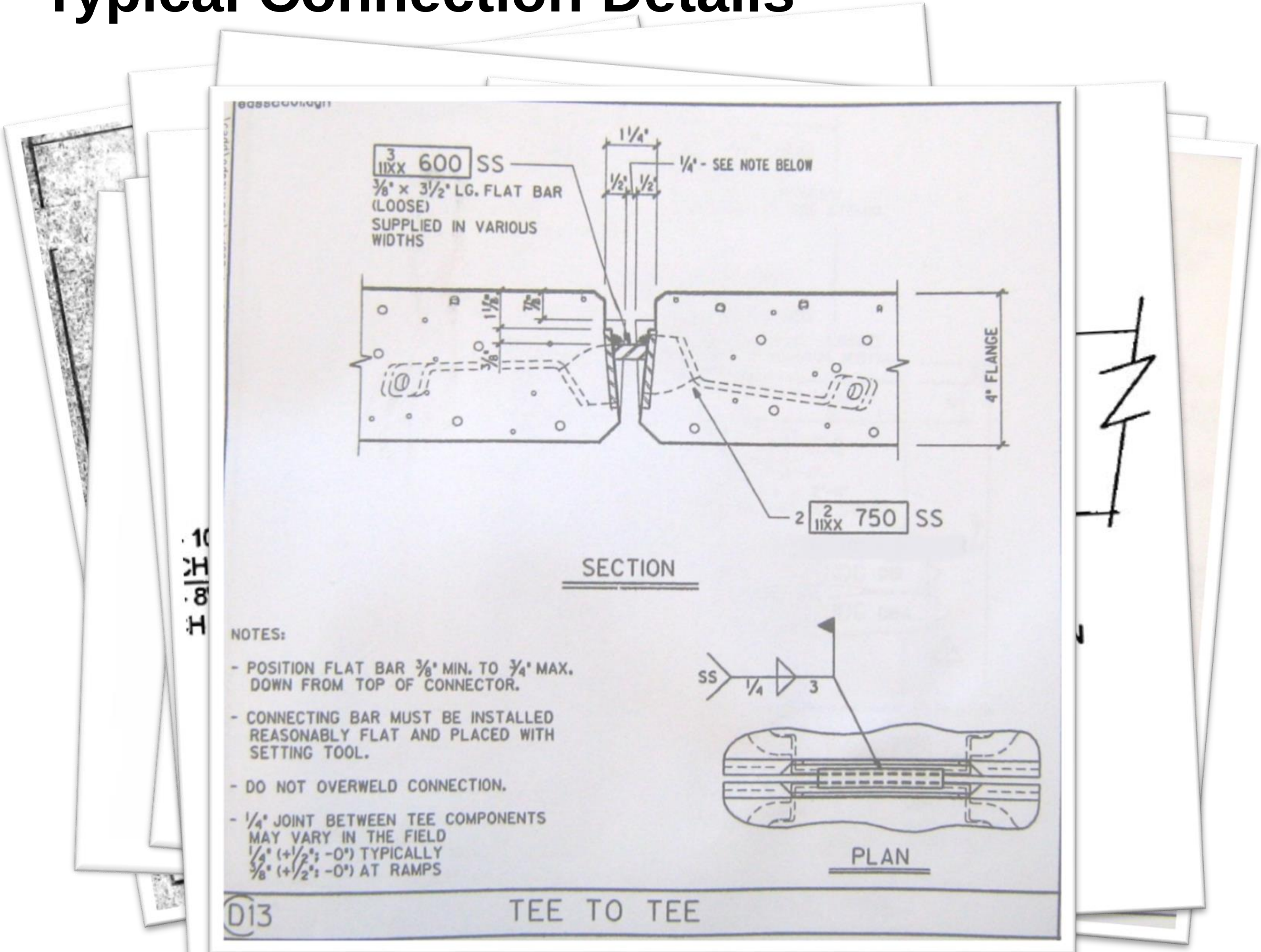
Lawrence E. Keenan, AIA PE
Director, Engineering

Typical Precast Double Tee Garage

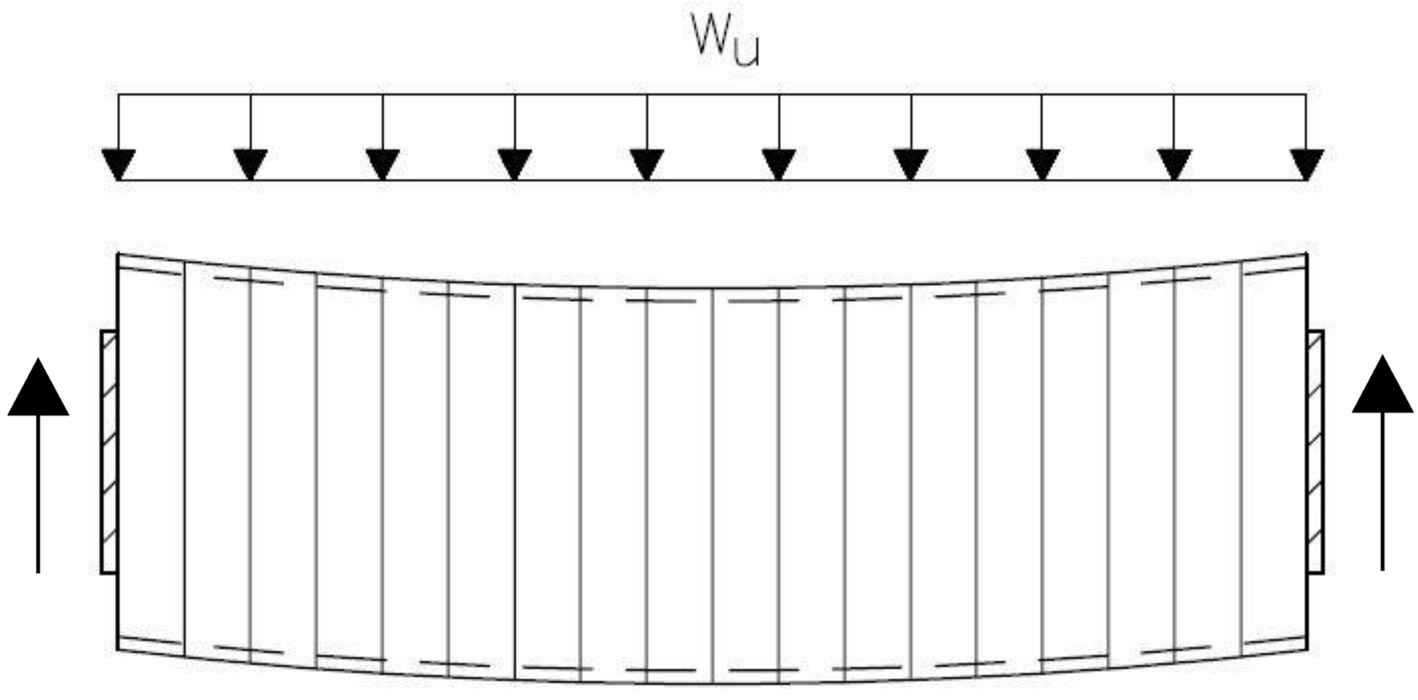


Typical Connection Details

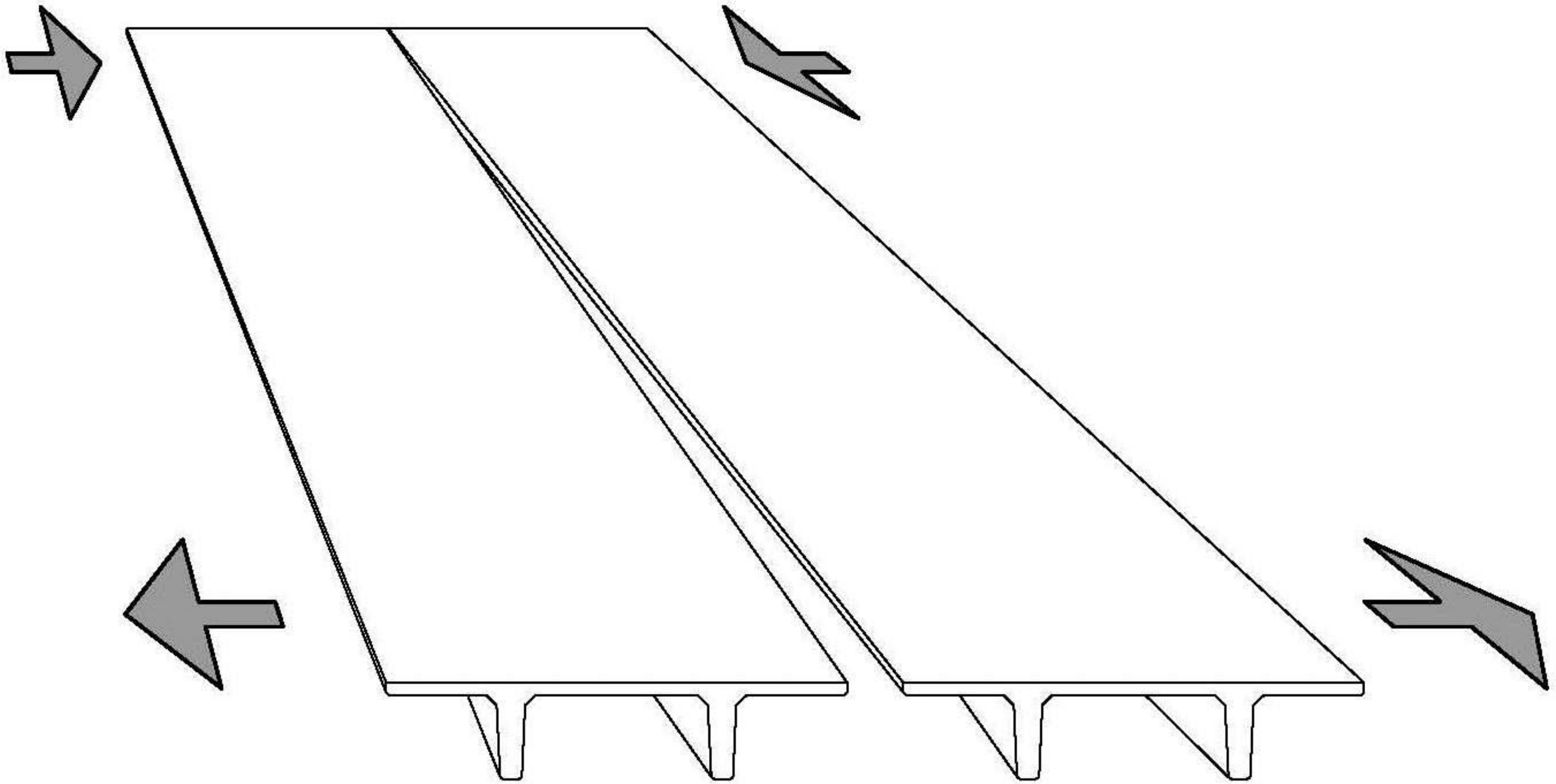
Fatigue Failure of Connections



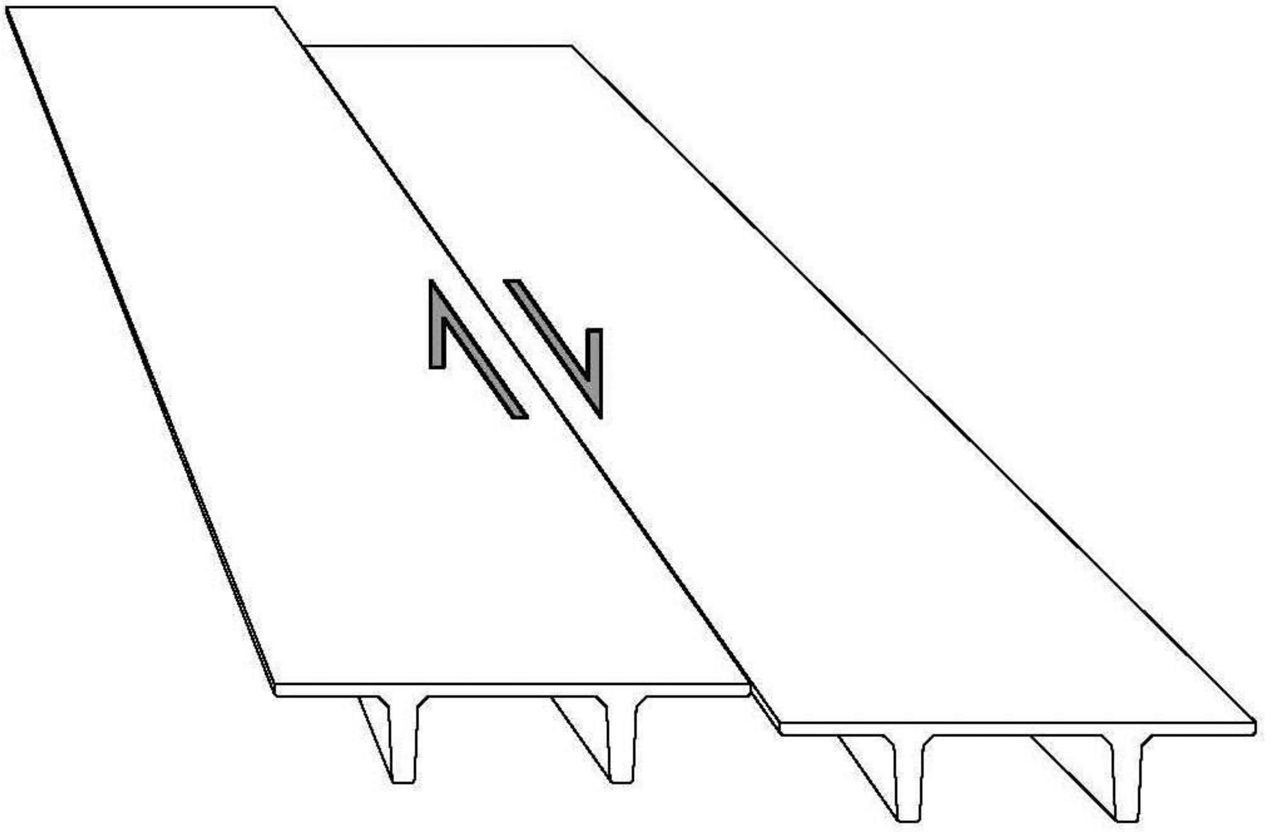
Diaphragm model



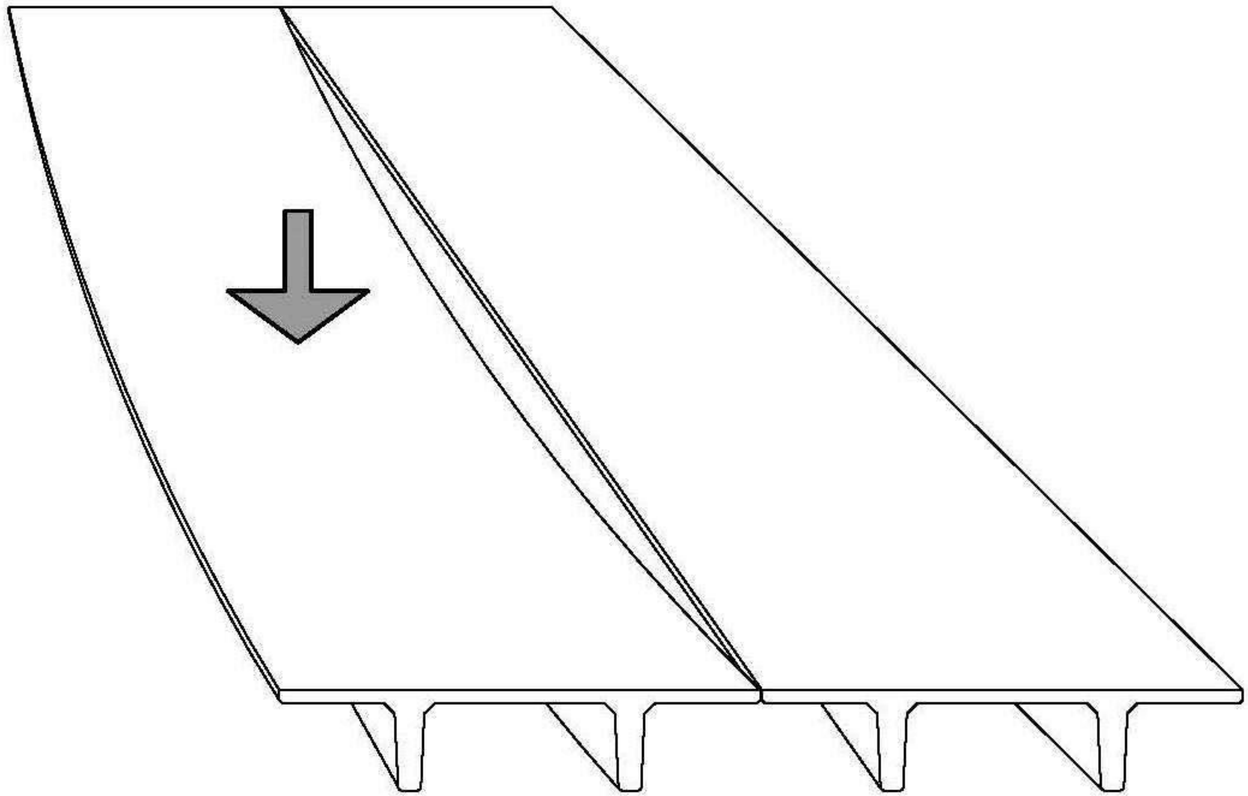
Deck Connection Forces - Chord



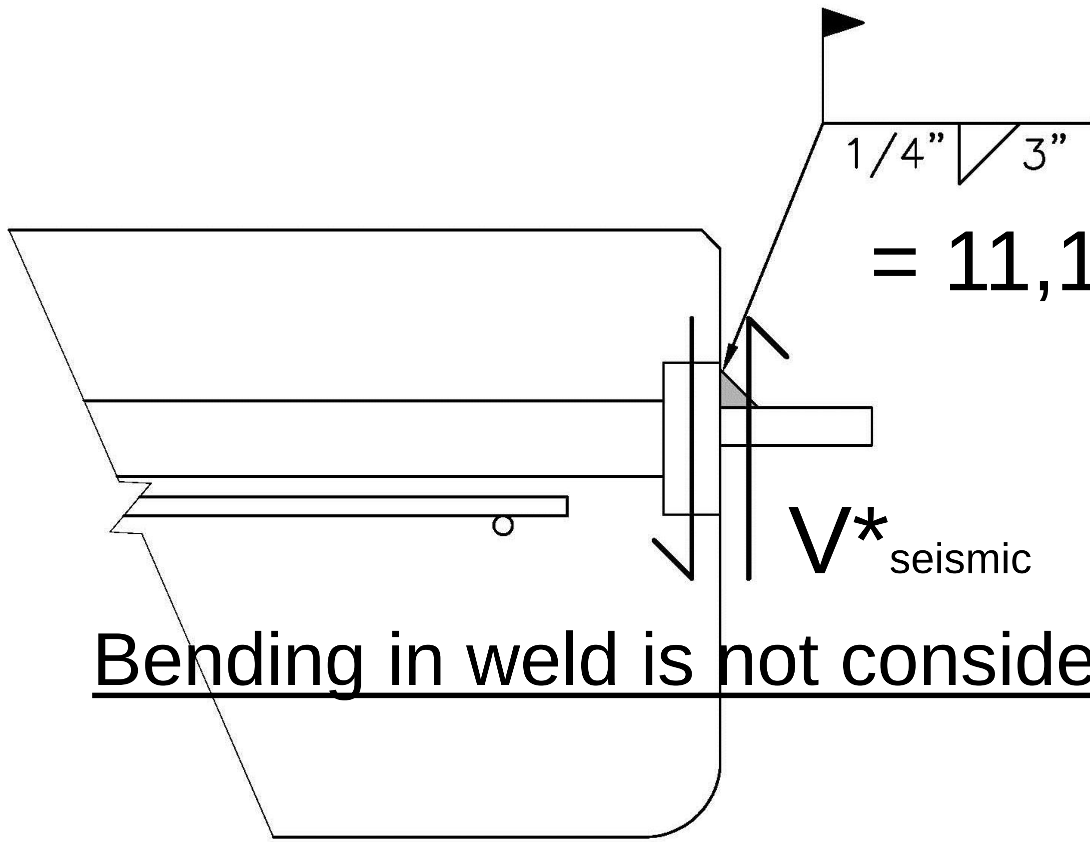
Deck Connection Forces - Shear



Deck Connection Forces - Gravity



Common Design Assumption…

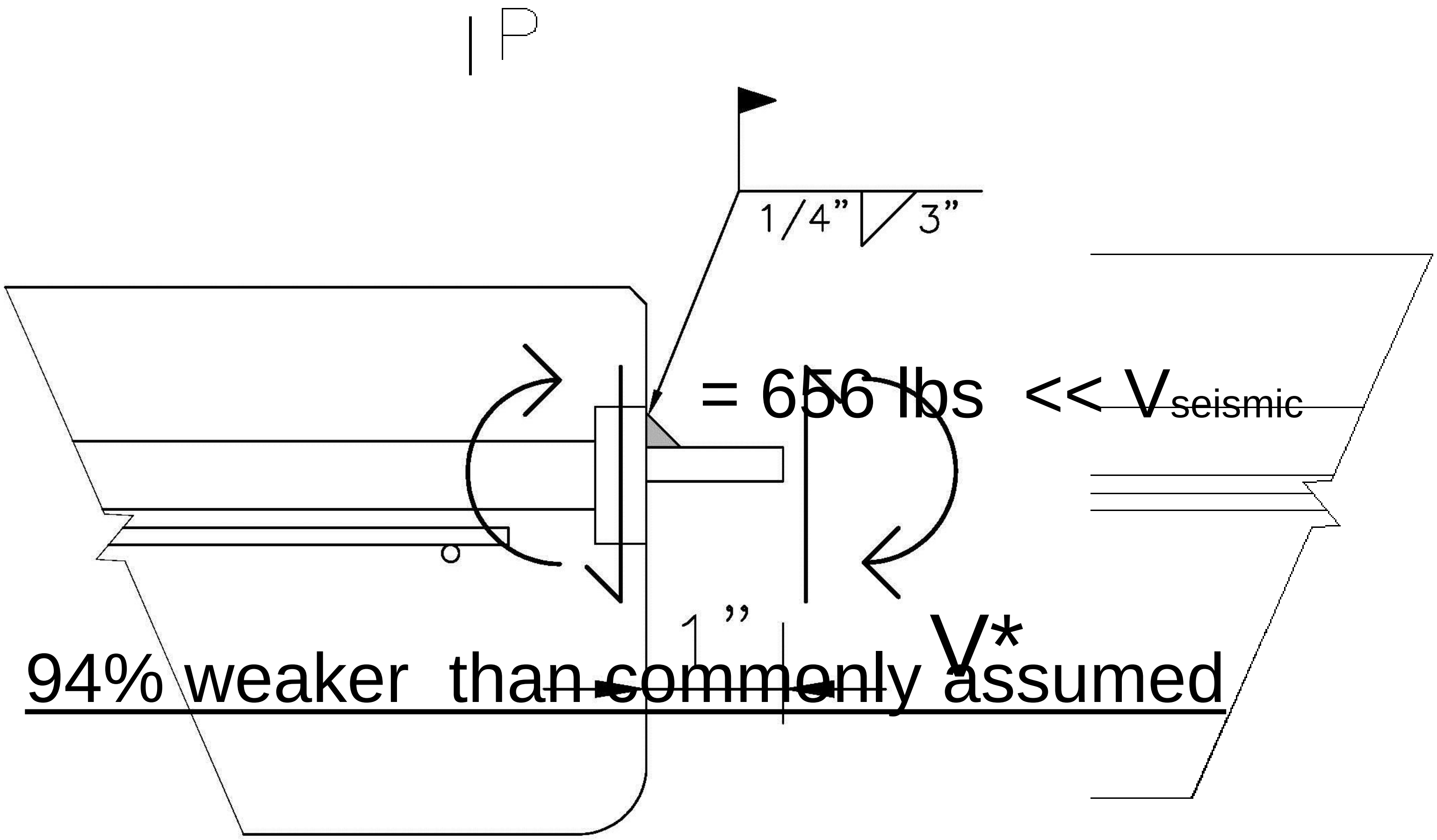


= 11,100 lbs

<u>Bending in weld is not considered</u>

*** Static shear strength using E70xx and allowable stress method**

…How it Actually Works

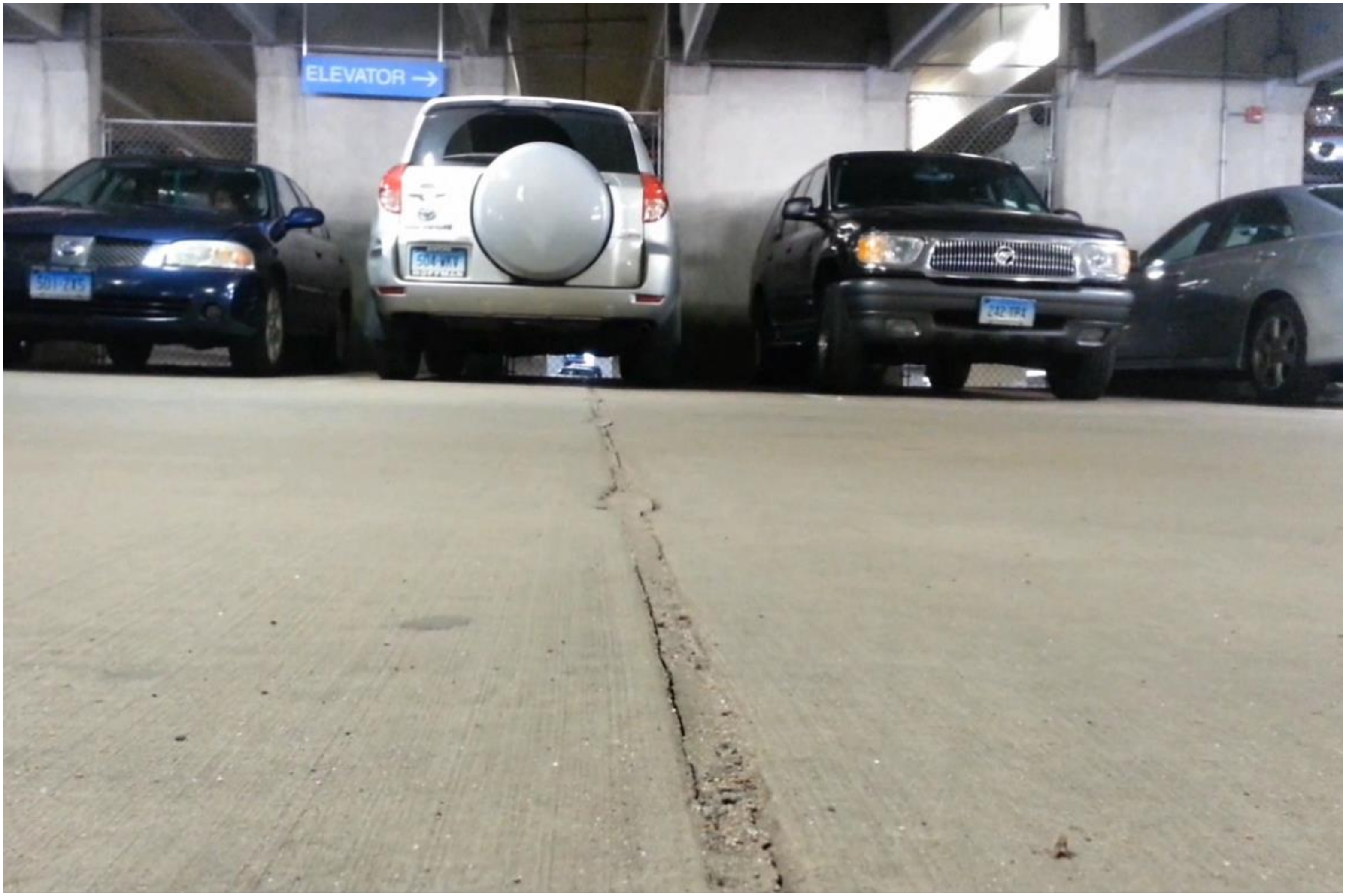


= 656 lbs << $V_{seismic}$

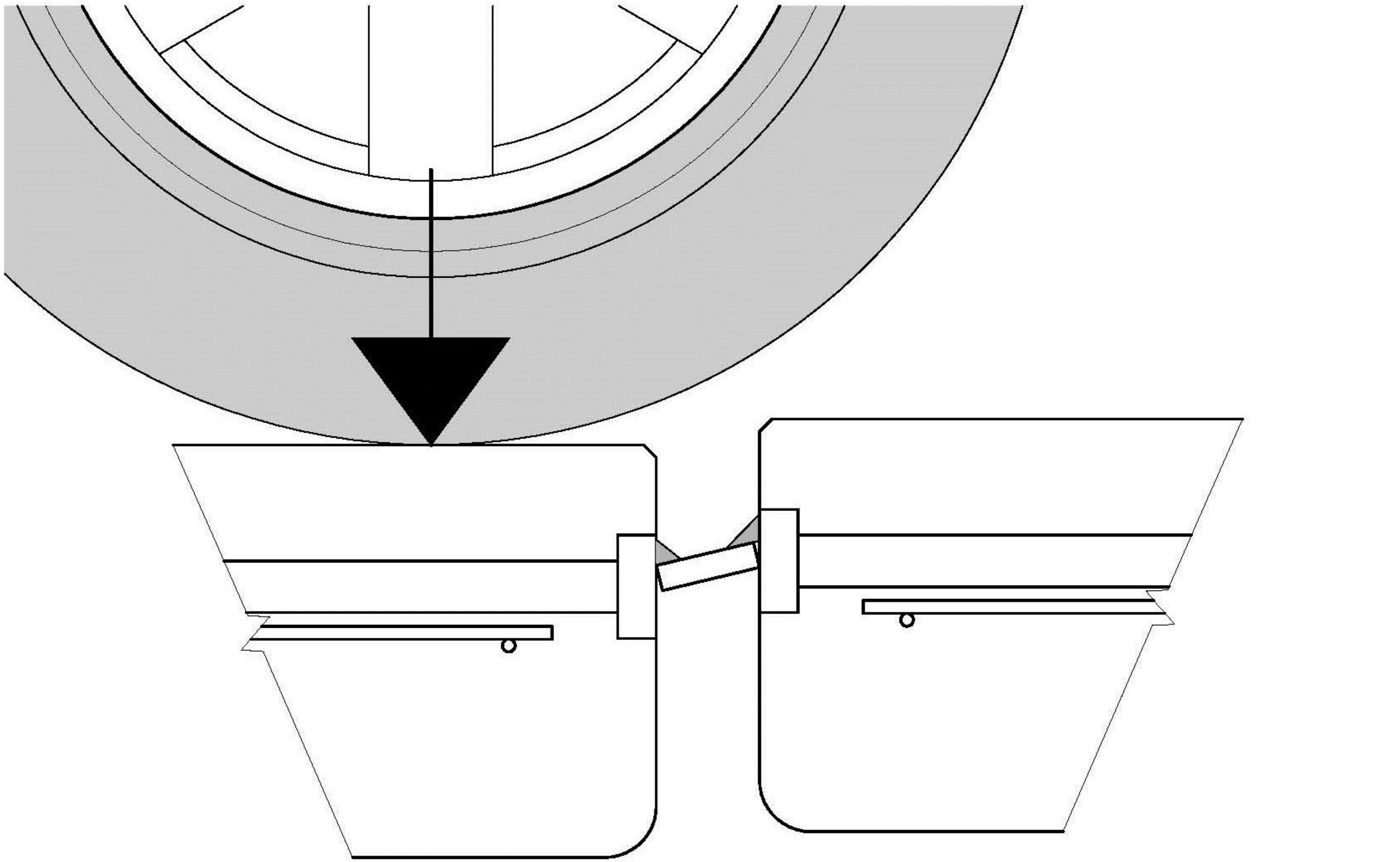
94% weaker than commonly assumed

*** Static strength using E70xx and allowable stress method**

…the ***Real*** Problem



Deck Connection Forces – Fatigue Loading



Fatigue Failure of Connections

…Fractured Field Welds Due to Fatigue

What is Fatigue?

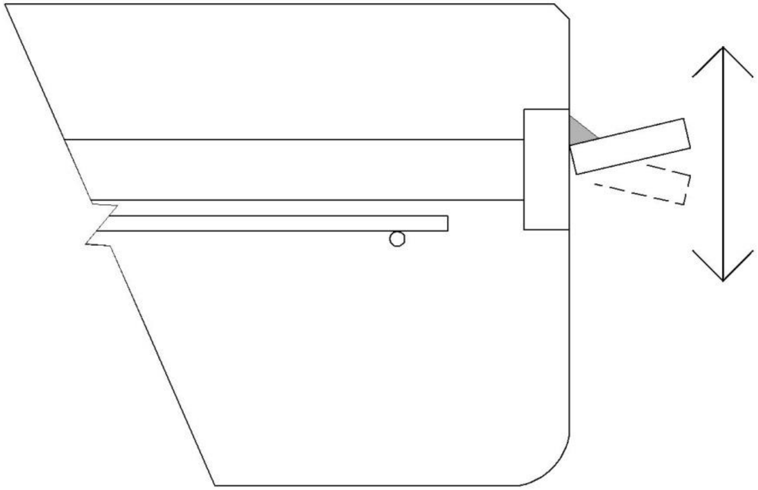
Fatigue - The process by which a material becomes weakened through cyclic loading

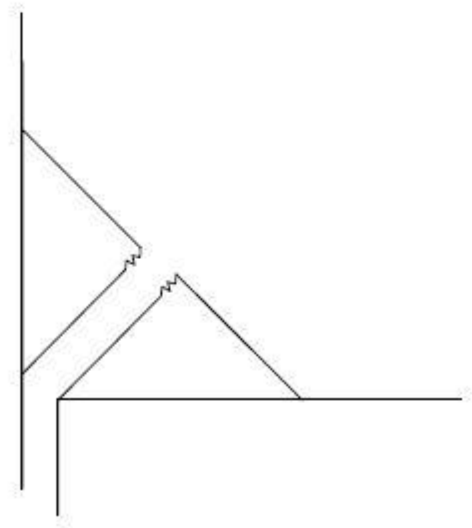
- Low Cycle Fatigue
  - Plastic deformation
- High Cycle Fatigue
  - Elastic deformation

The Fatigue Process

<u>Three Steps of Fatigue Failure:</u>

1. Crack Initiation
2. Crack Propagation
3. Failure





Fatigue Failure of Connections

Fatigue – What to look for…

Fractured surface is straight and uniform within the crack propagation zone

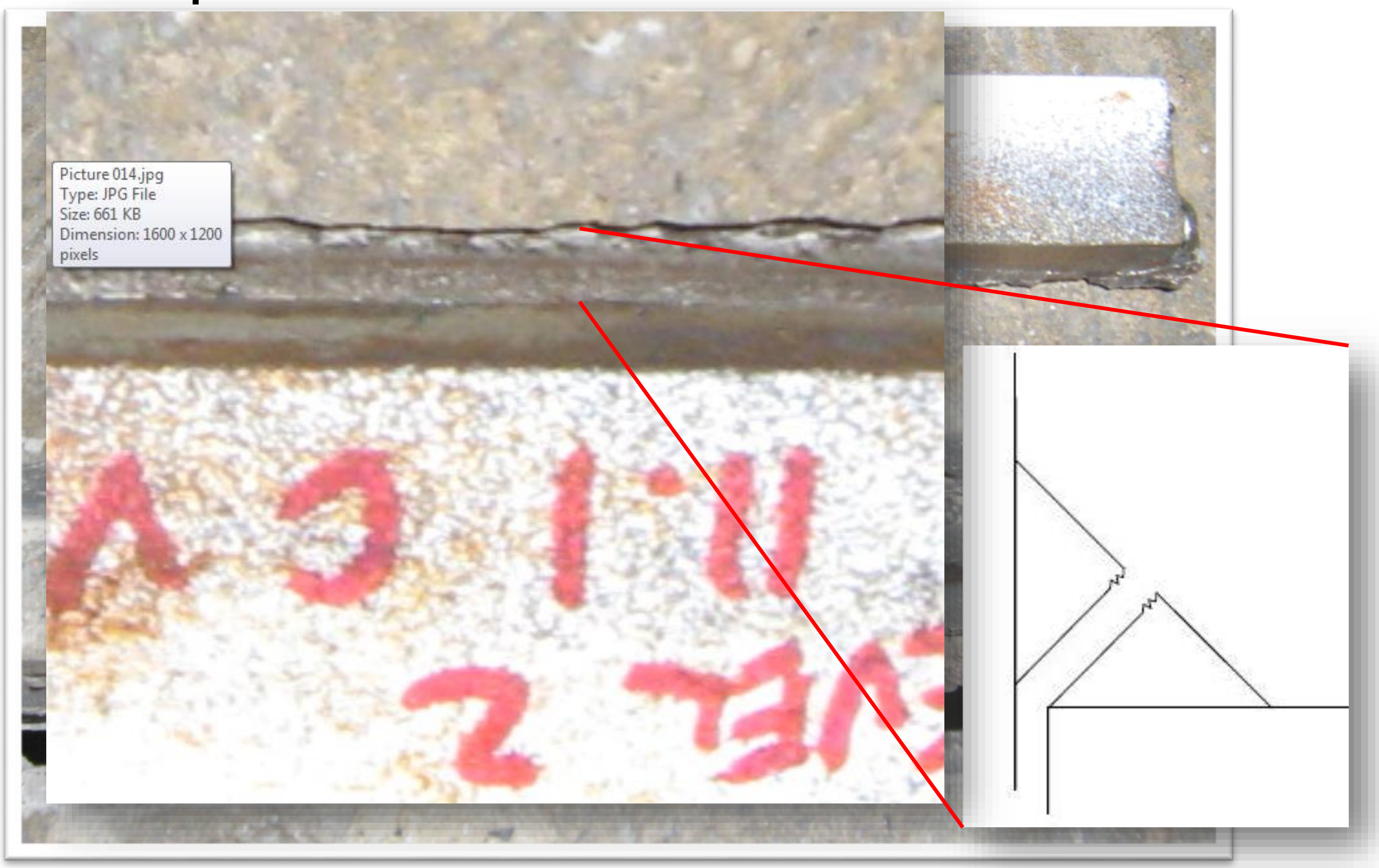
Fatigue – What not to look for…

Fractured surface jagged and wandering

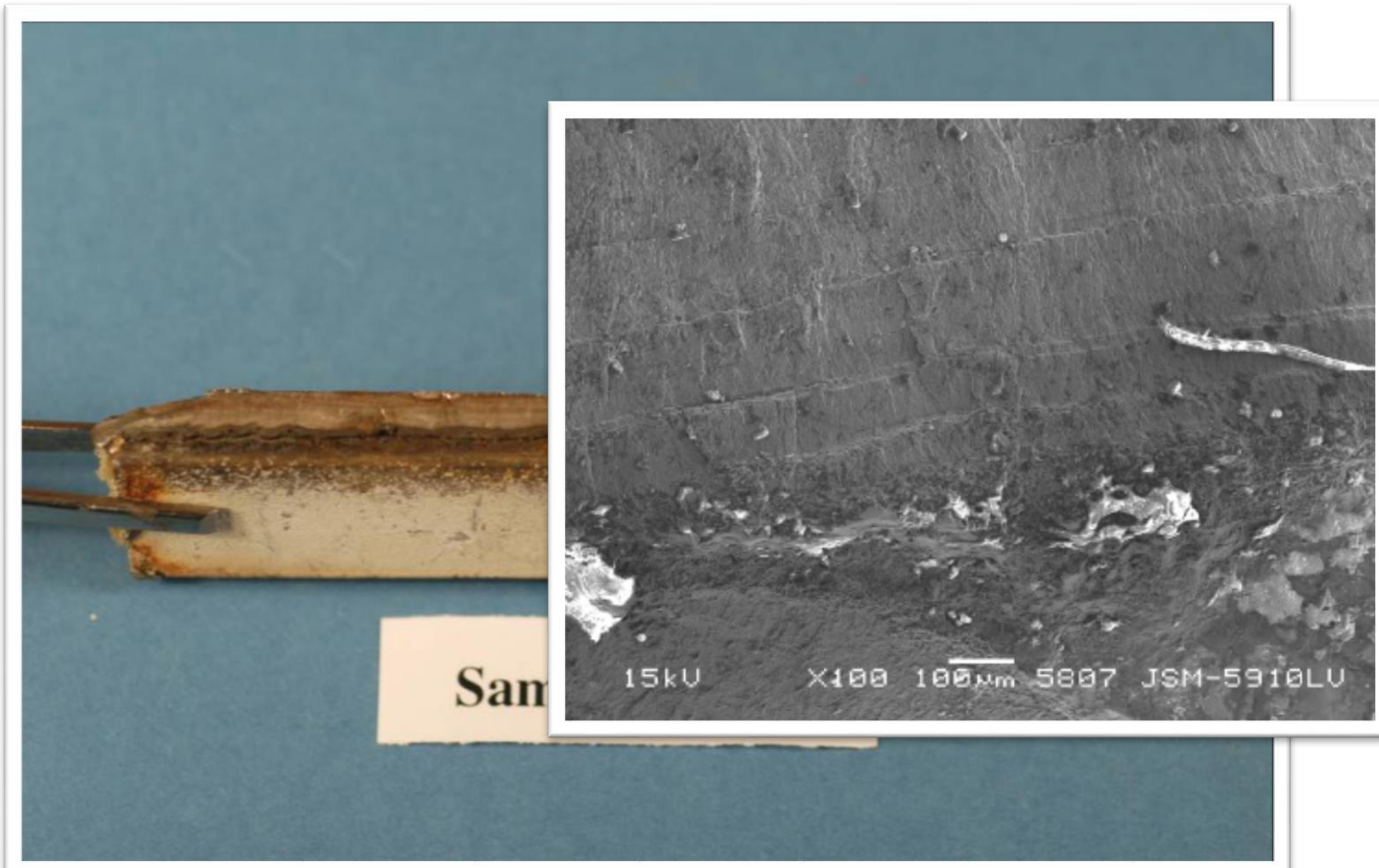
...these are abrupt failures

Fatigue – What to look for…

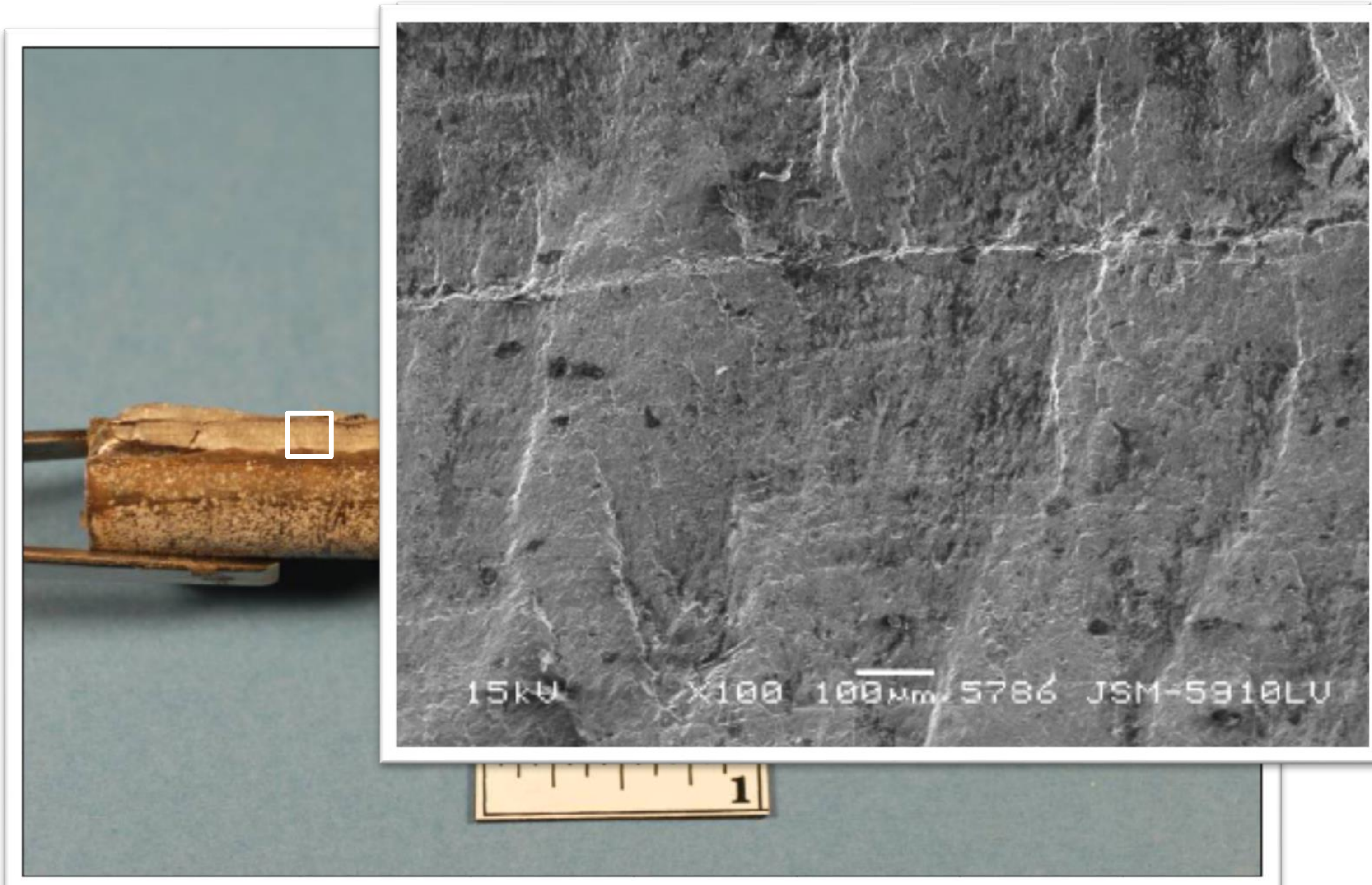
Crack initiation at root, propagation at throat, and rupture at face



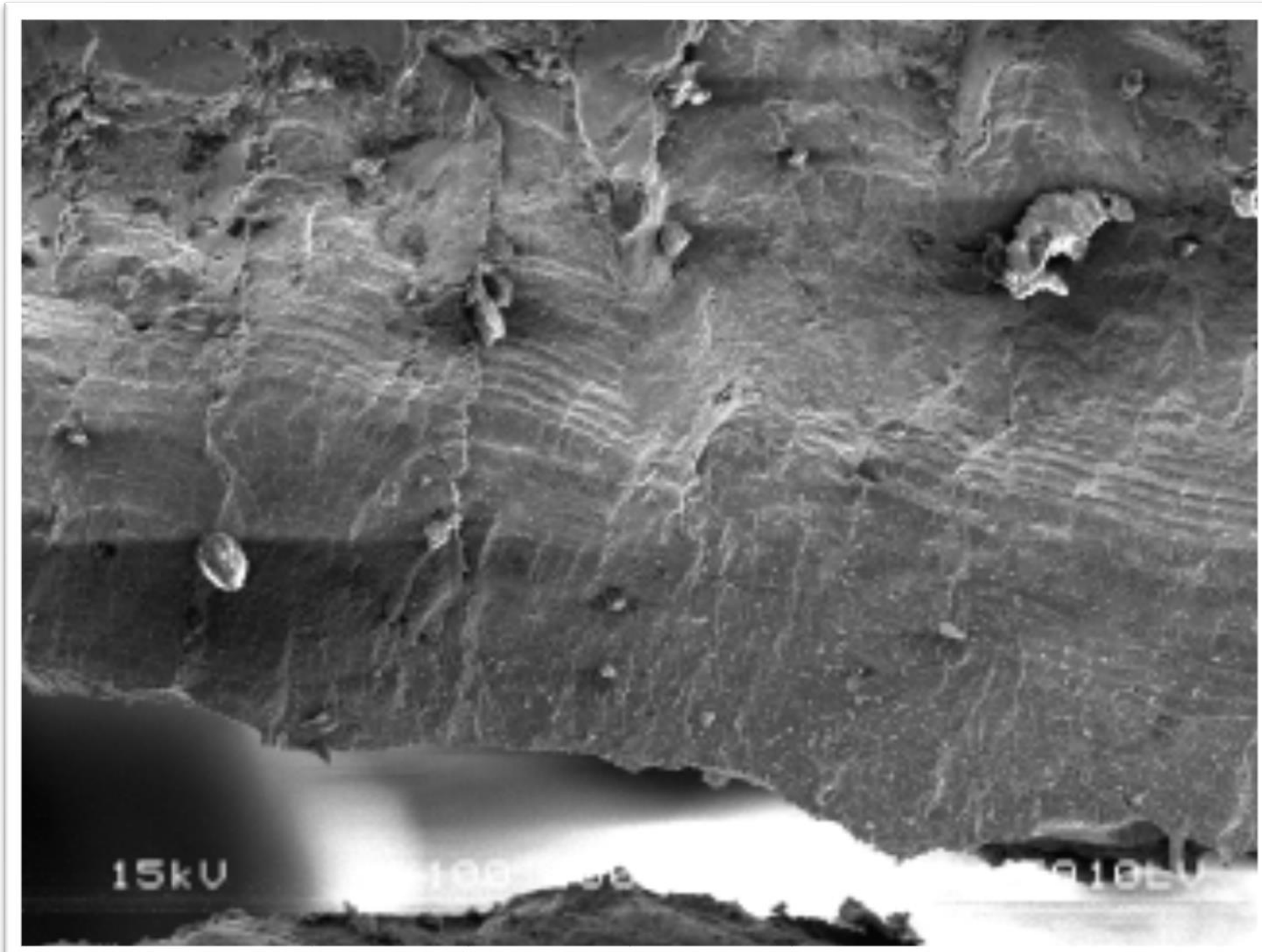
…and beach marks on weld fracture surface



…and beach marks on weld fracture surface



…and beach marks on weld fracture surface



…and moving / leaking joints

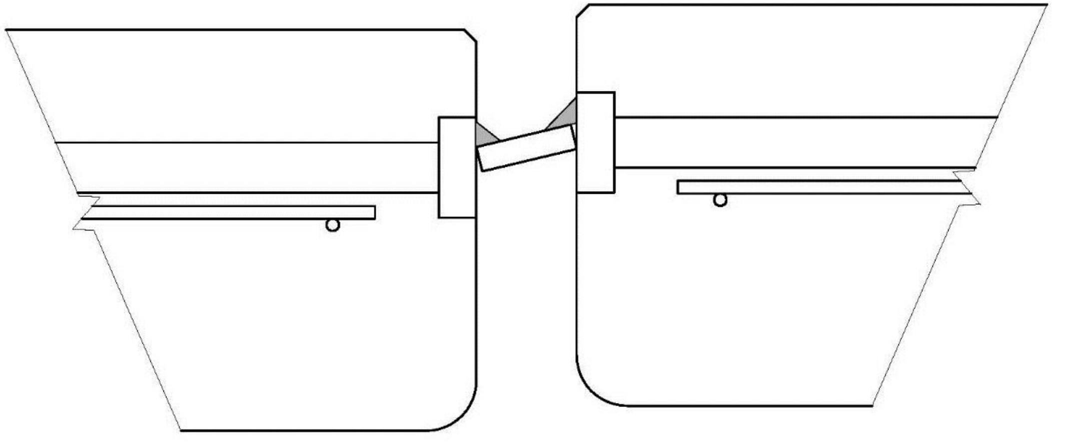
Designing for Fatigue

- 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)

Number of Cycles

Per AISC 360:

Fatigue analysis required for ≥ 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

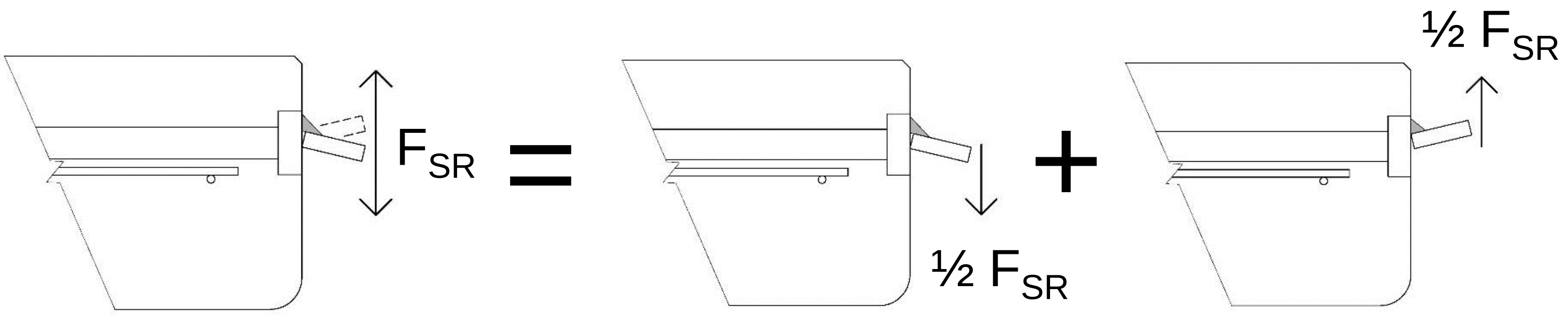
Stress Range

Per AISC and AWS Code (AWS D1.1)

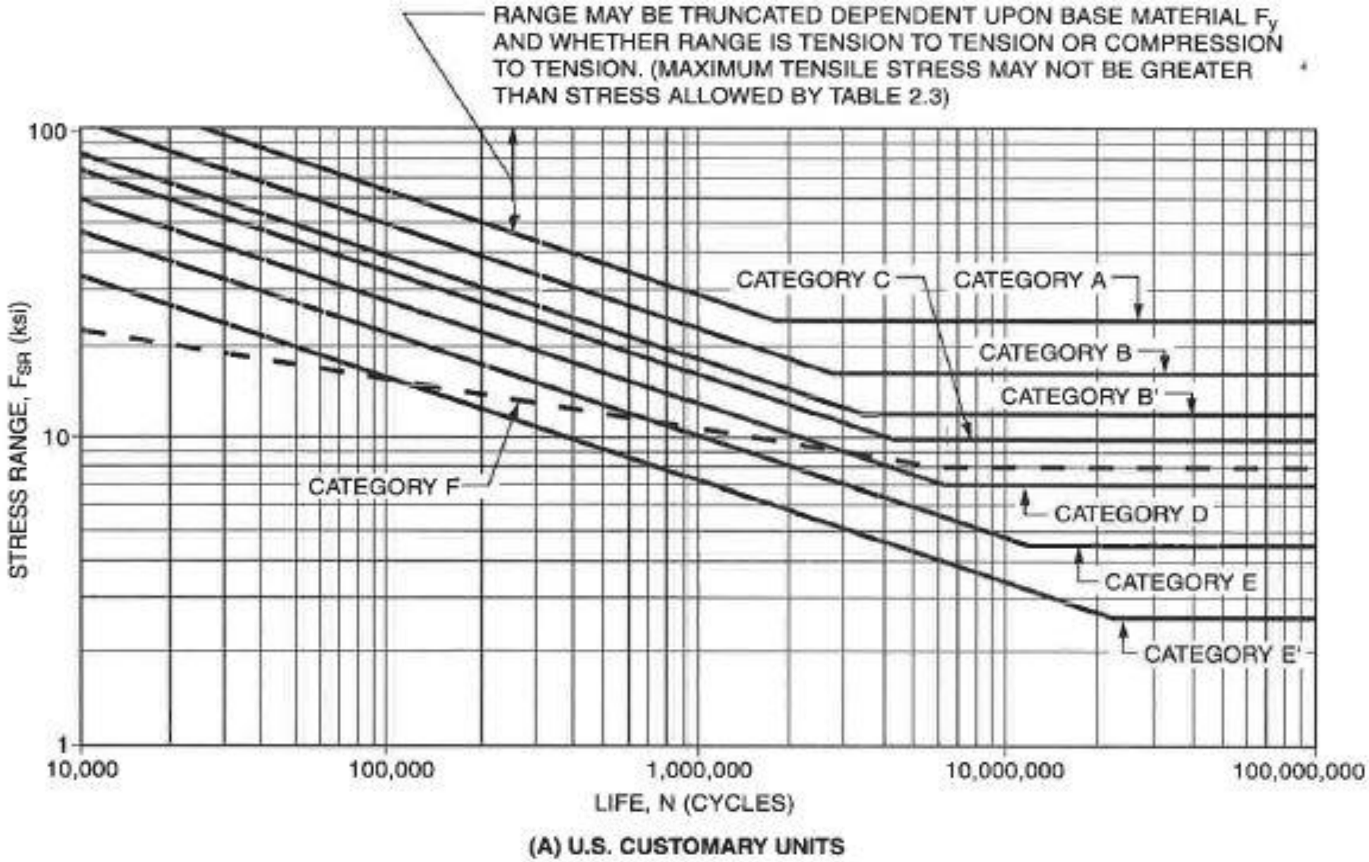
Allowable stress for fatigue:

Allowable Stress Range (F_{SR})

F_{SR} = Tension + Compression Stresses



S-N Curve



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

Stress Category

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

Stress Category:

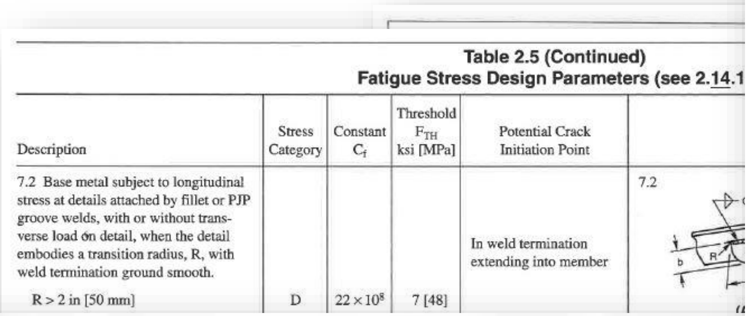
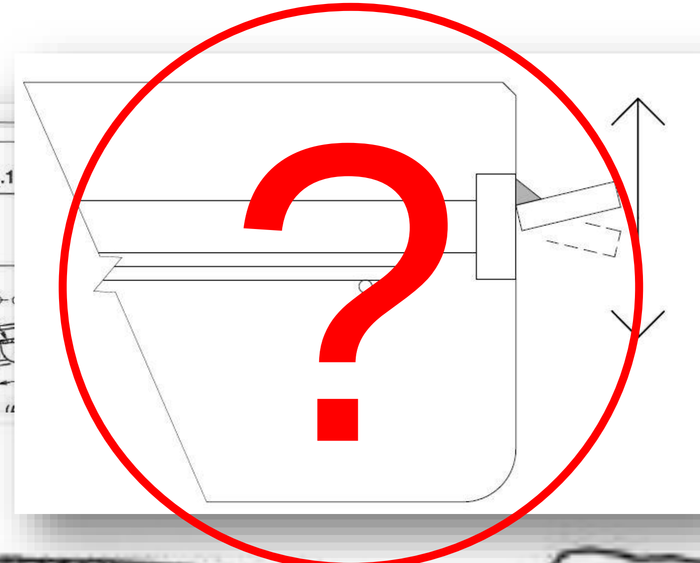
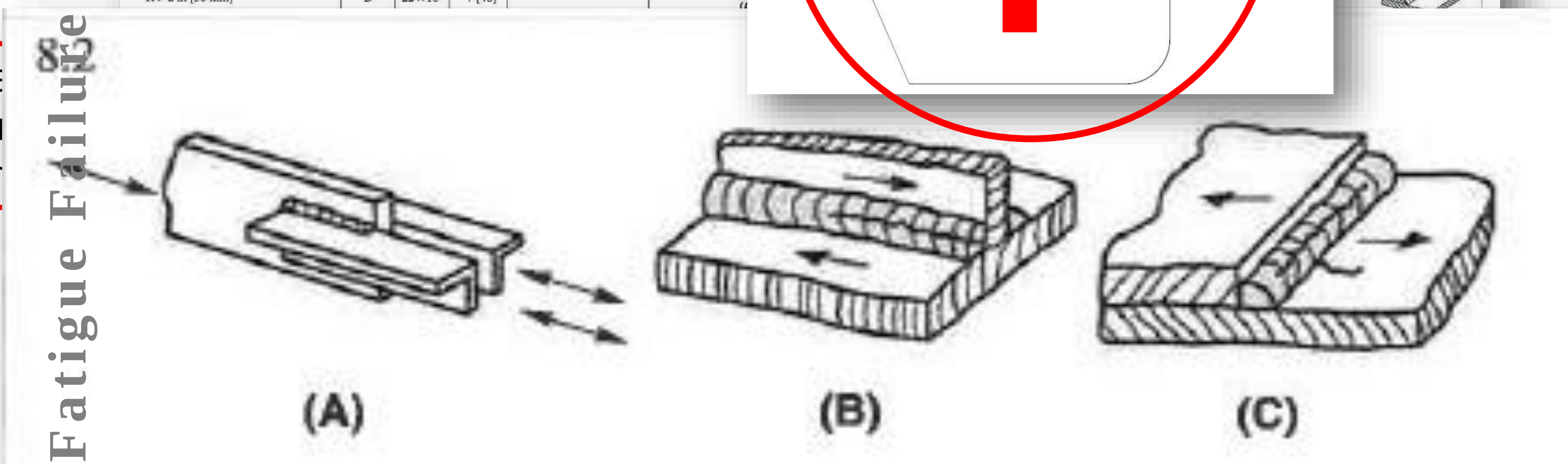


Table 2.5 (Continued)
Fatigue Stress Design Parameters (see 2.14.1

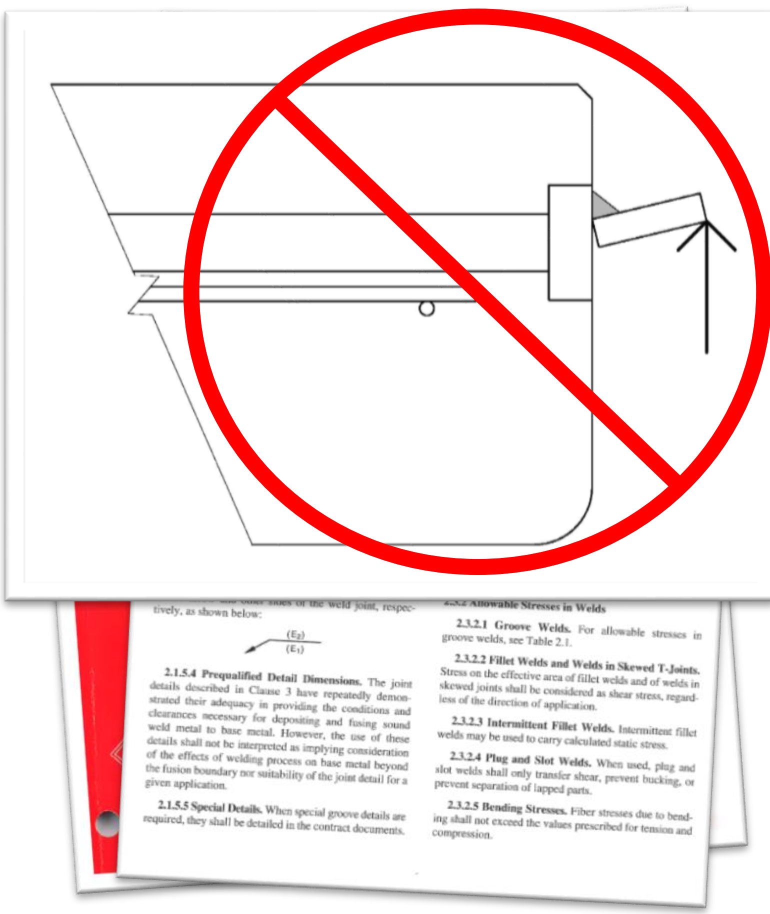
Description	Stress Category	Constant C_f	Threshold F_{TH} ksi [MPa]	Potential Crack Initiation Point
7.2 Base metal subject to longitudinal stress at details attached by fillet or PJP groove welds, with or without transverse load on detail, when the detail embodies a transition radius, R, with weld termination ground smooth.				In weld termination extending into member
R > 2 in [50 mm]	D	22×10^8	7 [48]	





What do the Experts Say?

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



Section 2, Part A 2.2.2 – Bending Stresses

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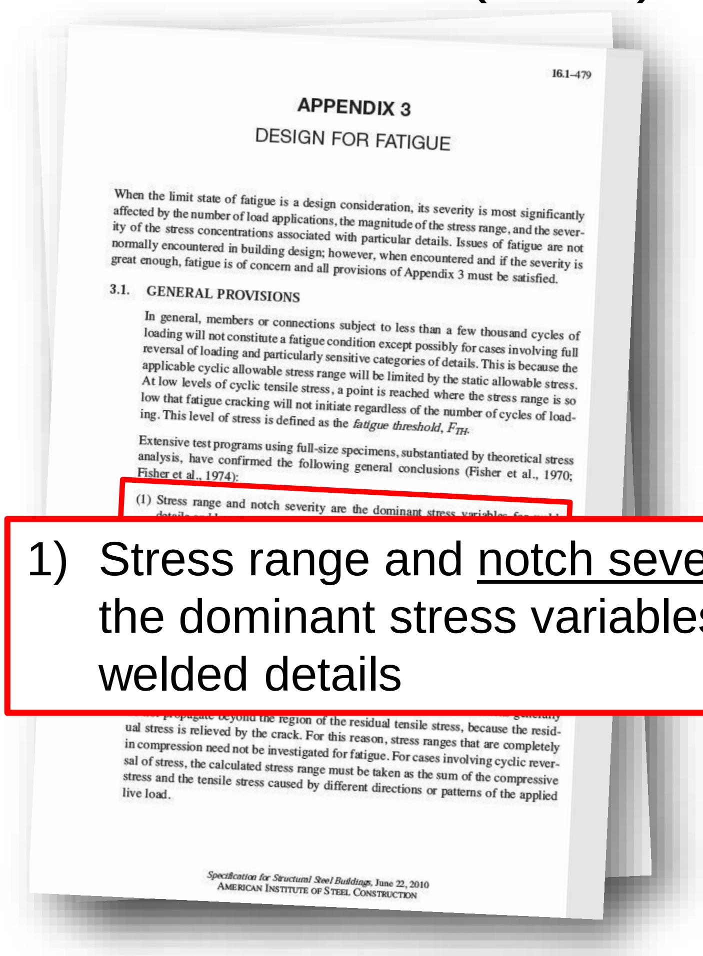
What do the Experts Say?

Fatigue Failure of Connections

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

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

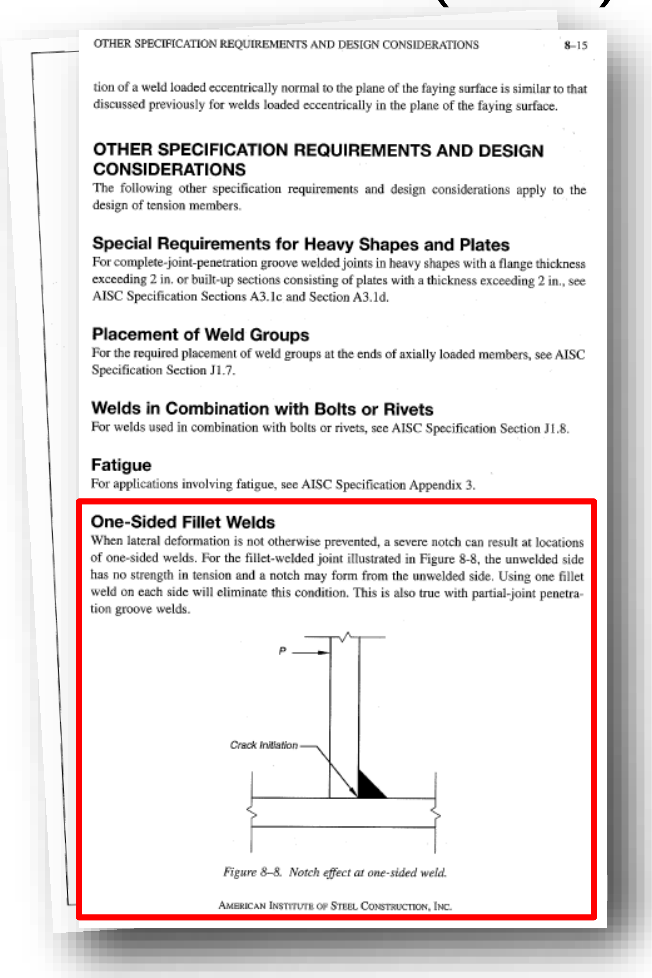
Appendix 3 Commentary

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

What do the Experts Say?

Fatigue Failure of Connections

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



tion of a weld loaded eccentrically normal to the plane of the faying surface is similar to that discussed previously for welds loaded eccentrically in the plane of the faying surface.

OTHER SPECIFICATION REQUIREMENTS AND DESIGN CONSIDERATIONS

The following other specification requirements and design considerations apply to the design of tension members.

Special Requirements for Heavy Shapes and Plates

For complete-joint-penetration groove welded joints in heavy shapes with a flange thickness exceeding 2 in. or built-up sections consisting of plates with a thickness exceeding 2 in., see AISC Specification Sections A3.1c and Section A3.1d.

Placement of Weld Groups

For the required placement of weld groups at the ends of axially loaded members, see AISC Specification Section J1.7.

Welds in Combination with Bolts or Rivets

For welds used in combination with bolts or rivets, see AISC Specification Section J1.8.

Fatigue

For applications involving fatigue, see AISC Specification Appendix 3.

One-Sided Fillet Welds

When lateral deformation is not otherwise prevented, a severe notch can result at locations of one-sided welds. For the fillet-welded joint illustrated in Figure 8-8, the unwelded side has no strength in tension and a notch may form from the unwelded side. Using one fillet weld on each side will eliminate this condition. This is also true with partial-joint penetration groove welds.

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

Part 8 - Design Consideration for Welds

One-Sided Fillet Welds

When lateral deformation is not otherwise prevented, a severe notch can result at locations of one-sided welds. For the fillet-welded joint illustrated in Figure 8-8, the unwelded side has no strength in tension and a notch may form from the unwelded side. Using one fillet weld on each side will eliminate this condition. This is also true with partial-joint penetration groove welds.

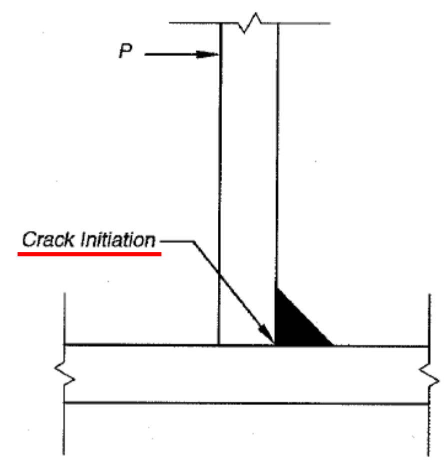
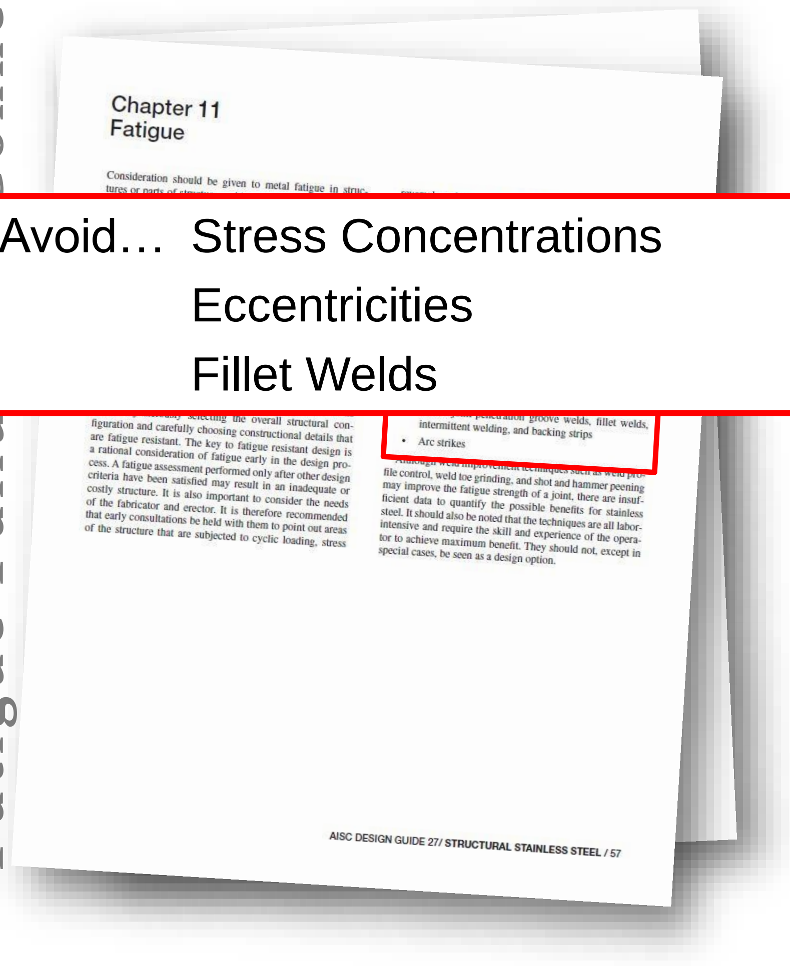


Figure 8–8. Notch effect at one-sided weld.

What do the Experts Say?

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


Chapter 11
Fatigue

Consideration should be given to metal fatigue in struc-

figuration and carefully choosing constructional details that are fatigue resistant. The key to fatigue resistant design is a rational consideration of fatigue early in the design process. A fatigue assessment performed only after other design criteria have been satisfied may result in an inadequate or costly structure. It is also important to consider the needs of the fabricator and erector. It is therefore recommended that early consultations be held with them to point out areas of the structure that are subjected to cyclic loading, stress

groove welds, fillet welds, intermittent welding, and backing strips

- Arc strikes

file control, weld toe grinding, and shot and hammer peening may improve the fatigue strength of a joint, there are insufficient data to quantify the possible benefits for stainless steel. It should also be noted that the techniques are all labor-intensive and require the skill and experience of the operator to achieve maximum benefit. They should not, except in special cases, be seen as a design option.

AISC DESIGN GUIDE 27/ STRUCTURAL STAINLESS STEEL / 57

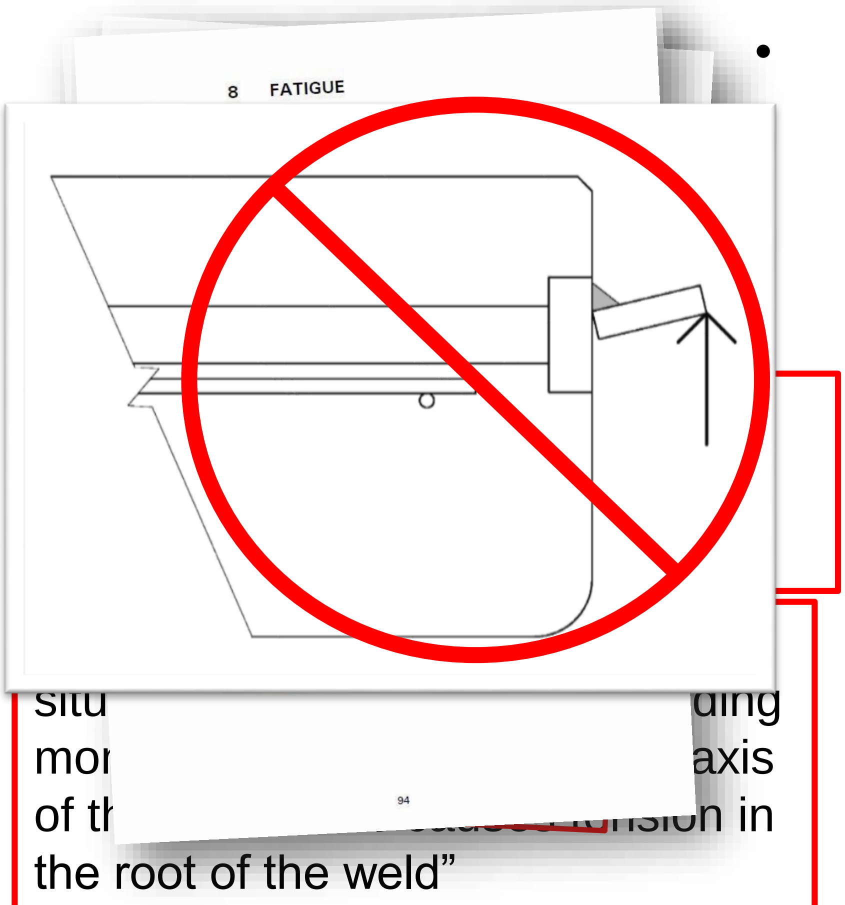
Chapter 11 Fatigue

Avoid… Stress Concentrations
Eccentricities
Fillet Welds

What do the Experts Say?

Design Manual for Structural Stainless Steel
The Steel Construction Institute

- Section 6.4.2 Fillet Welds

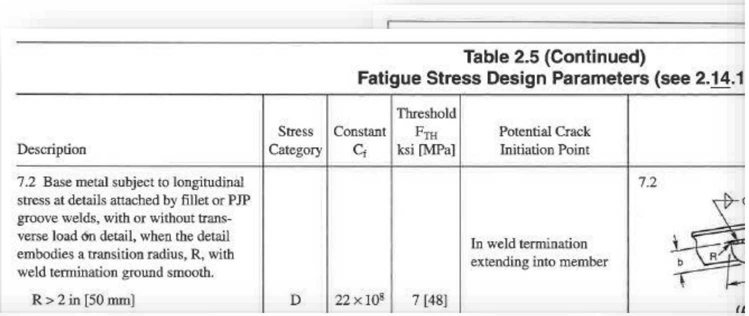


Section 8 Fatigue

Stress Category

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

Stress Category:



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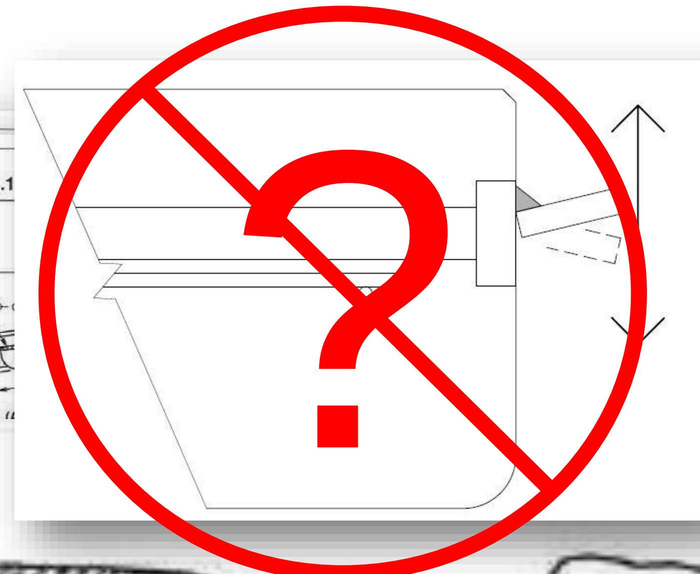
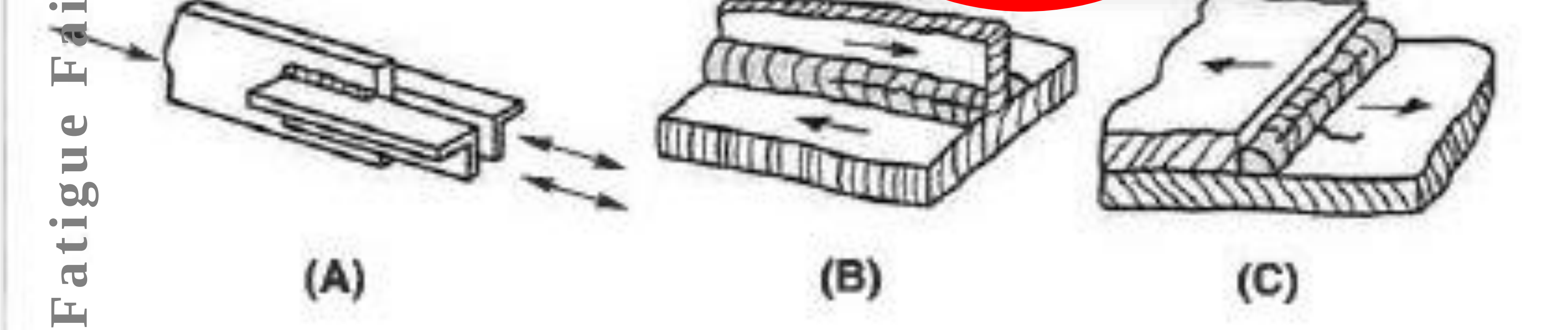
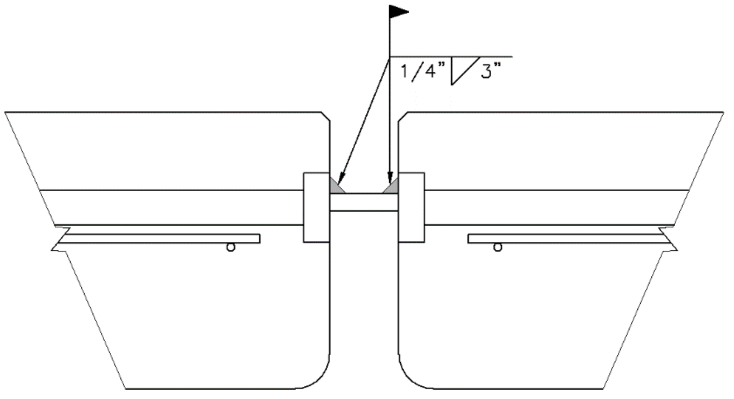
R > 2 in [50 mm]	D	22×10^8	7 [48]		





Strength Comparison

Allowable Load on Example:



<u>Seismic Strength</u>

V = 11,100 lbs

<u>Static Strength</u> (w/ 1" joint)

V_S = 636 lbs

<u>Fatigue Strength</u>

None

How to Improve Fatigue Resiliency

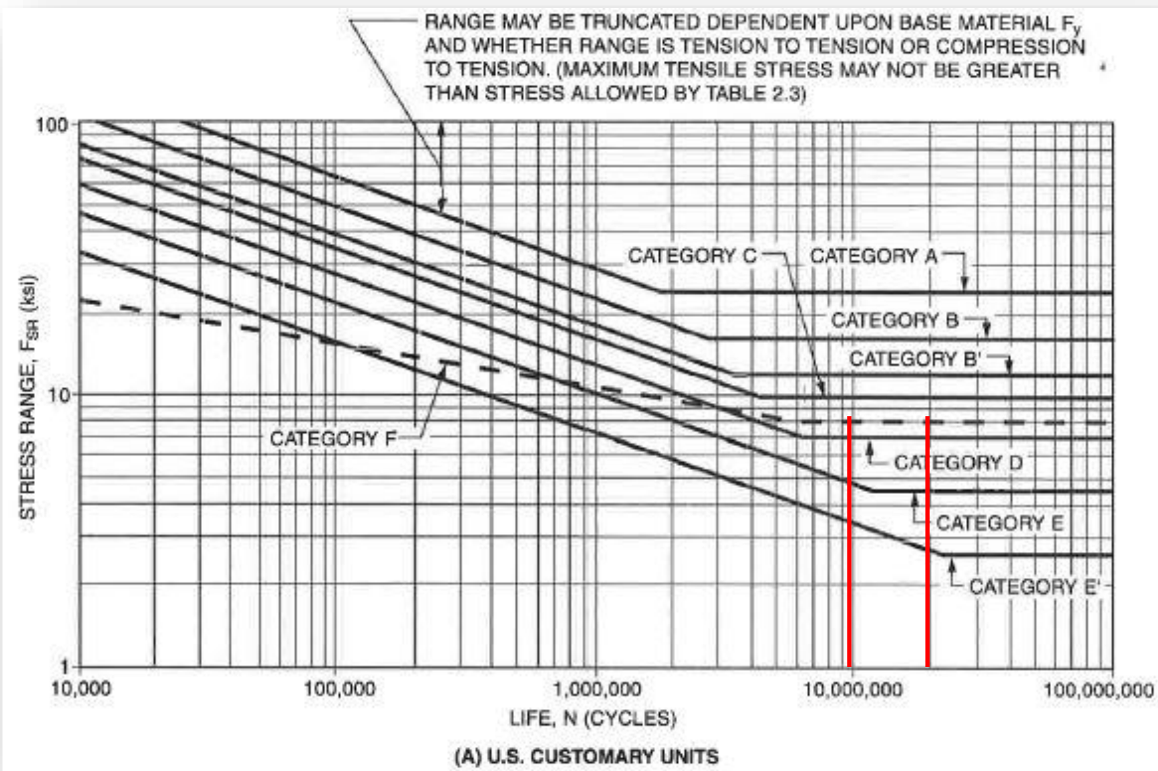
Main factors influencing fatigue are:

- Number of cycles
- Severity of stress concentration
- The Stress Range

How to Improve Fatigue Resiliency

Reducing the Number of Cycles

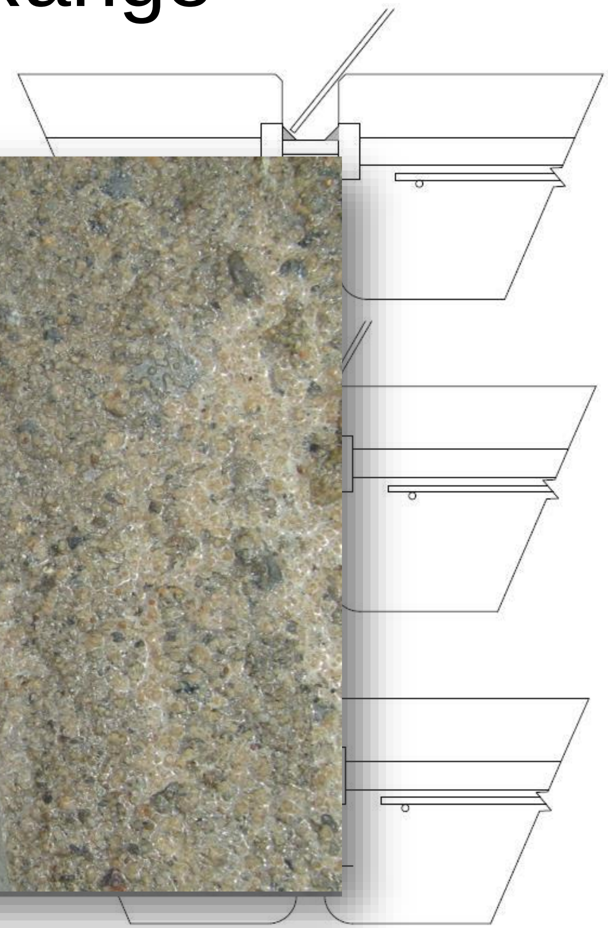
- Reroute traffic ?



How to Improve Fatigue Resiliency

Reduce Severity of Stress Concentration / Decrease the Stress Range

- Larger welds
-
-
-
-



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Hoffmann Architects

Fatigue Failure of Precast Double-Tee Garage Connections due to Vehicular Loading

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Director, Engineering