Investigations of Fractures in Three Kentucky Transportation Cabinet Steel Bridges

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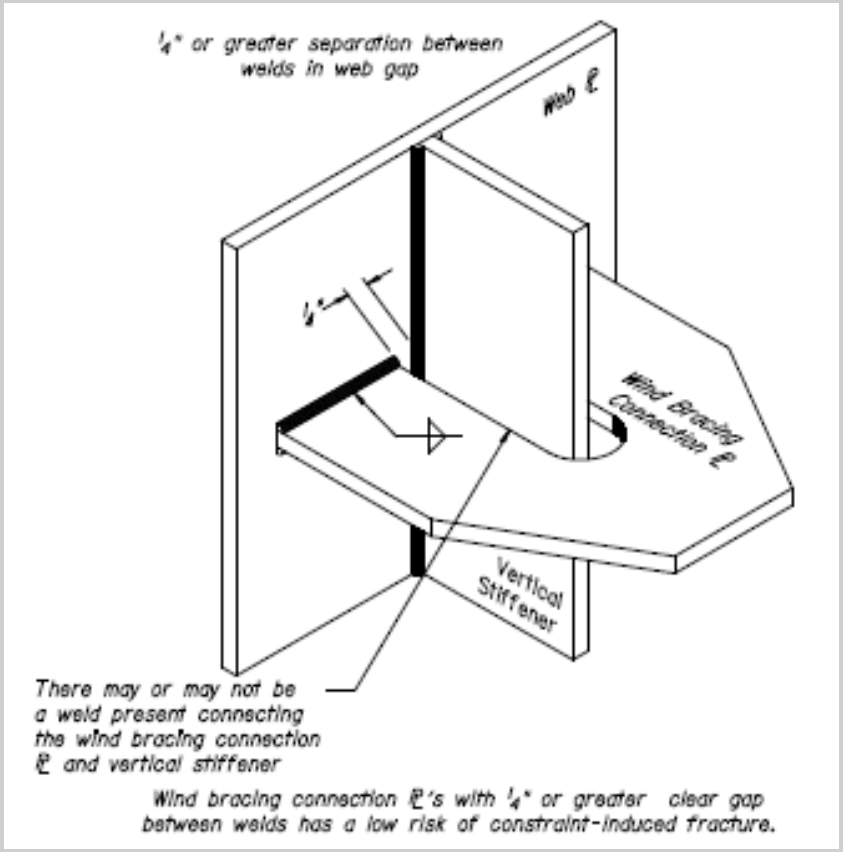
NEBPP Annual Conference
September 9, 2019

I-75 NB Bridge Over Lynn Camp Creek in Whitley County KY

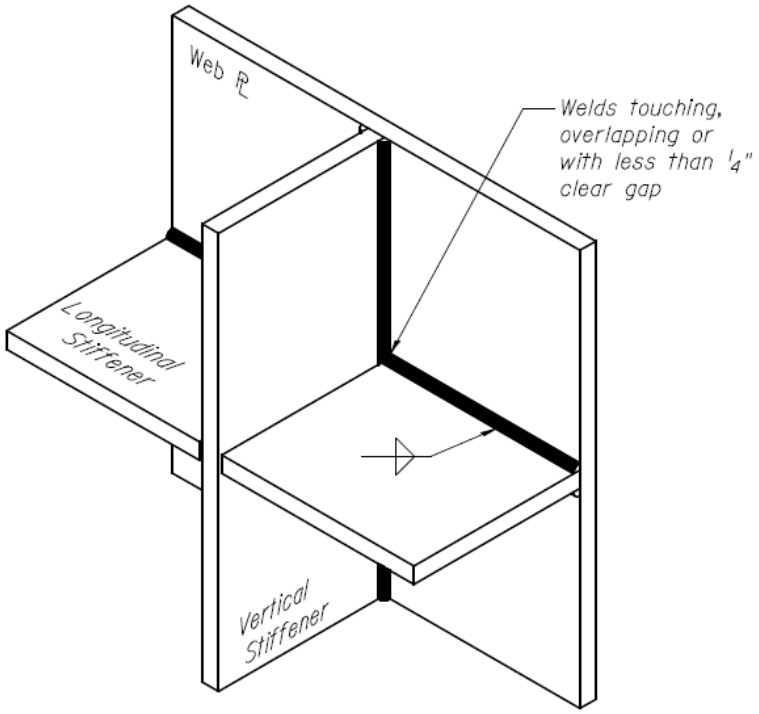
- Built in 1966 (SB & NB twin bridges)
- Continuous welded steel girder structure with 4 girder lines
  - 140’-200’-140’ spans
  - 84” deep girders (webs)
- Made from ASTM A36 steel
- Traffic count over bridge 18,000 vehicles
- Fractures in center span of both bridges in 2012
- Fracture in center span of NB bridge in 2014

Girder Cracking in NB & SB Bridges in 2012

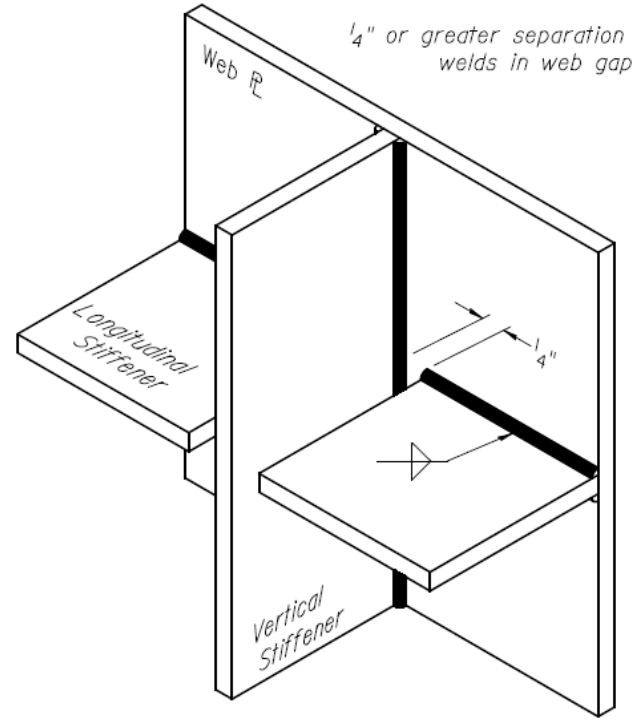
IDOT Circular Letter 2010-09



Wind bracing connection ℄'s with ¼" or greater clear gap between welds has a low risk of constraint-induced fracture.

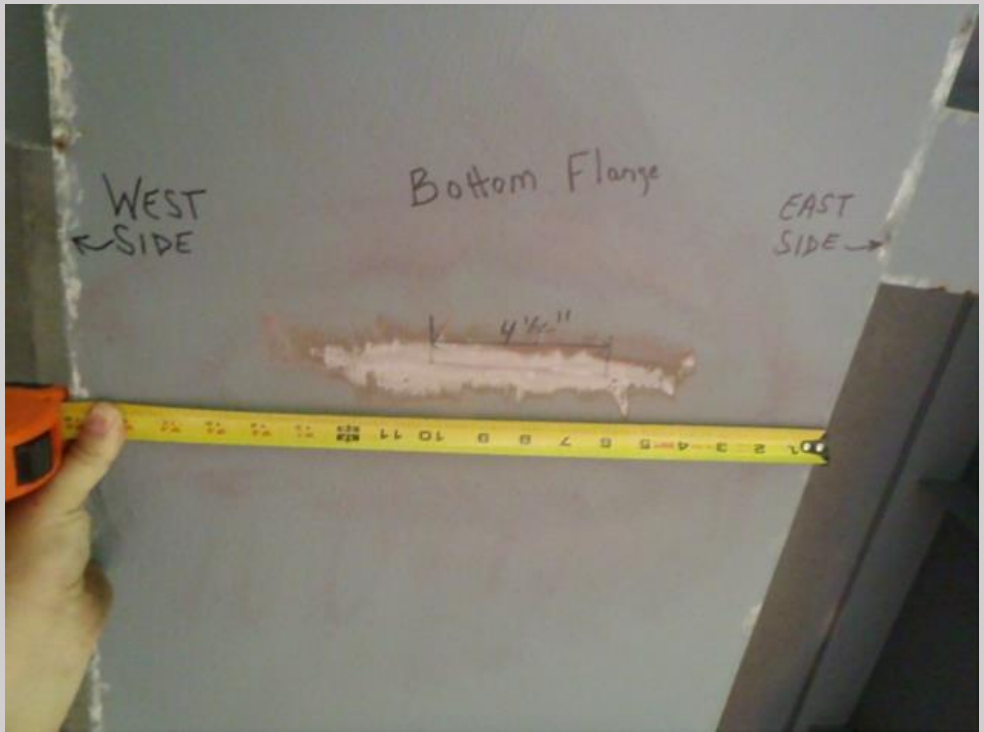


Longitudinal stiffener terminations in areas of the web subject to tension are vulnerable to constraint-induced fracture if there is insufficient weld clearance.

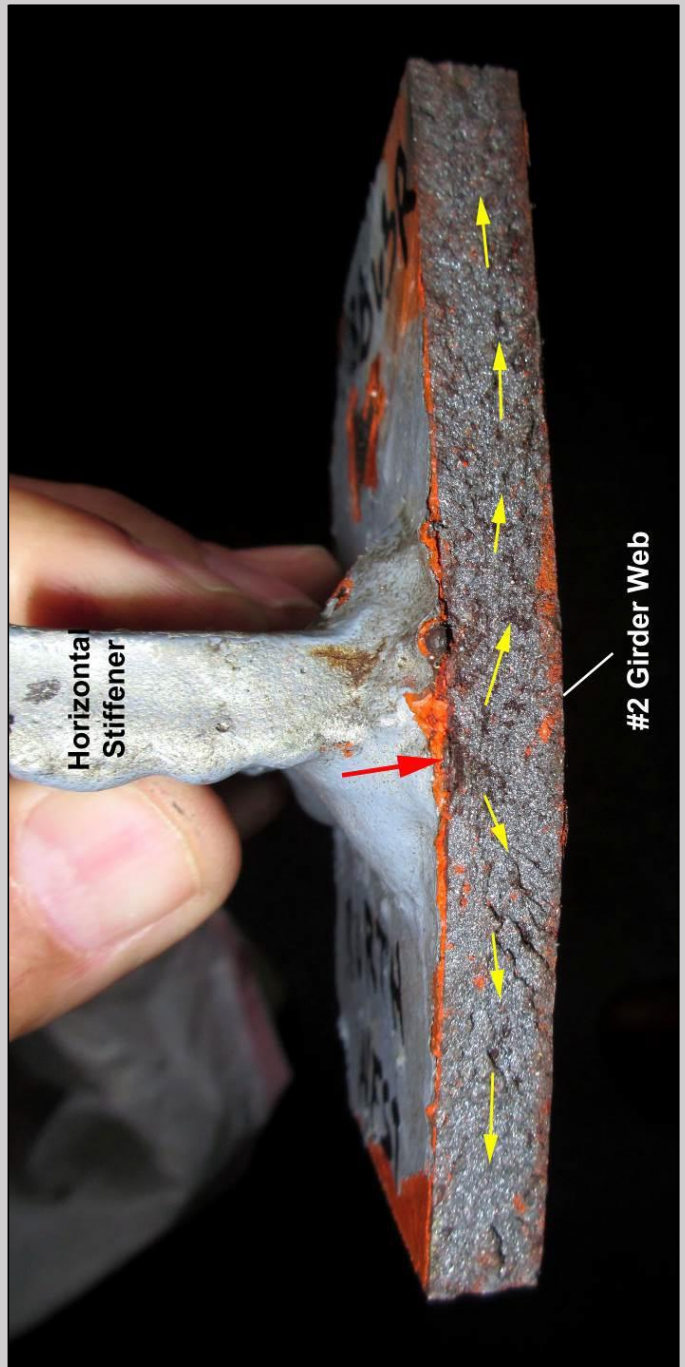


Longitudinal stiffener terminations with ¼" or greater clear gap between welds present a low risk for constraint-induced fracture.

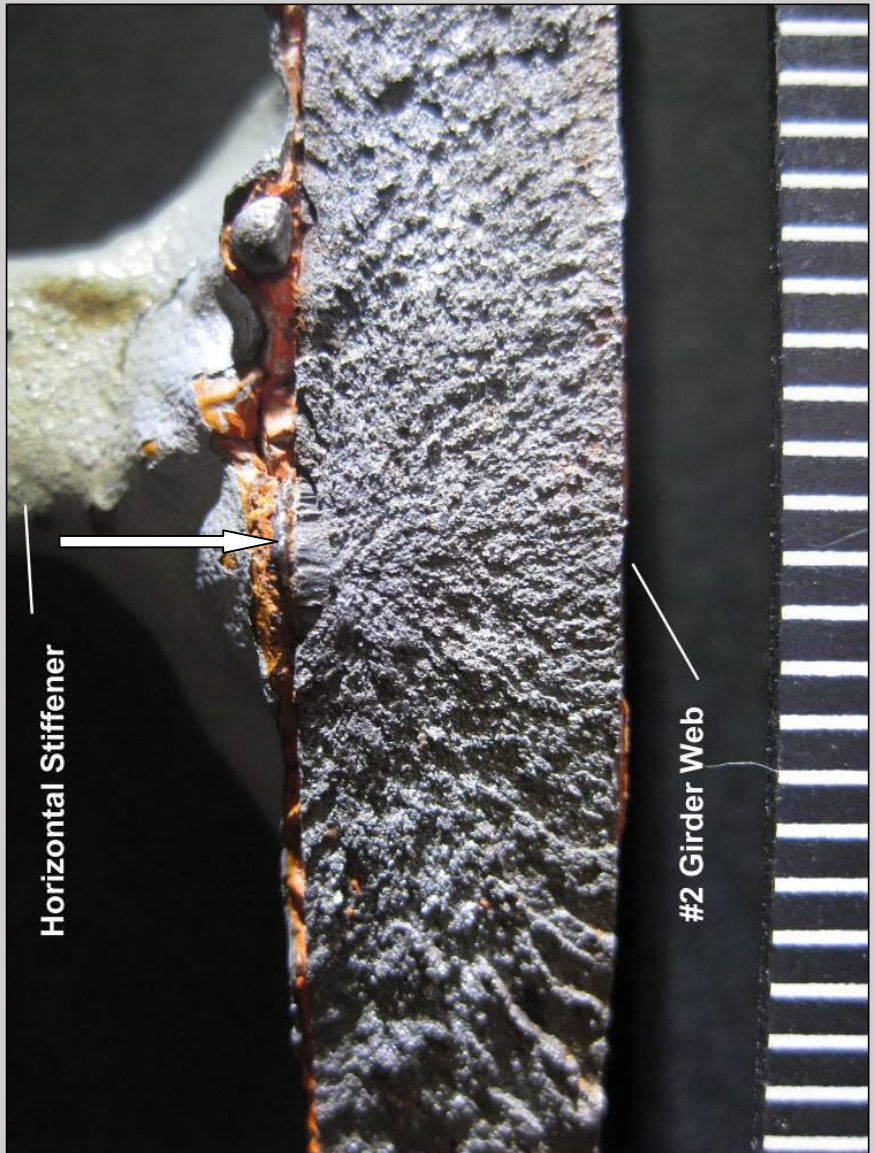
Cracking in N.B. Bridge June 2014

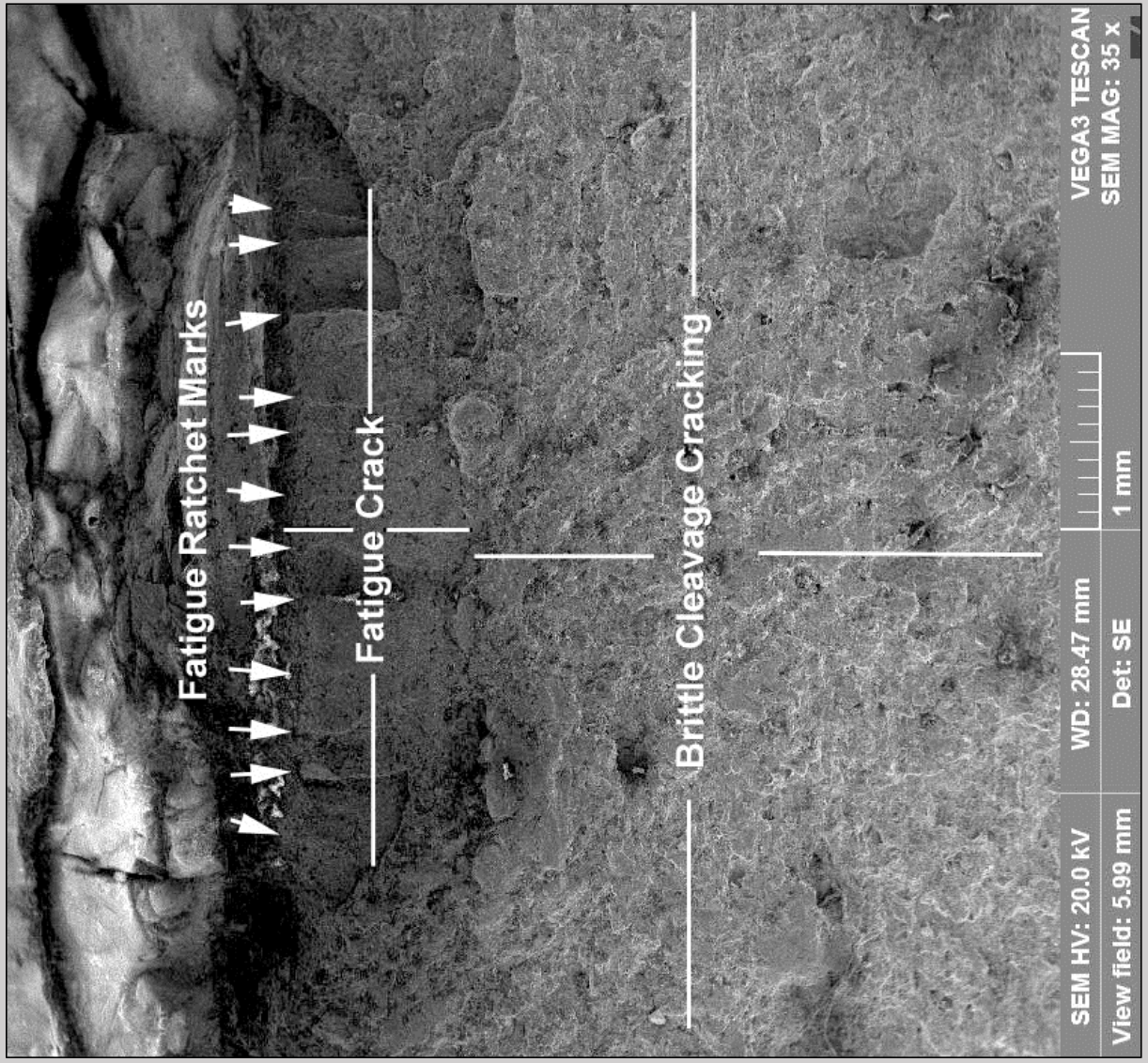


Fracture Surface Analysis

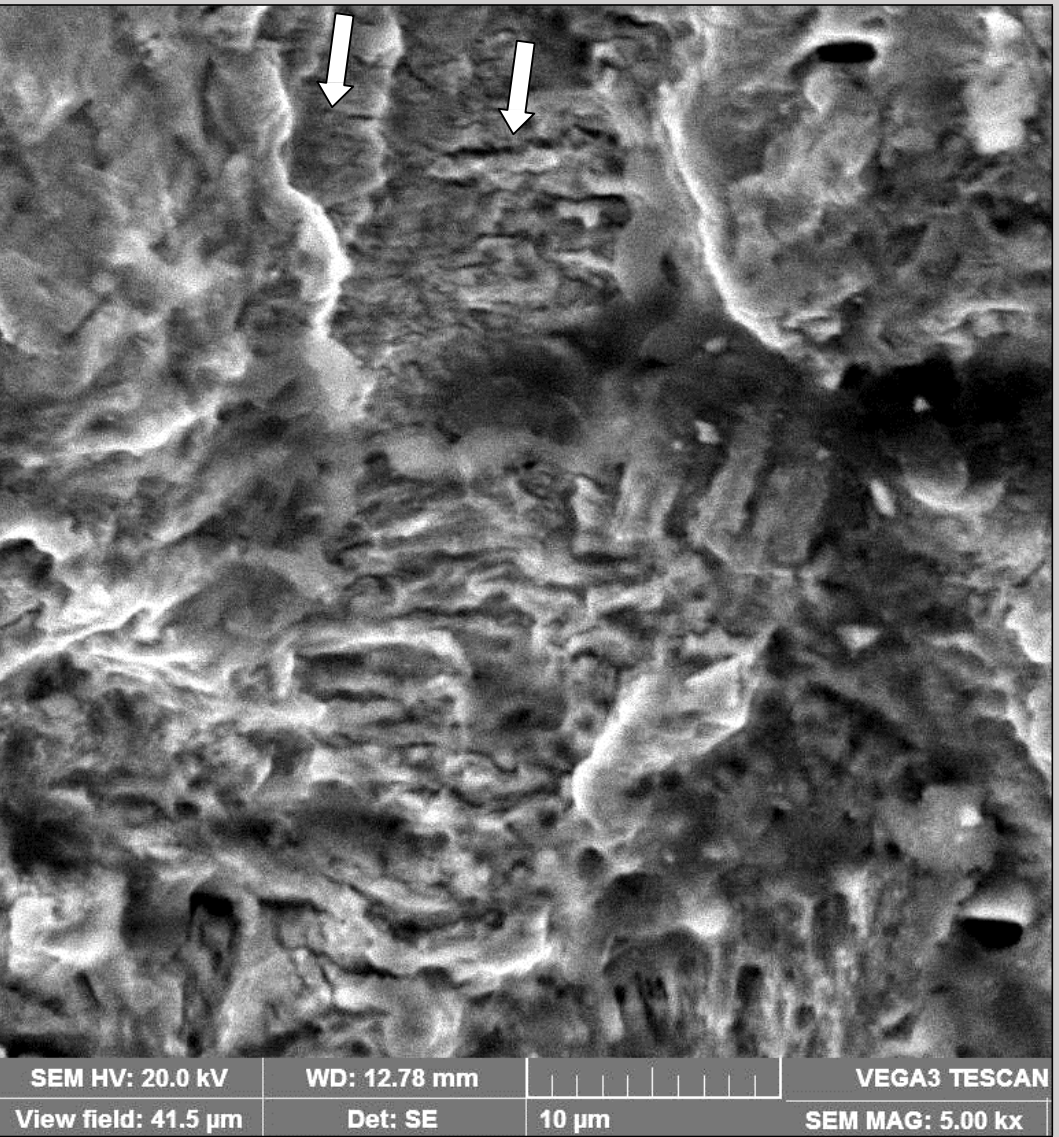


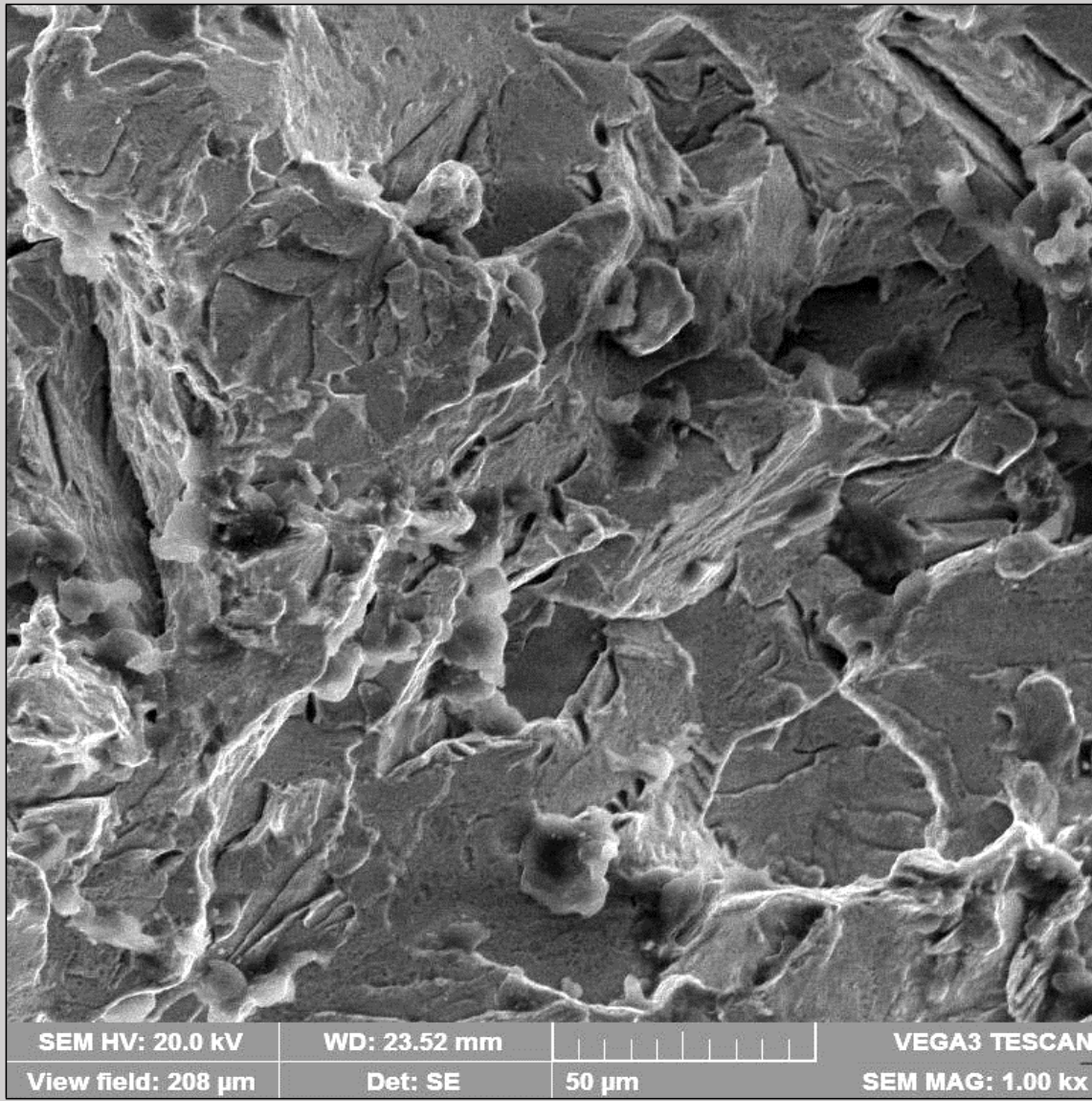
Fracture Origin





Fracture Details





Investigation findings

- Girder experienced unstable brittle fracture in the web
  - Unstable fracture initiated by a 5mm x 1 mm fatigue crack
- Web base metal was found to:
  - Meet the physical & mechanical properties met the ASTM A36 “Carbon Structural Steel” Standard
  - Satisfy the requirements for Charpy V-Notch toughness for Zone II (non-fracture critical structures)
    - 15 ft-lb. @ 40^{o} F
- Fracture mechanism - possible CIF/fatigue interaction causing unstable fracture
  - Small fatigue crack at horizontal stiffener termination (Cat E fatigue detail)
  - Interaction with CIF detail (vertical & horizontal fillet welds for lateral bracing attachment in girder webs)
- At time of repair, the crack in the lower flange and was growing by fatigue

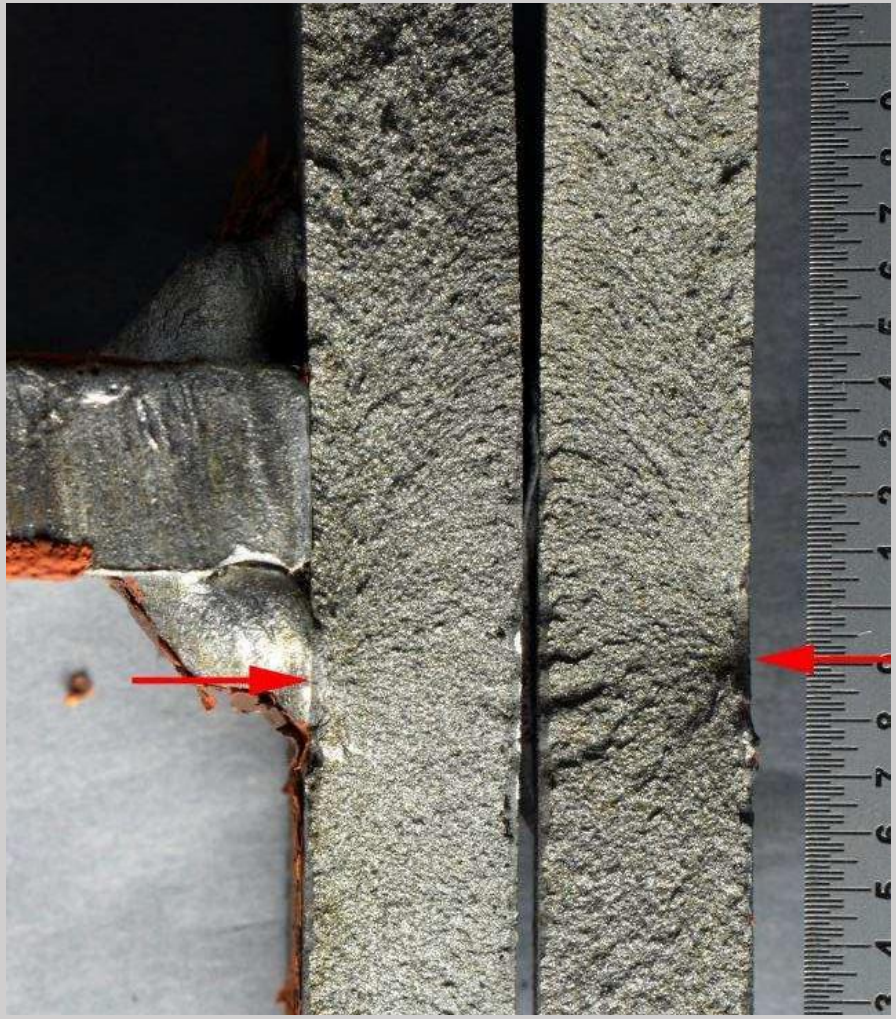
Bush Road over I-24 Trigg County KY

- Built in 1978
- Continuous welded steel girder structure with 4 girder lines
  - 97’-121’-97’ spans
  - 60” deep girders
- Made from ASTM A36 steel
- Traffic count over bridge ??
- Twin cracks were detected a on fascia girder in 2016
  - Negative moment area at pier

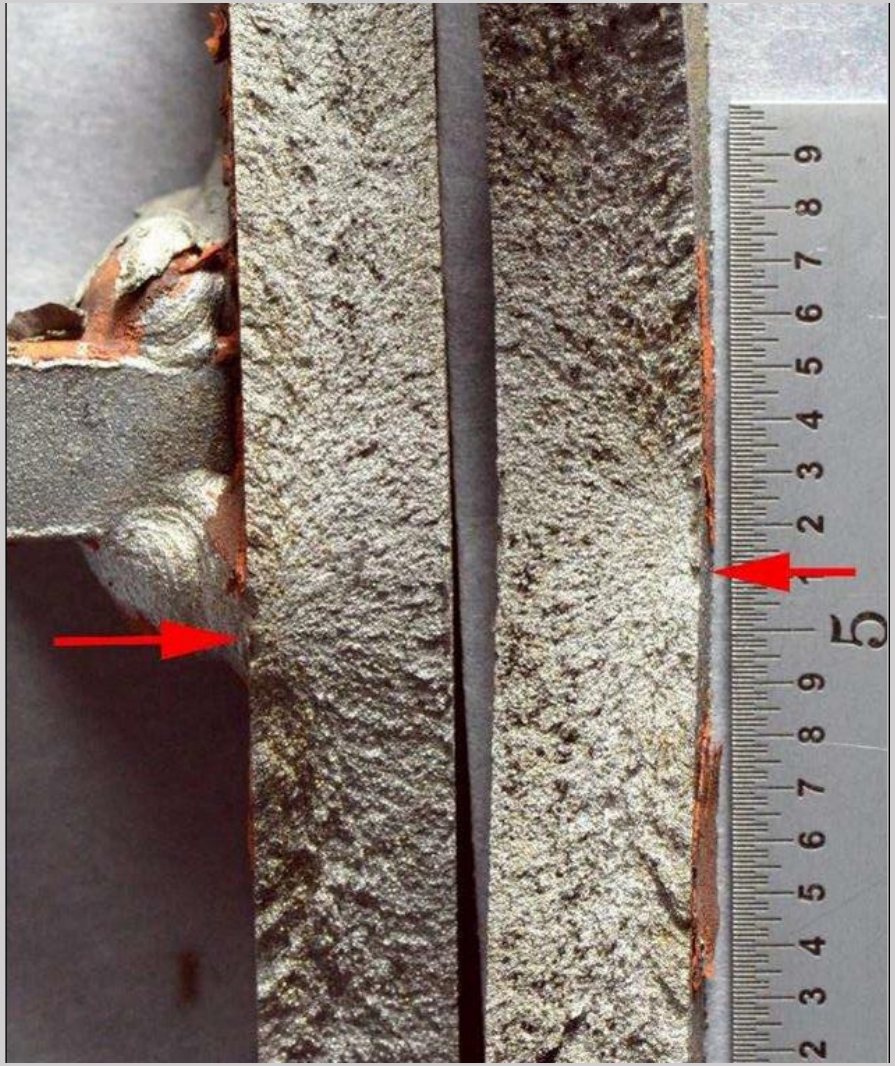
Bush Road Bridge & Fracture Location

Fractures in Horizontal Stiffener

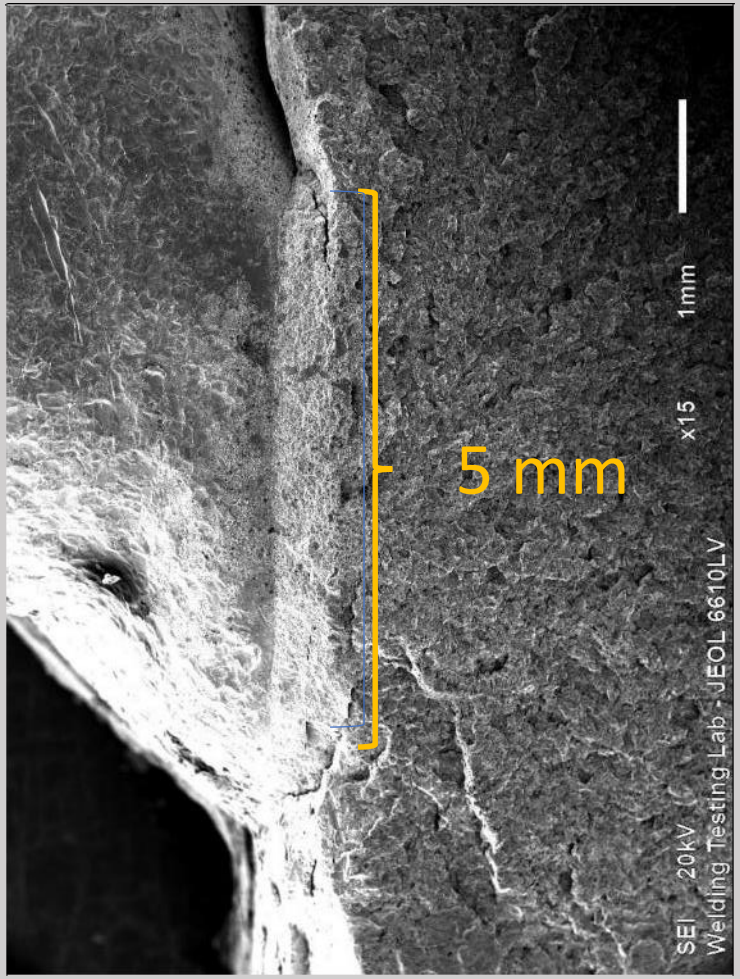
Upper Stiffener



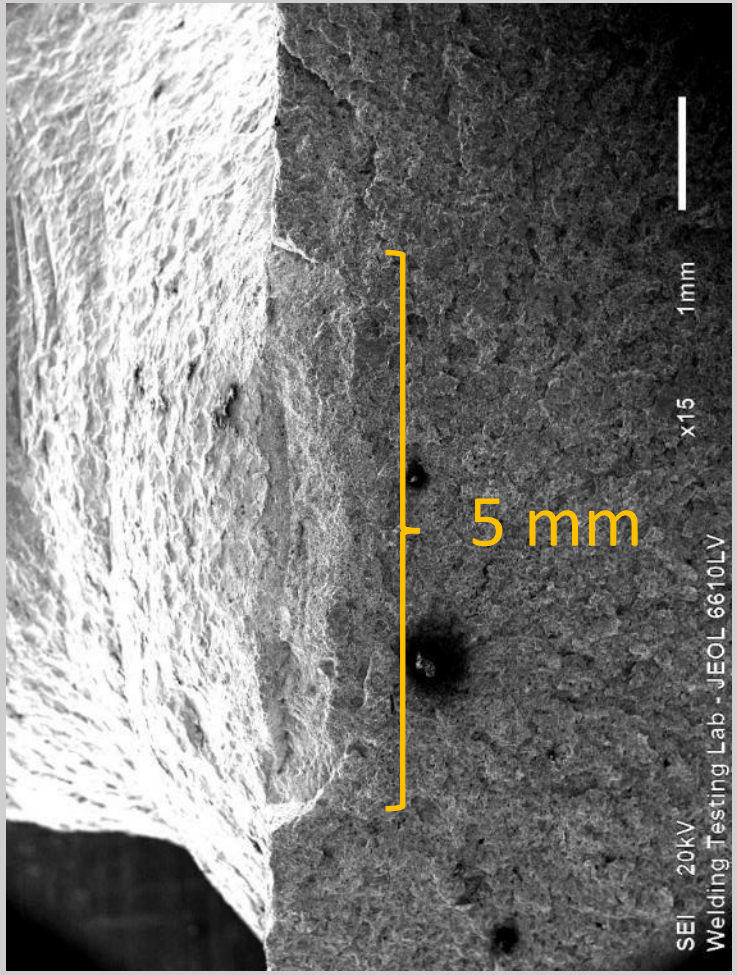
Lower Stiffener



SEM Pictures of Fatigue Crack Surfaces



Upper Horizontal Stiffener



Lower Horizontal Stiffener

Lateral Displacement of Web Fracture Surfaces

Investigation findings

- Girder experienced unstable brittle fractures in the web
  - Fractures were initiated by two 5mm x 1 mm fatigue cracks
- Web base metal was found to:
  - Meet the physical & mechanical properties met the ASTM A36 “Carbon Structural Steel” Standard
  - Satisfy the requirements for Charpy V-Notch toughness for Zone II (non-fracture critical structures)
    - 15 ft-lb. @ 40^{o} F
- Category E fatigue details at horizontal stiffener termini
  - No constraint present
- Fractures caused by low-cycle fatigue
  - Due to periodic heavy farm-to-grain elevator farm loads
  - Girder presumed to be highly stressed at time of failure

KY 259 over Rough River

- Built in 1960
- Continuous welded steel girder structure with 4 girder lines
  - 120’-170’-120’ spans
  - 78” deep girders (webs)
- Made from ASTM A373 steel
- Traffic count over bridge 1,800 vehicles
  - 6.6 percent trucks
- 2018 fracture on interior girder
  - Found by boater

Girder Fracture

- Girder #3
  - 14’ from C.L of 170’ span
  - Located in lower flange weld
    - 1-1/8” to 1-3/8” thick transition
- Fracture
  - Lower flange 100%
  - Web 100%
  - Upper flange (~ 5% + arrest)

Crack Surface Observation

Thumbnail Crack Feature

- Located at flange transition butt-weld adjacent to web-to-flange welds
- Appears to be semi-circular or elliptical
  - From ruled scale in picture, the feature appears to be ≈ 3/ 4” wide x ≈ 3/8” deep
- Surface texture doesn’t match balance of the fracture surface
  - Smooth vs. granular & irregular
  - Possible concentric “beach marks” indicating a fatigue crack

AASHTO S-N Diagram for Steel Bridge Details

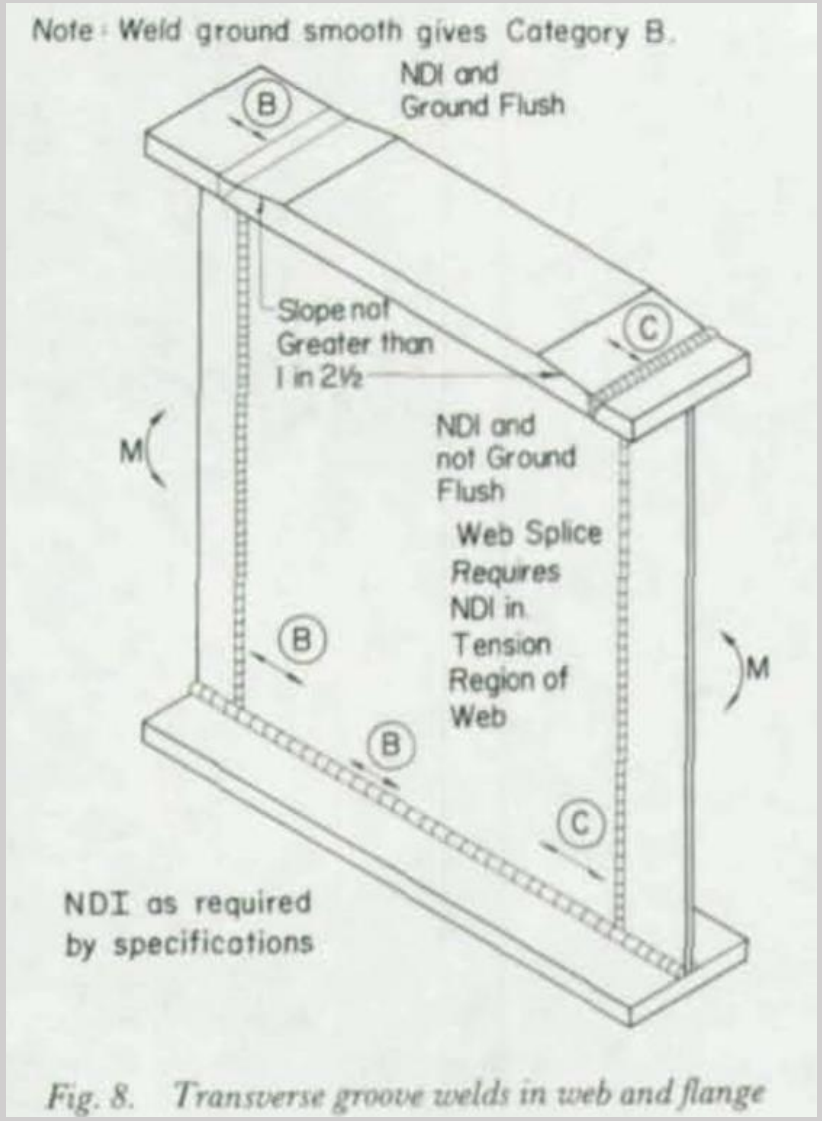
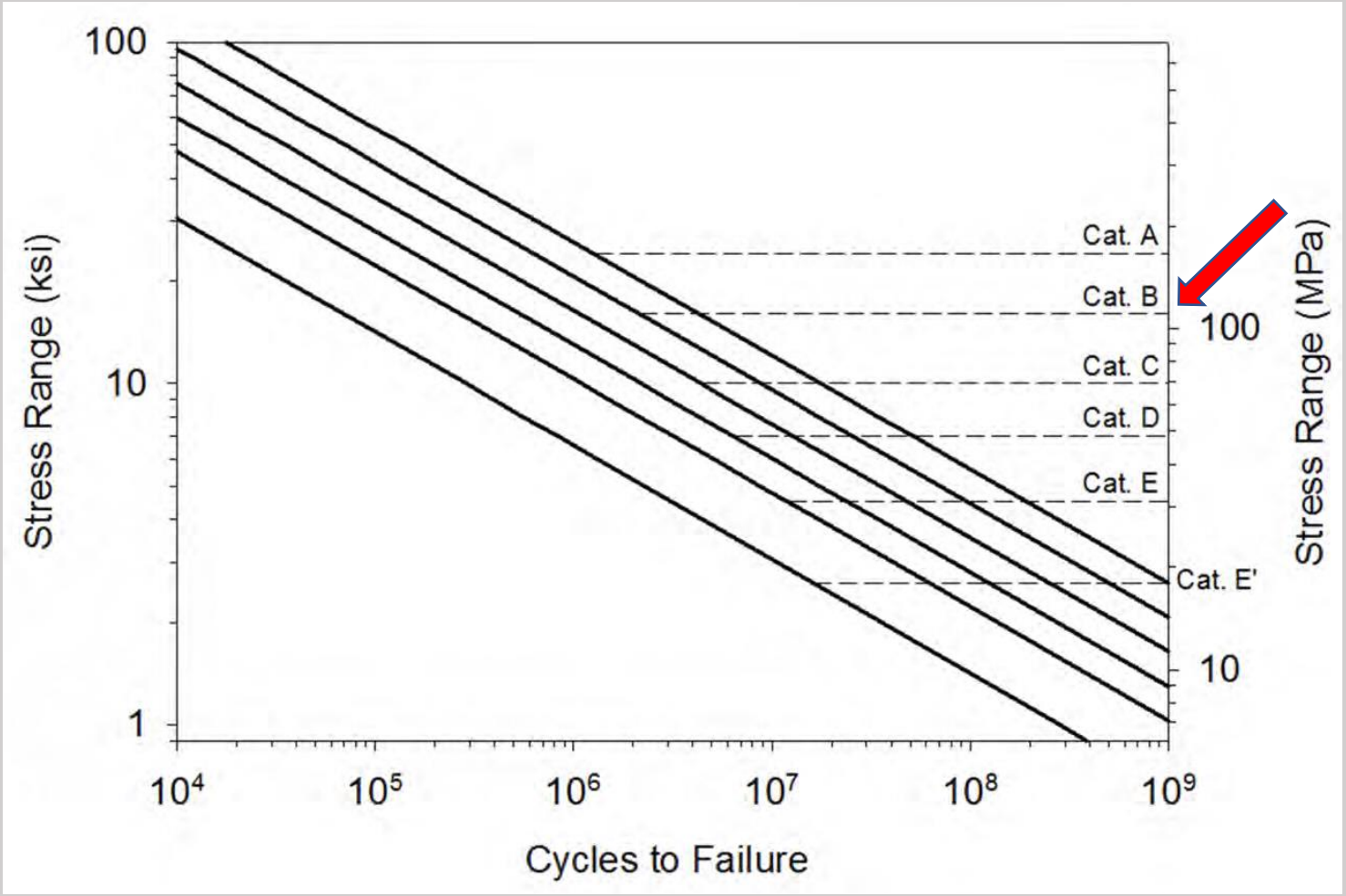


Fig. 8. Transverse groove welds in web and flange



Calculation of Initial Defect Size

(1) $K_{Imax} = 1.12 M_k \sigma (\pi \alpha)^{0.5}$

(2) $da/dN = 3.6 \times 10^{-10} (\Delta K_I)^3$

(3) $N = 1/\Delta\sigma\ (3.6 \times 10^{-10})\ [(1.12)\ (\pi)^{0.5}]^3 (-\frac{1}{2}\ \alpha_i^{-0.5} + \frac{1}{2}\ \alpha_f^{-0.5})$

Solving for α_i = initial crack depth where:

$N = 1.56 \times 10^6$ stress cycles

α_f = final crack size= 0.375”

Case 1 $S_r = \Delta\sigma = 3.0$ ksi

$\alpha_i \approx 0.35$”

Case 2 $S_r = \Delta\sigma = 6.0$ ksi

$\alpha_i \approx 0.23$”

Investigation findings

- Girder experienced unstable brittle fracture
  - Initiated at a defect in the lower flange butt weld or flange-to-web fillet weld
- Web base metal was found to:
  - Meet the physical & mechanical properties met the ASTM A373 “Structural Steel for Welding” Standard
  - Satisfy the requirements for Charpy V-Notch toughness for Zone II (non-fracture critical structures)
    - 15 ft-lb. @ 40^{o} F
- Number of stress cycles and equivalent stress range too low to cause fatigue initiation at weld details
  - Possible weld defect missed by QC & QA (shop NDE)
  - Gradual crack growth by fatigue to critical size for unstable brittle fracture

Differing Factors in the Bridge Fractures

- Traffic volumes
- Loading
- Cause of fractures
  - CIF as a contributing factor only on I-75 bridge
  - Weld details (Category E) only in two cases
  - Weld defect only in one case

Common Factors in the Bridge Fractures

- Bridge type - continuous steel girder
  - Redundant 3-spans with 4-girder lines
- Welded construction
- Service lives (40-60 years)
- Use of carbon structural steels
  - All met ASTM & AASHTO requirements
    - Similar to Hoan Bridge
- Small crack sizes able to initiate unstable brittle fractures

Implications

- The critical crack sizes in carbon steel bridge members were too small to be reliably detected visually
  - Even using arms-length inspections
    - NDE is needed
  - The only current safeguard using visual inspection is structural redundancy
- Girder fractures incur costs
  - Reactive maintenance
  - Motorist delays
- Potential risk of collapse
- Other actions are needed to prevent further incidents
  - Bridges with FCMs, fatigue-prone and/or CIF details are primary concerns

Proactive Steps to Address the Situation

- 859 steel Cabinet-owned bridges were built between 1955 and 2000
  - Average age – 46 years
  - Possible welded construction (begun in 1955)
  - Primarily made from carbon steels - ASTM A7, A373 & A36 (ended in 2000)
- KTC is identifying bridges with CIF details for the Cabinet
  - Past work by KTC in identifying QT and problematic HSLA steels
- Arm-length inspections could prove inadequate in some cases
  - That situation needs to be addressed
- Anticipate future work to identify fatigue-prone weld details
  - AASHTO fatigue categories E, E’ and F
- Hidden weld defects?
- Some prioritization will be needed to focus future work

The End

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