LPI, Inc. Consulting Engineers

Advanced Analysis & Fitness for Service
Failure & Materials Evaluation
Nondestructive Engineering

Root Cause Assessment of Fractured Girder Flanges

Transbay (Salesforce) Transit Center, San Francisco

TJPA Board
March 14, 2019

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CEO

Timeline

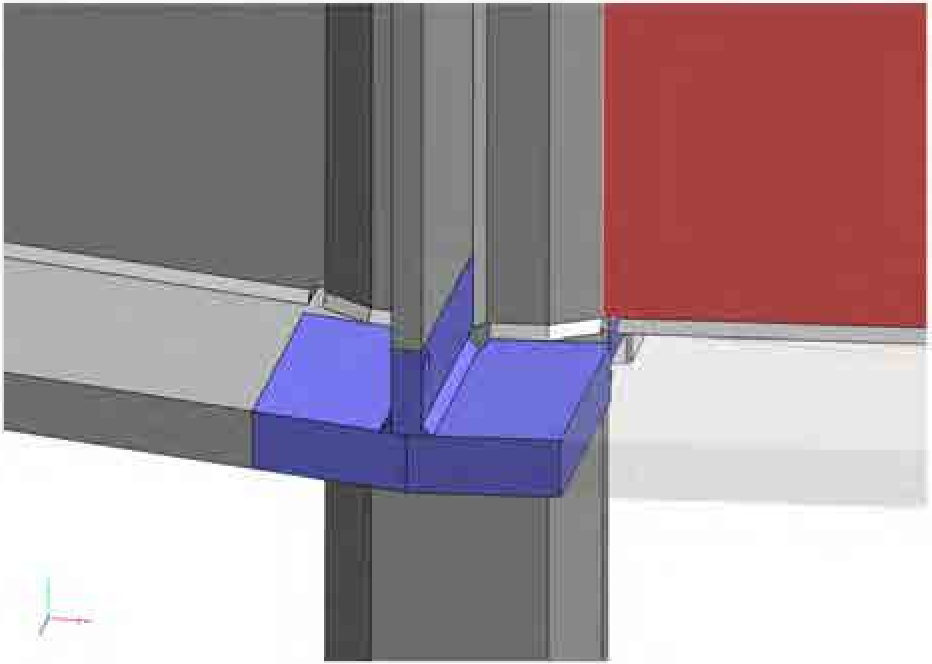
- **August 12, 2018:** Transbay Transit Center opens to the public
- **September 25, 2018**: Cracks found in two girder flanges
- **October 1, 2018**: LPI retained to perform root cause assessment of girder fractures and the removal and testing of the fractured sections
- **October 23 through 29, 2018**: Girder samples removed by IPM under direction of TT and LPI - samples shipped to LPI's New York facilities
- **November 14-15, 2018**: Joint laboratory examination at LPI with all interested parties
- **December 2018**: Metallurgical and mechanical testing completed
- **March 2019**: Girder fracture assessment completed

Fremont and First Street Girders During Construction

Fractured Fremont St Girder

Girder Sample Removal

Typical Fremont Street Girder Sample



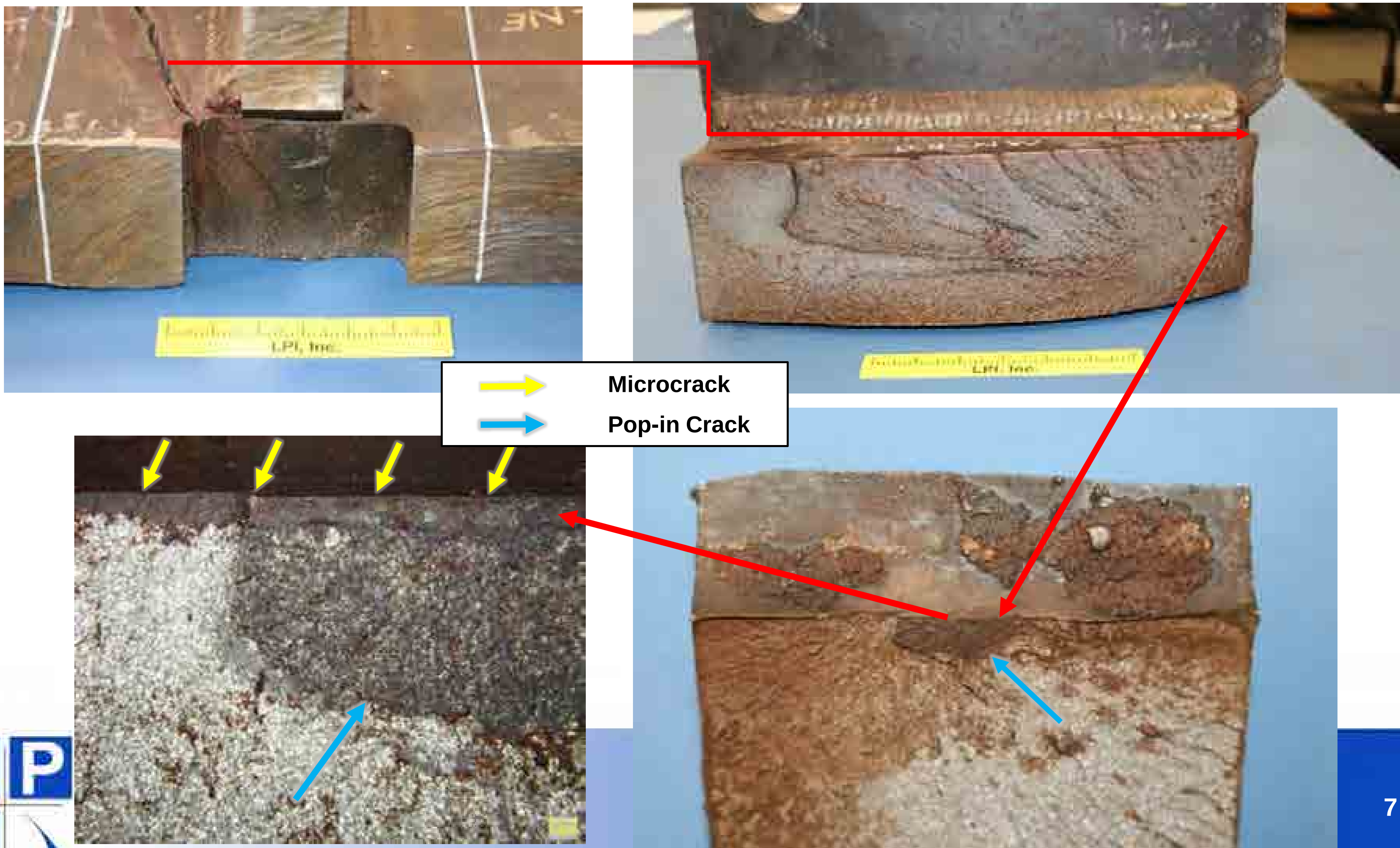
- Fremont St, South girder, E.6-SE-SW (fractured)

Fracture Surface Examination

Fracture Origin in the Weld Access Hole of Girder Sample E.6-SW

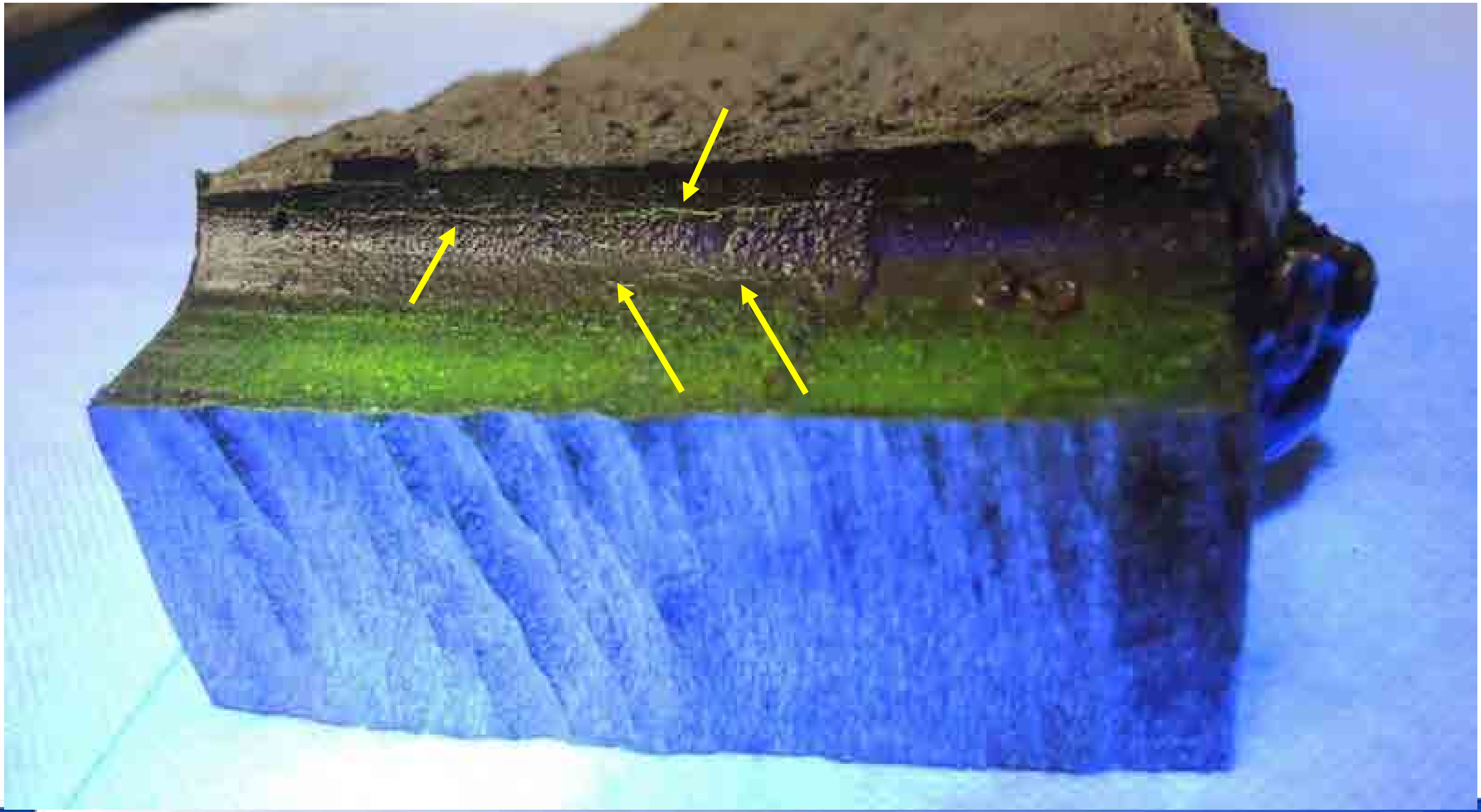
Fracture Surface Examination

Fracture Origin in the Weld Access Hole of Girder D.4-NW



Fluorescent Magnetic Particle Testing

Microcracks in the D.4-SW weld access hole radius

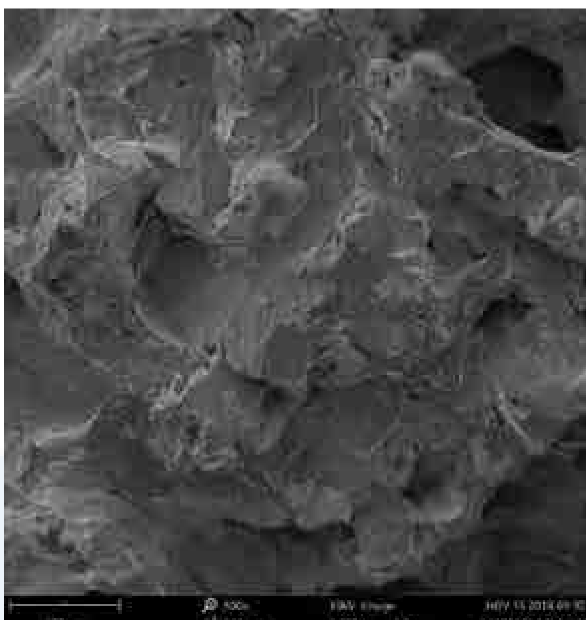


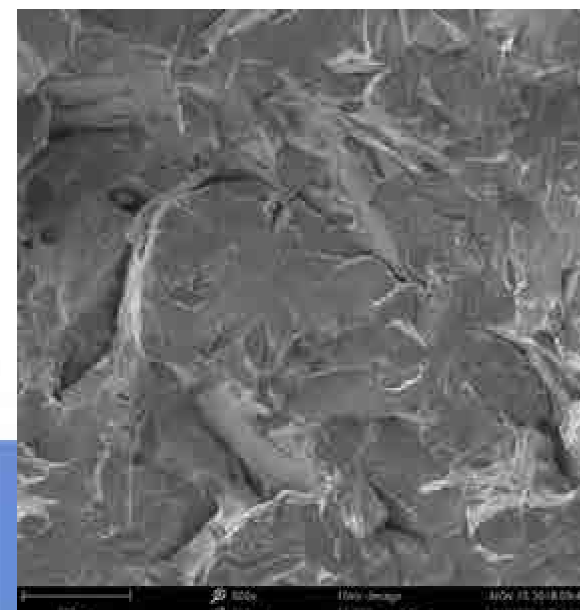
Metallography

Metallographic cross-section specimens through weld access hole radii revealed a brittle martensitic surface layer from thermal cutting containing multiple small cracks.

Scanning Electron Microscopy (SEM)

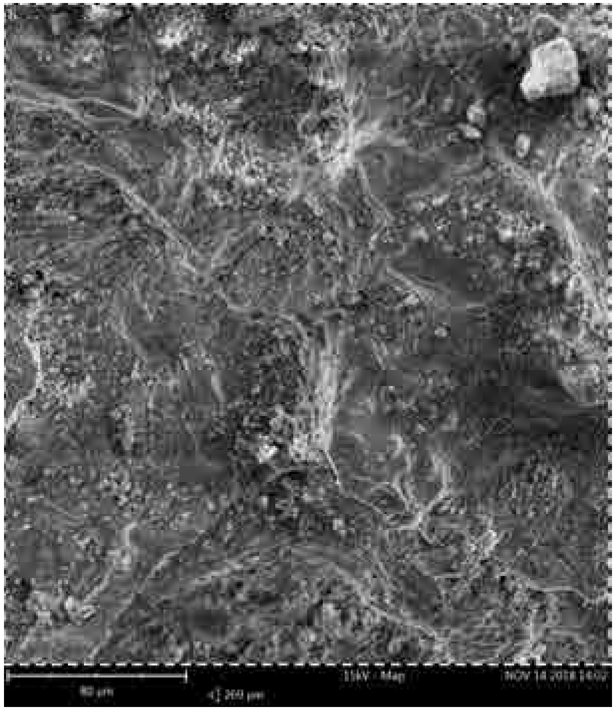
Initiation sites (pre-existing Microcracks and Pop-in cracks) for all girder fractures exhibited tenacious dark oxide (elevated temperature) with underlying low-energy (brittle) cleavage fracture. The remainder of the fracture surfaces also exhibited a cleavage fracture morphology.



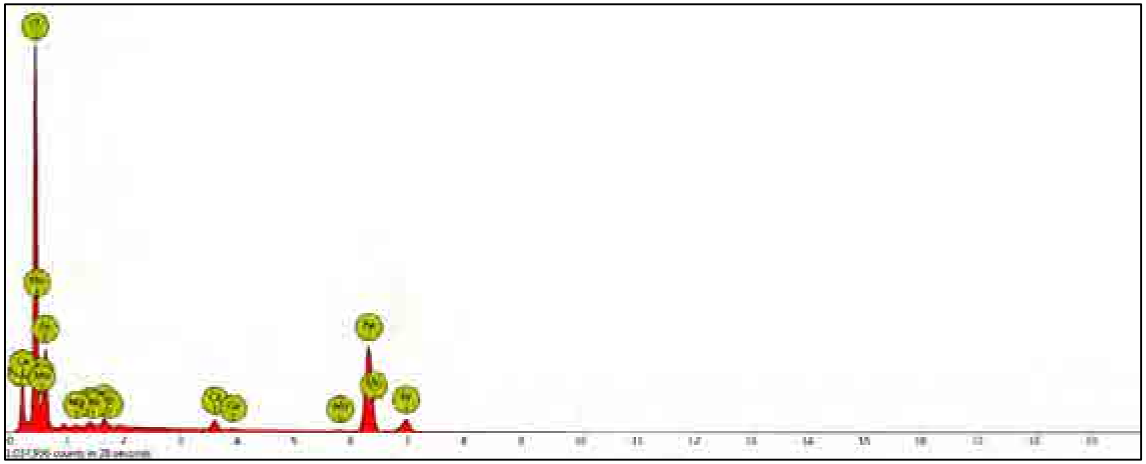


Crack Surface Compositional Analyses (EDS)

E.6-SW: EDS of surface oxide at the origin



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
8	O	Oxygen	74.92	48.85
26	Fe	Iron	20.61	46.91
20	Ca	Calcium	0.83	1.36
6	C	Carbon	2.25	1.10
14	Si	Silicon	0.49	0.56
25	Mn	Manganese	0.23	0.51
13	Al	Aluminium	0.42	0.47
12	Mg	Magnesium	0.24	0.24

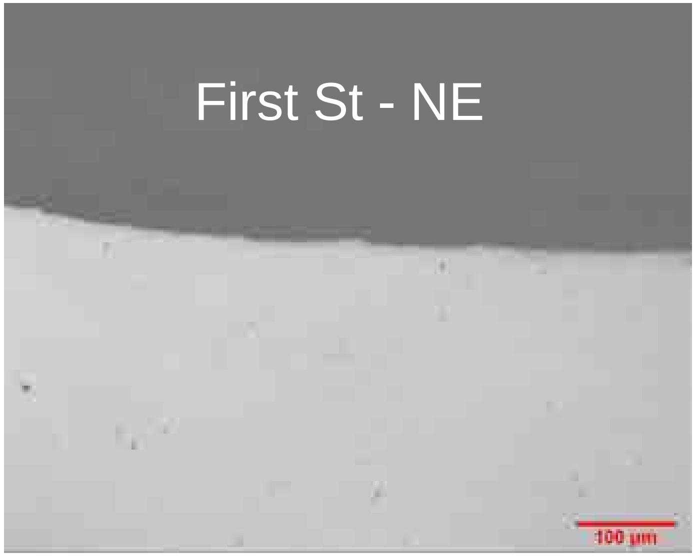


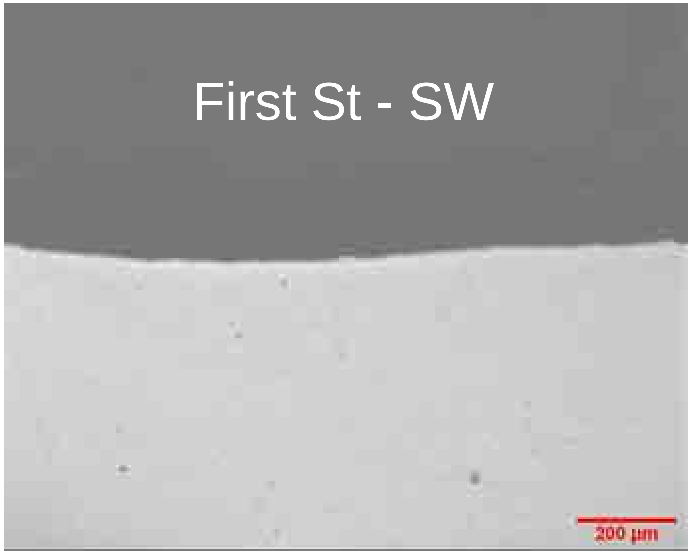
All flange crack surfaces exhibited tenacious dark oxide (high temperature) with underlying low-energy (brittle) cleavage fracture as can only develop at elevated temperature during thermal cutting and CJP butt welding of the flange plates

First St Core Sample Examination

Access Hole Surfaces Were Ground Following the Fremont Street Fractures

First St Core Sample Examination

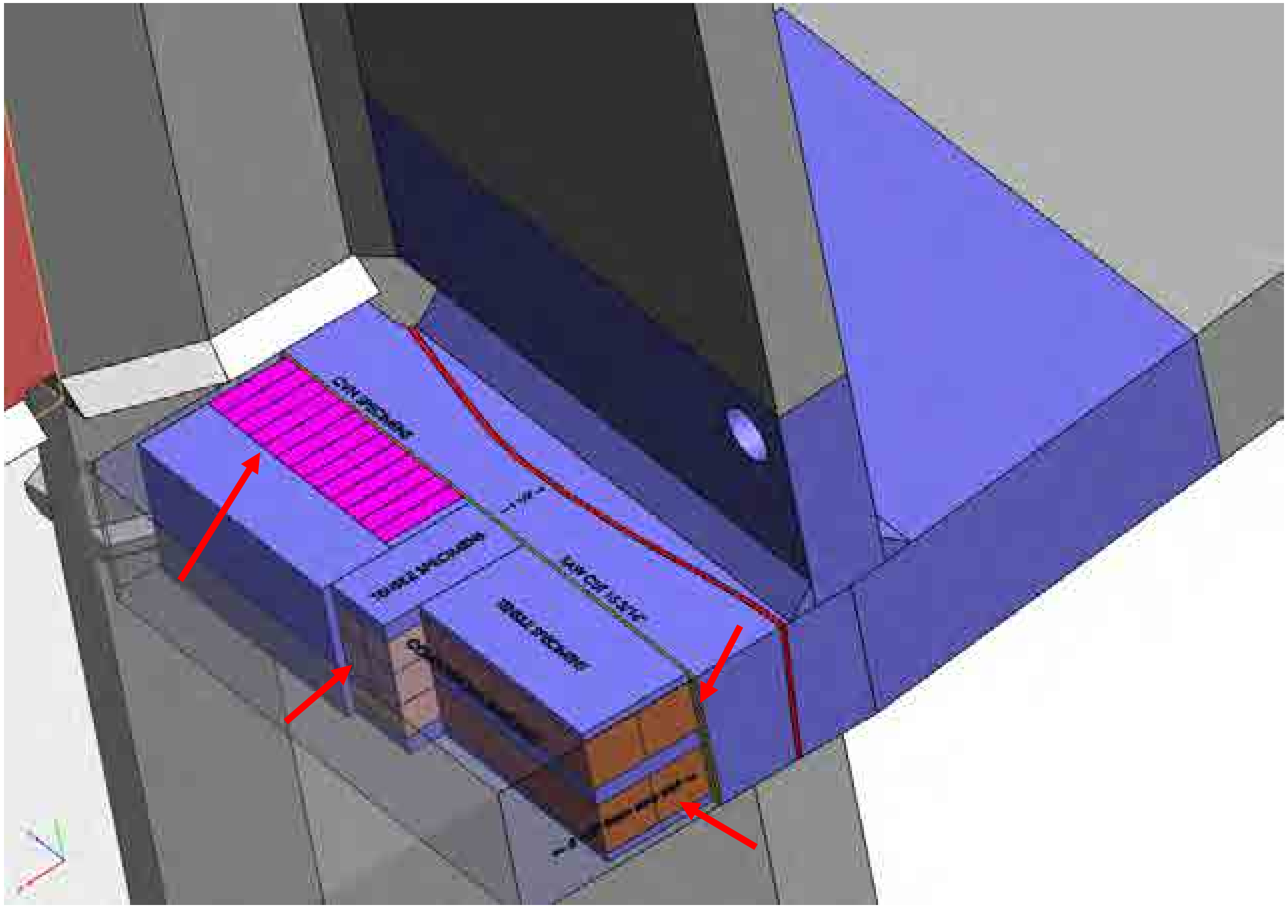




- No Microcracks or Pop-in cracks were observed in any of the cores removed from the First Street flange weld access holes
- However, the absence of Microcracks at First Street may be attributable to the grinding performed on the access hole surfaces following the Fremont Street fractures
- The weld access holes at First Street were fabricated differently from those at Fremont St, that is, they were cut after the flange CJP butt weld was completed
- The Fremont Street access holes were made prior to welding of the flange CJP butt weld

LPI

Tensile and CVN Toughness Test Specimens



Fremont Street girder sample tensile and CVN specimen removal locations and orientation

Tensile Test Results

Base Metal:

Tensile Test Summary

	Yield Strength (ksi)	Ultimate Tensile Strength (ksi)
Avg	**60.8**	**87.1**
Std.Dev	2.3	1.9
Min	59.0	85.0
Max	75.0	95.0
No. Tests	68	

Weld Metal:

Hardness to UTS Conversion

	Ultimate Tensile Strength (ksi)
Avg	**89.0**
Std. Dev	2.92
Min	86.0
Max	93.0
No. Tests	12

Yield Strength

Lincoln's E7018 (AWS A5.1)

	Yield Strength[2] MPa (ksi)	Tensile Strength MPa (ksi)
Requirements AWS E7018-1 H4R	400 (58) min.	490 (70) min.
Typical Results[3] As-Welded	440-530 (64-77)	540-630 (79-91)
Stress Relieved 48 hrs @ 620°C (1150°F)	410-470 (59-68)	500-560 (72-81)

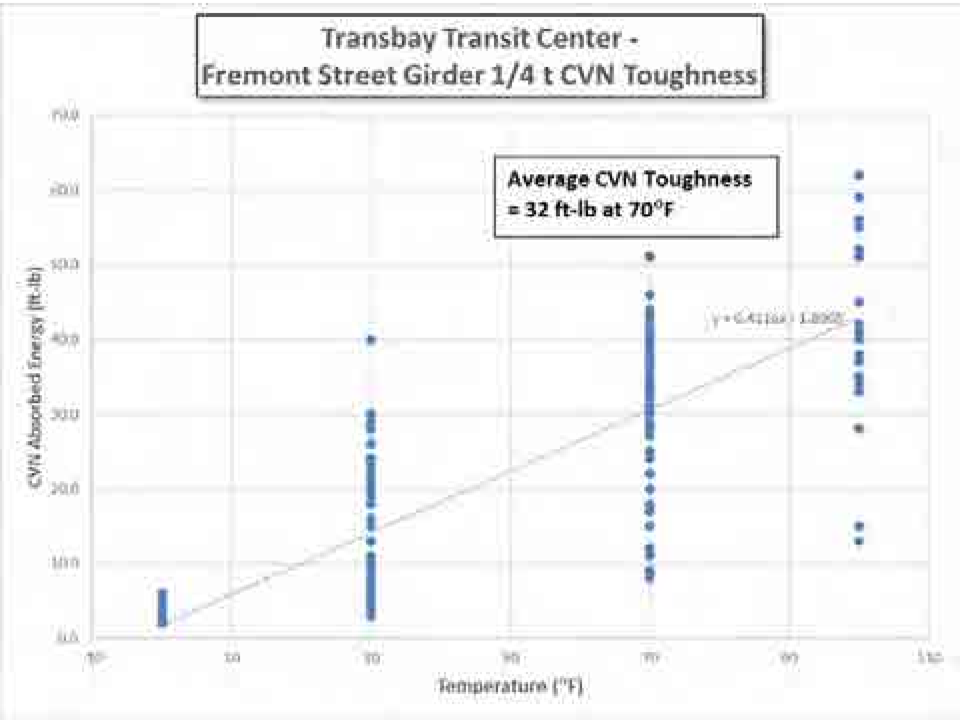
Lincoln's XLH-70 (AWS A5.20)

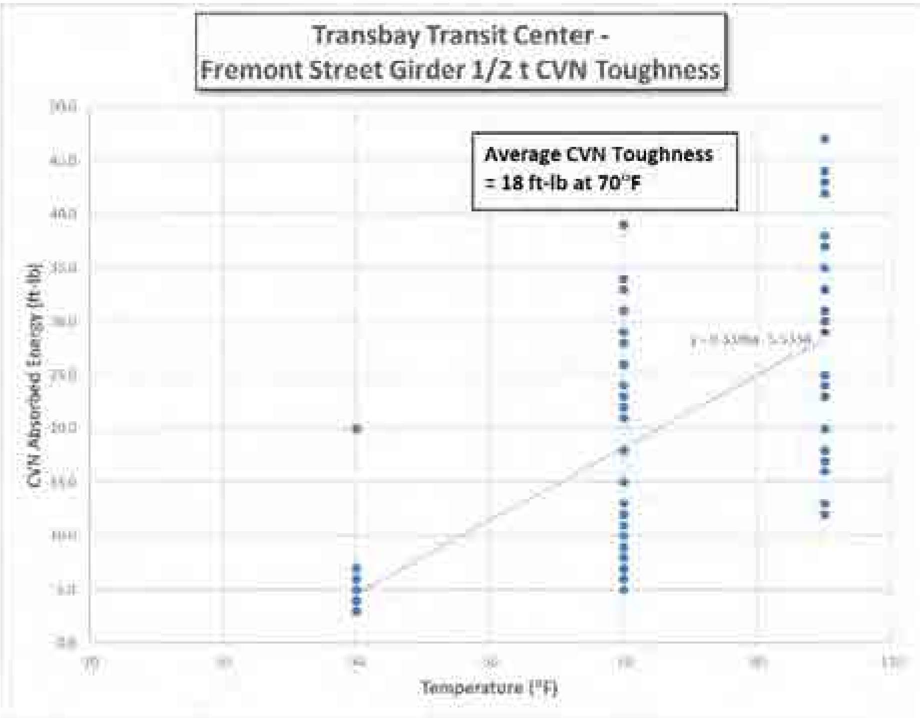
Lincoln's L-56 (AWS A5.17)

Yield Strength = **70.5** ksi

- ➢ **Yield and tensile strength levels are typical of ASTM A572, Gr. 50, and are considered typical of common industry levels**
- ➢ **Weld metal hardness levels are considered normal and typical of 70 ksi filler metals**

Fremont St CVN Toughness Results





- Toughness measured by CVN testing is an indirect assessment of a material's resistance to brittle, low-energy fracture in the presence of a crack-like flaw such as the observed Pop-in cracks in the Fremont Street girder flange
- CVN toughness, as measured in absorbed energy (ft-lb), is considered to be reasonable at a level of 20 ft-lb and higher

Fremont St CVN Toughness Results

- Two large-scale industry studies determined average (mean) ¼-t CVN toughness levels for A572, 4-in. thick, plate to be approximately 46 ft-lb (1989) and 52 ft-lb (2003) at 70°F
- Although the Fremont Street girder flange plates met the AISC requirement of 20 ft-lb at 70°F at ¼-t, the girder plates exhibited CVN toughness levels significantly lower than typical industry levels
- Additionally, the ½-t (mid-thickness) toughness is dramatically lower than industry averages at 70°F
- The average flange CVN toughness at 50°F, the temperature close to the temperature at which the fractures occurred, was only 11 ft-lb and the lower bound toughness was less than 5 ft-lb

	¼-t CVN (ft-lb) 70°F	½-t CVN (ft-lb) 70°F	¼-t to ½-t Reduction
Fremont St Flange	32	18	44%
Hanger Plates	84	54	36%

Findings Based on Fracture Surface Evaluations and Material Property Testing

- The girder fractures at the Transbay Transit Center initiated from pre-existing cracks that developed during thermal cutting of the weld access hole radii and subsequent welding of the flange CJP butt welds:
  - Initially, shallow surface Microcracks developed during thermal cutting of the access holes in the highly hardenable and brittle martensitic surface layer
  - Thereafter, much larger Pop-in cracks formed due to residual stresses that developed at the access hole surfaces during CJP butt welding of the flange plates

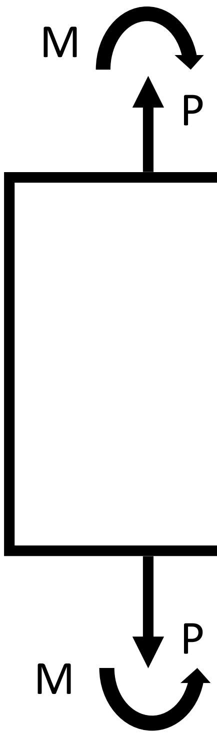
Findings Based on Fracture Surface Evaluations and Material Property Testing

- Dark, tenacious oxides were present on both the Microcrack and larger Pop-in crack surfaces, confirming both crack types formed at elevated temperatures, which only occur during fabrication
- The Pop-in fracture origins were located in the mid-thickness of the flange plates
- Abnormally low fracture toughness in the mid-thickness region of the plates (confirmed by CVN toughness testing), provided little resistance to the presence of the pre-existing Pop-in cracks, which subsequently initiated flange fracture under the combination of typical weld-induced residual and normal service-induced stresses

Fracture Analysis Overview

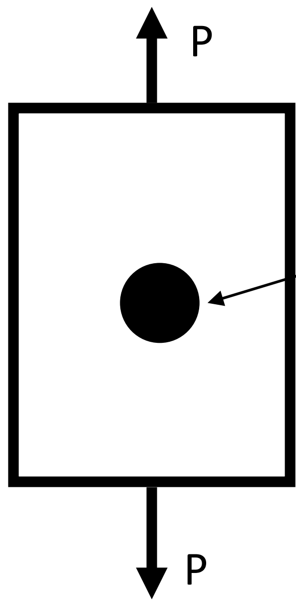
Fremont St Fracture Initiation

Stress (σ) Analysis of Plates

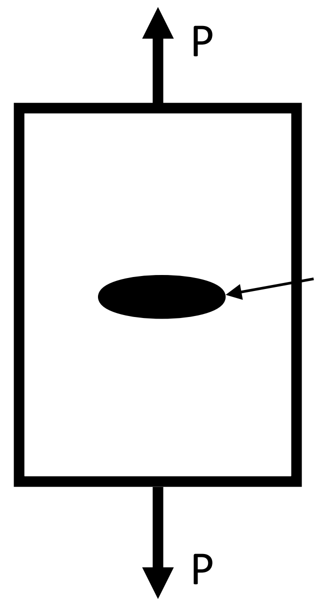


$$\sigma_m = \frac{P}{A}$$

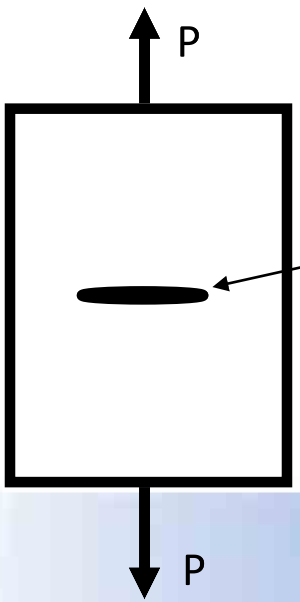
$$\sigma_b = \frac{M}{Z}$$



$$\sigma_m = \frac{3P}{A}$$



$$\sigma_m = \frac{6P}{A}$$

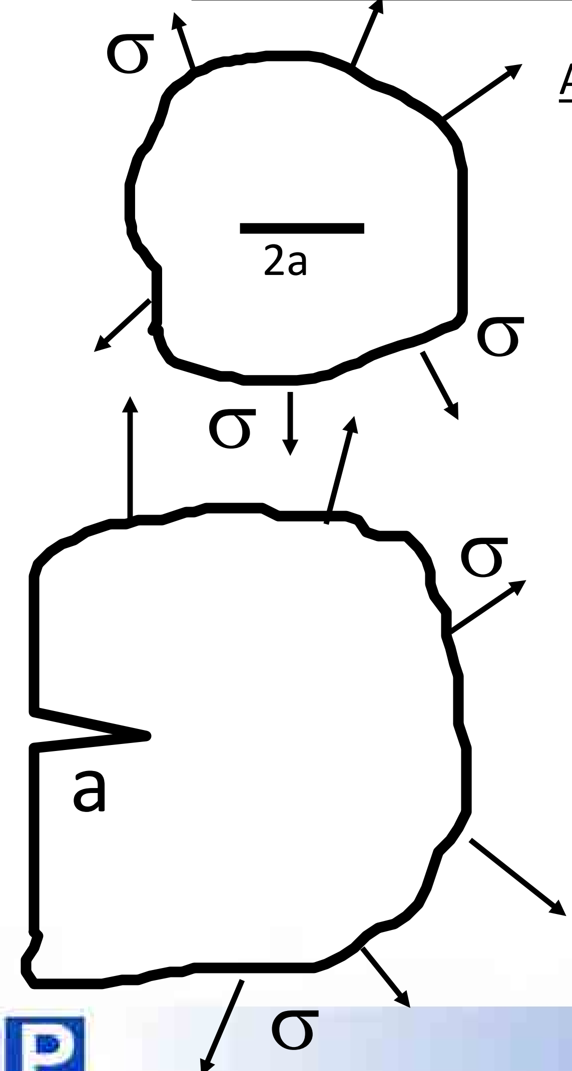


$$\sigma_m = \frac{?\,P}{A}$$

Failure occurs when the applied stress (σ_m and/or σ_b) exceeds the yield strength (σ_y) or ultimate tensile strength (σ_u) of the plate material

Fremont St Fracture Initiation

Fracture Mechanics is used to assess cracked structures



Arbitrary crack in a plate subjected to σ

$$K = \sigma \sqrt{\pi a}$$

Edge crack in a plate

$$K = 1.12 \sigma \sqrt{\pi a}$$

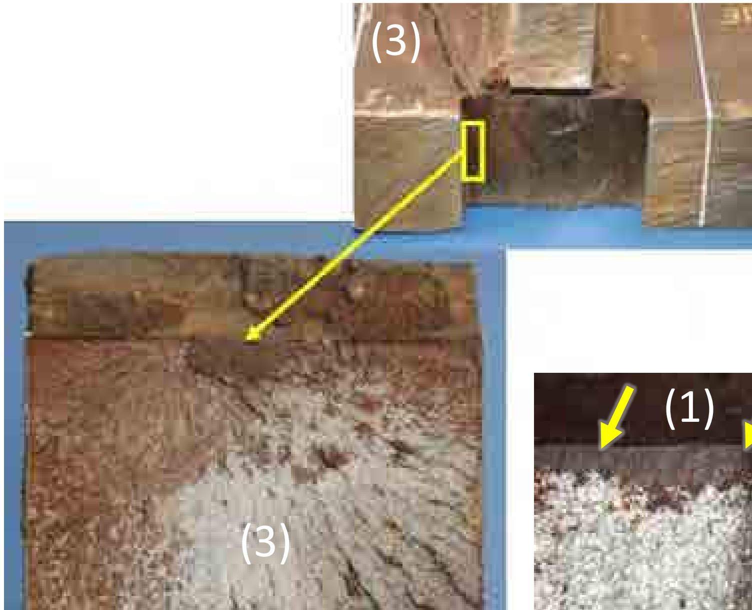
Fracture occurs when the applied stress intensity (K) exceeds the fracture toughness (K_{1c}) of the plate material

Fracture Toughness (K_{1c}) calculated from the CVN test data to be 55-60 ksi √in. at 50°F

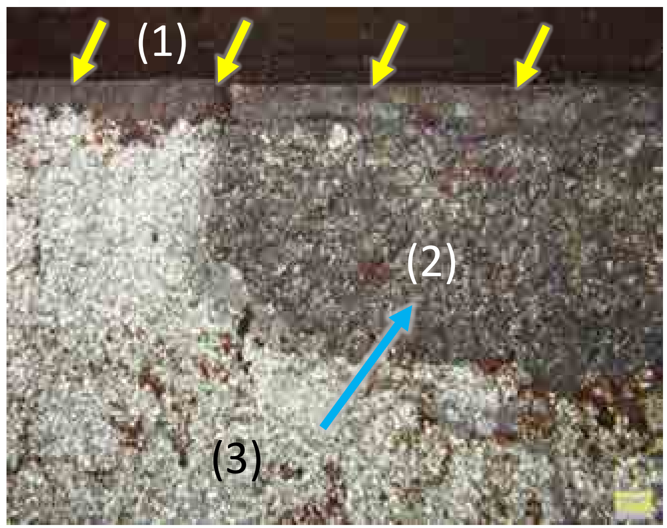
Girder Flange Fracture Sequence

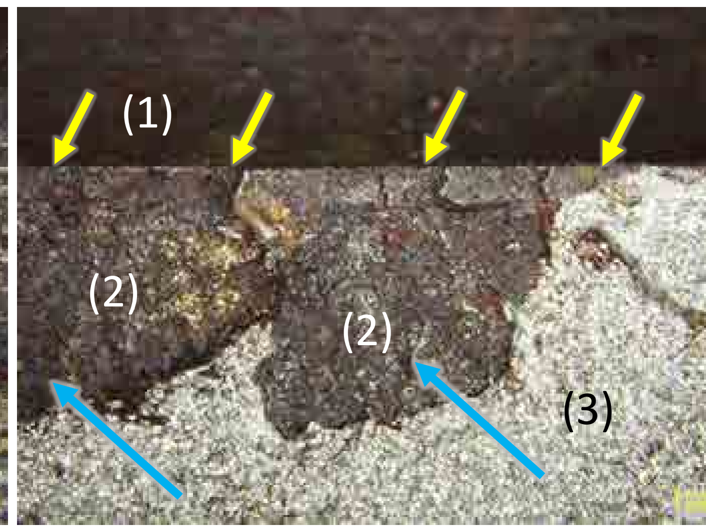
1) Microcrack → Pop-in Crack Initiation
2) Pop-in Crack Arrest
3) Pop-in Crack Flange Fracture Initiation

Fremont St D.4-NW Fracture Origin



Microcrack
Pop-in Crack





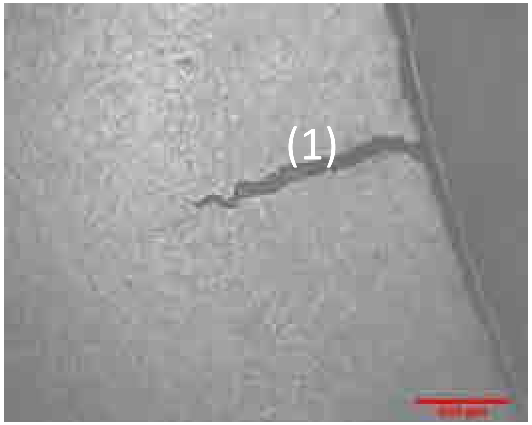
Microcrack (1) - Elliptical

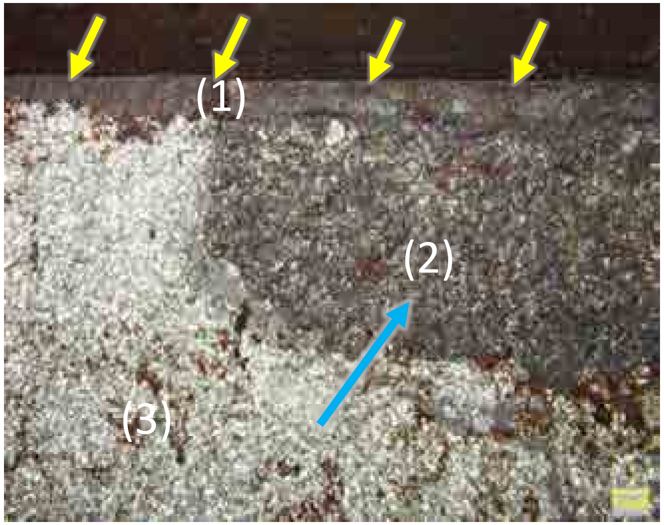
Depth ~ 0.04 to 0.06 in. x ~ 1.5 in.

Pop-in Crack (2) – Elliptical

0.38 (a) x 1.2 (2c) in.

Fremont St Pop-in Crack Initiation



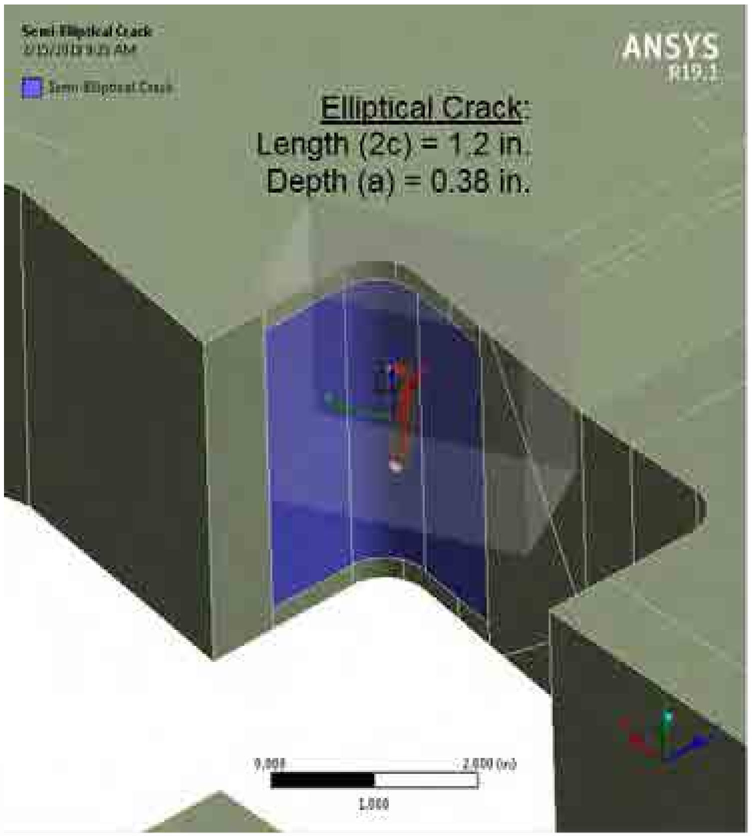


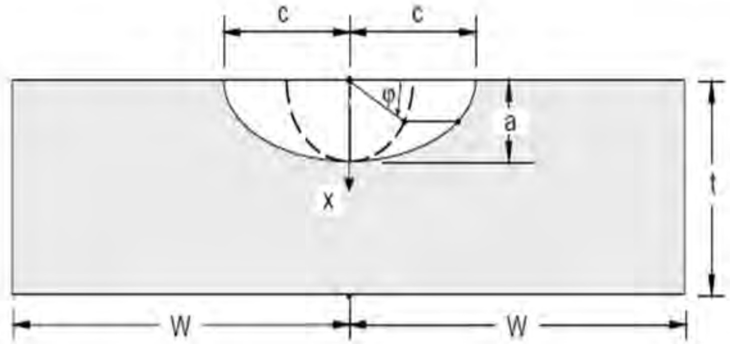
- Microcracks (1) formed during thermal cutting of the weld access holes and varied in depth (a) to a maximum of <u>0.06 in.</u>
- Microcracks located in untampered martensite → Fracture toughness (K_{1c}) could be at the lower bound for structural steel, which is ~ <u>25-30 ksi√in.</u> and up to the maximum ½-t toughness of 55-60 ksi√in. at 50°F
- The only stress present at the time the Pop-in cracks initiated was the self-limiting residual stress associated with welding of the flange CJP butt weld
- This residual stress is highest at the access hole surfaces and drops off rapidly as the distance from the access hole surface increases into the flange width
- An estimate of the residual stress developed during welding and, necessarily present to initiate the Pop-in crack, can be determined by calculating the stress required to initiate the Pop-in crack from the Microcracks

Fremont St Fracture Initiation

Fracture Mechanics Model of Pop-in Crack

Fracture Mechanics Crack Model





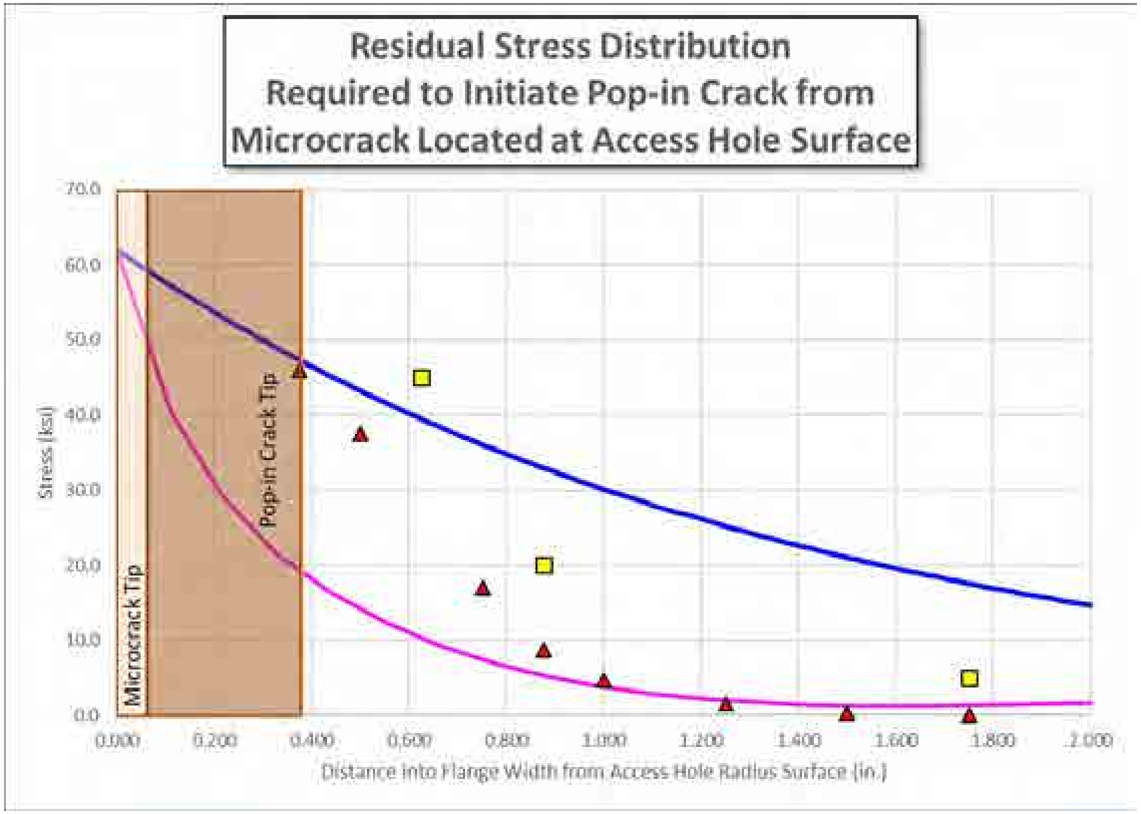
Stress Intensity Factor Solution (K)

$$K_I = \left[G_0(\sigma_0 + p_c) + G_1\sigma_1\left(\frac{a}{t}\right) + G_2\sigma_2\left(\frac{a}{t}\right)^2 + G_3\sigma_3\left(\frac{a}{t}\right)^3 + G_4\sigma_4\left(\frac{a}{t}\right)^4\right]\sqrt{\frac{\pi a}{Q}}\, f_w$$

Reference Stress Solution (σ_{ref})

$$\sigma_{ref} = \frac{gP_b + \left[(gP_b)^2 + 9P_m^2(1-\alpha)^2\right]^{0.5}}{3(1-\alpha)^2}$$

Fremont St Pop-in Crack Initiation

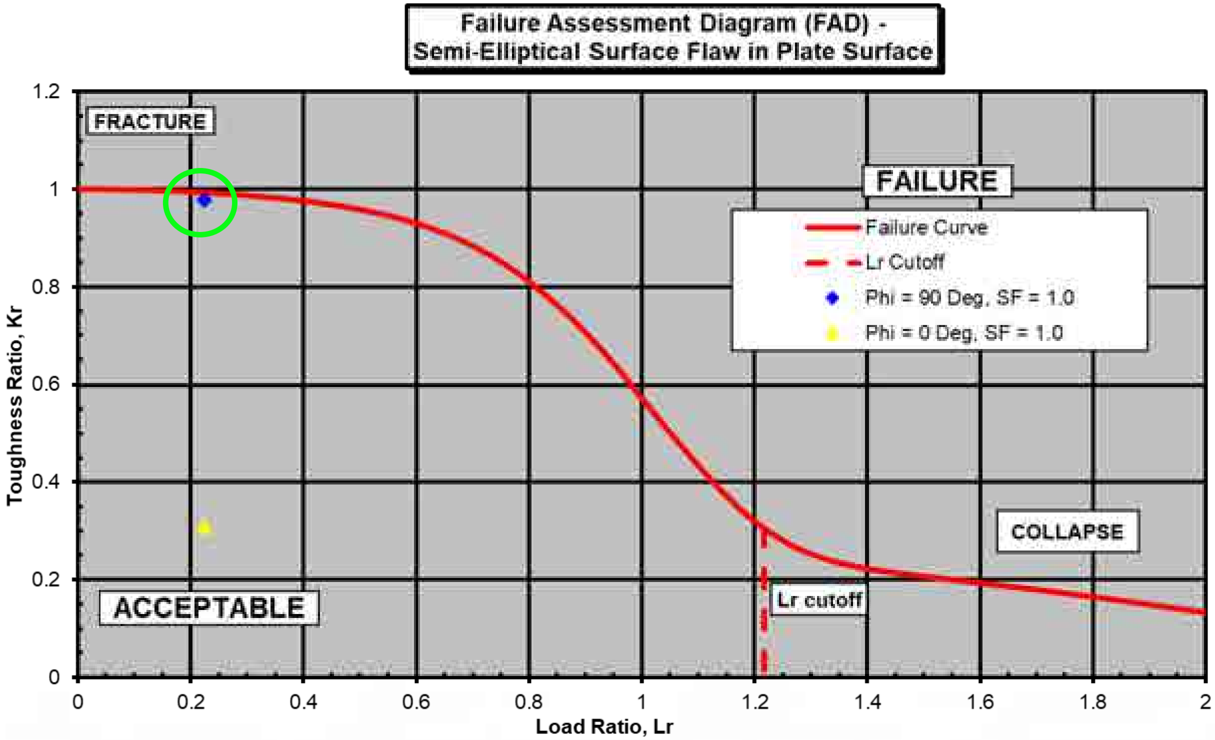


- Initially assumed that the access hole surface stress is subjected to yield strength level residual stress that decreases rapidly with distance into the flange, which is consistent with all reported measured and simulated residual stress analyses
- There is very good agreement between the LPI assumed residual stress distribution (blue curve) required to initiate Pop-in crack from Microcracks and the experimental (EXP) and finite element (FE) results obtained by the US Army Corp of Engineers' research performed in 1992 (Jaeger et. al.) for a comparable joint configuration
- LPI's Thermal FE simulation results (purple curve) of the weld access hole geometry are also in very good agreement with the 1992 US Army Corp of Engineers' research results
- The LPI distribution (blue curve) upper-bounds the results shown and, as such, slightly over estimates the induced stress intensity level (K)

Fremont St Pop-in Crack Initiation

Pop-in crack initiation occurs under the following conditions:

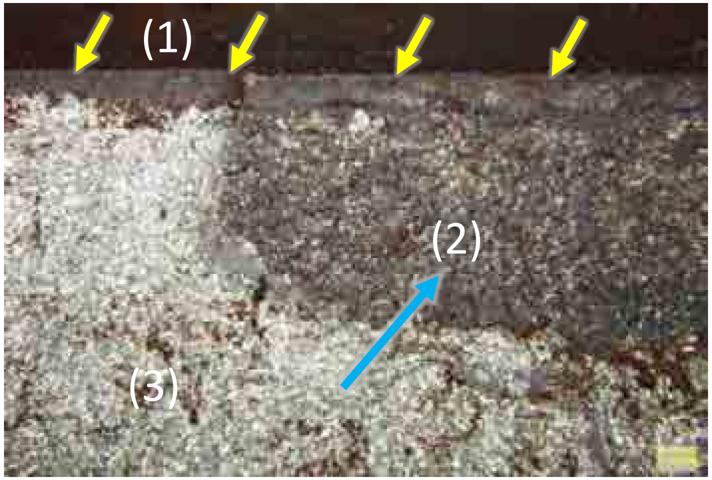
- The residual stress distribution shown in the previous slide
- A Microcrack depth (a) of 0.06 in.
- Fracture toughness (K_{1c}) of ~ 30 ksi√in.



Girder Flange Fracture Sequence

1) Microcrack → Pop-in Crack Initiation
2) Pop-in Crack Arrest
3) Pop-in Crack Flange Fracture Initiation

Fremont St Pop-in Crack Arrest

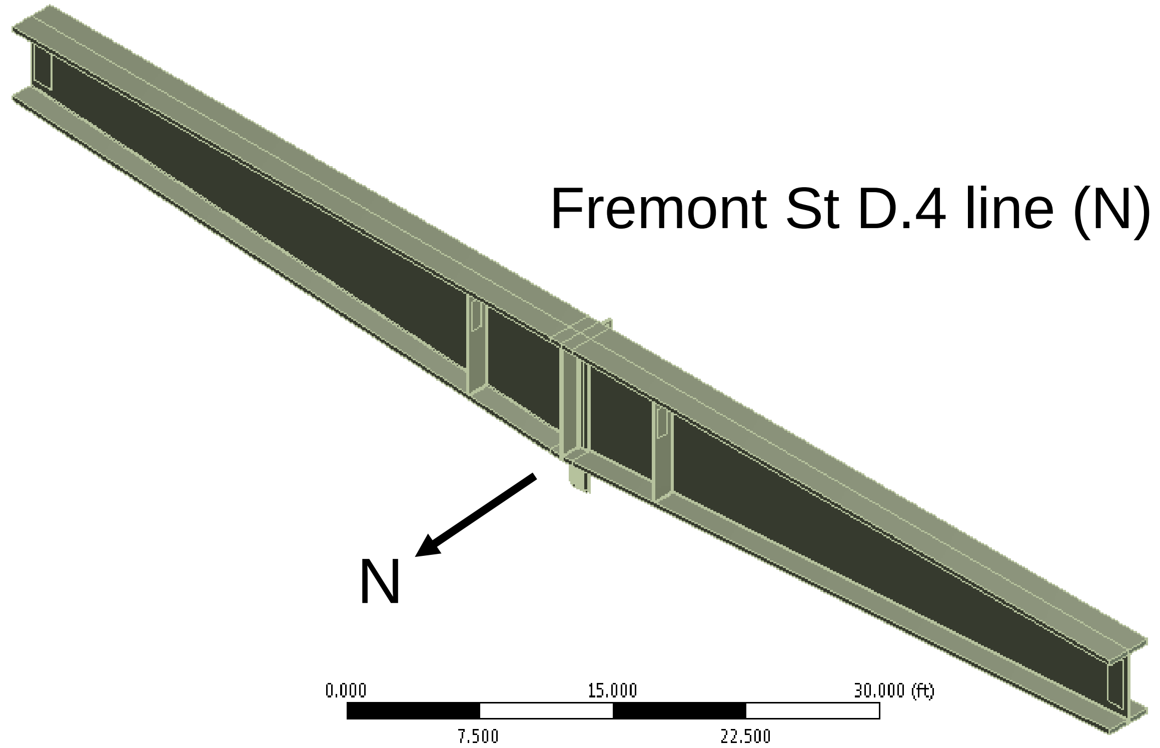


- The only stress present at the time the Pop-in crack arrested was the self-limiting residual stress associated with welding of the CJP butt weld
- Unstable Pop-in crack propagation occurred until the combination crack size, local stress, and fracture toughness were low enough to arrest Pop-in crack extension
- The Pop-in crack was located at mid-thickness (½-t) of the flange, where the fracture toughness (K_{1c}) was determined to be approximately <u>55-60 ksi√in. at 50°F</u>
- Depending upon the temperature the flange access hole region attained during CJP butt welding, the maximum toughness that the flange could have attained was the limiting upper shelf toughness, modified by the crack arrest fracture toughness (K_{1a})
- Thus, the Pop-in crack (2) formed during welding of the flange CJP butt weld and attained a maximum depth <u>(a) of 0.38 in.</u> and surface length <u>(2c) of approximately 1.2 in.</u>

Girder Flange Fracture Sequence

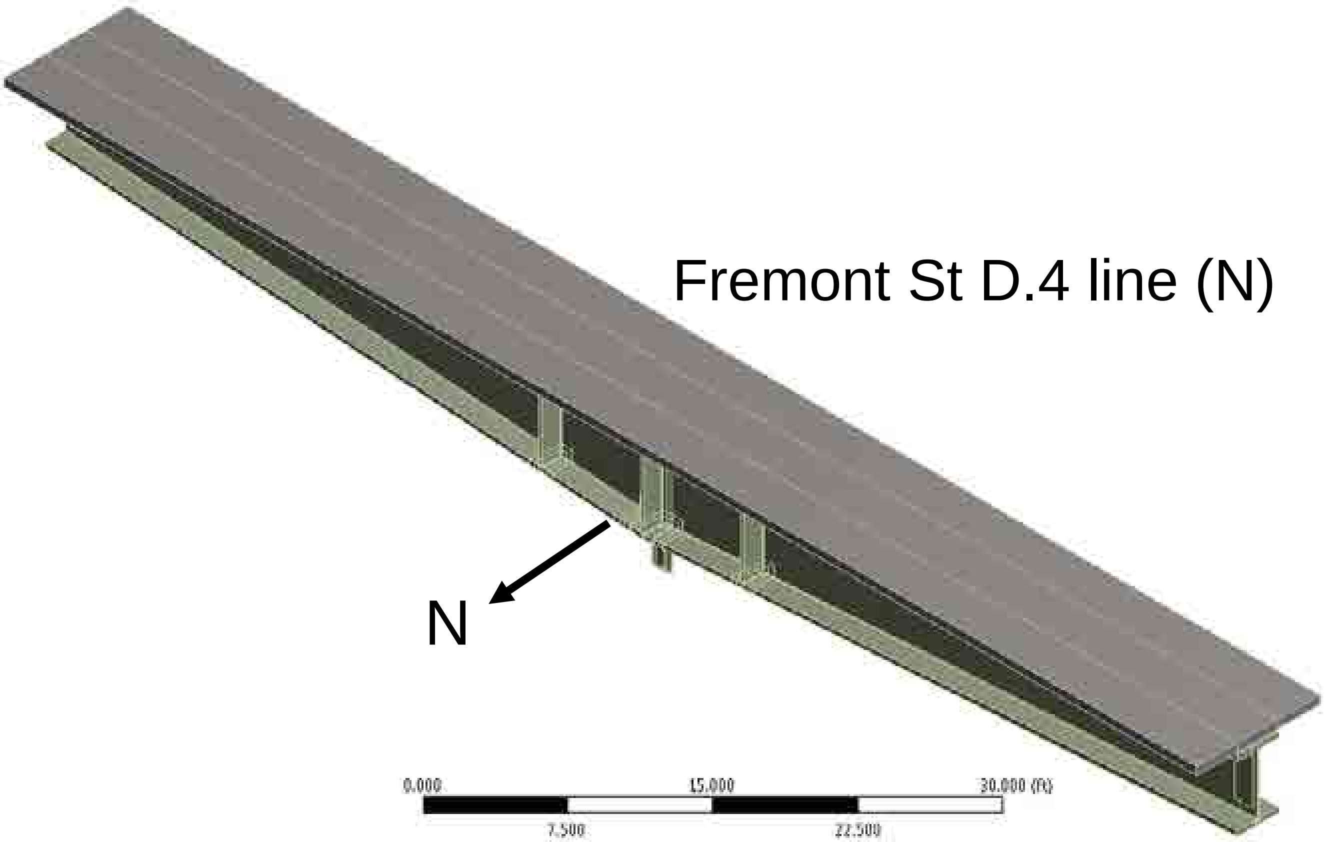
1) Microcrack → Pop-in Crack Initiation
2) Pop-in Crack Arrest
3) Pop-in Crack Flange Fracture Initiation

TPG3 Finite Element (FE) Model



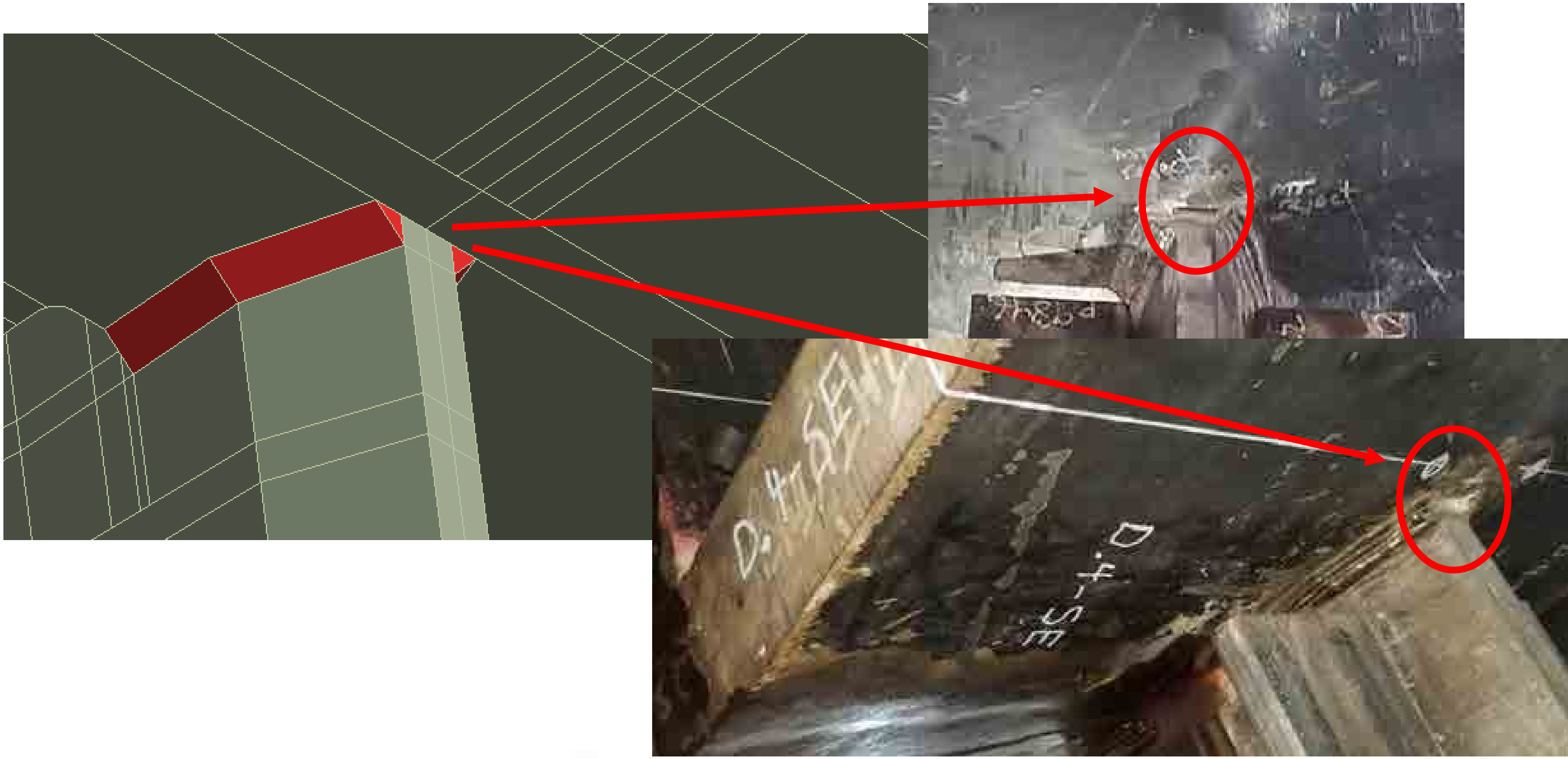
Fremont St D.4 and E.6 and First St D and F lines are similar

Composite Behavior Considered

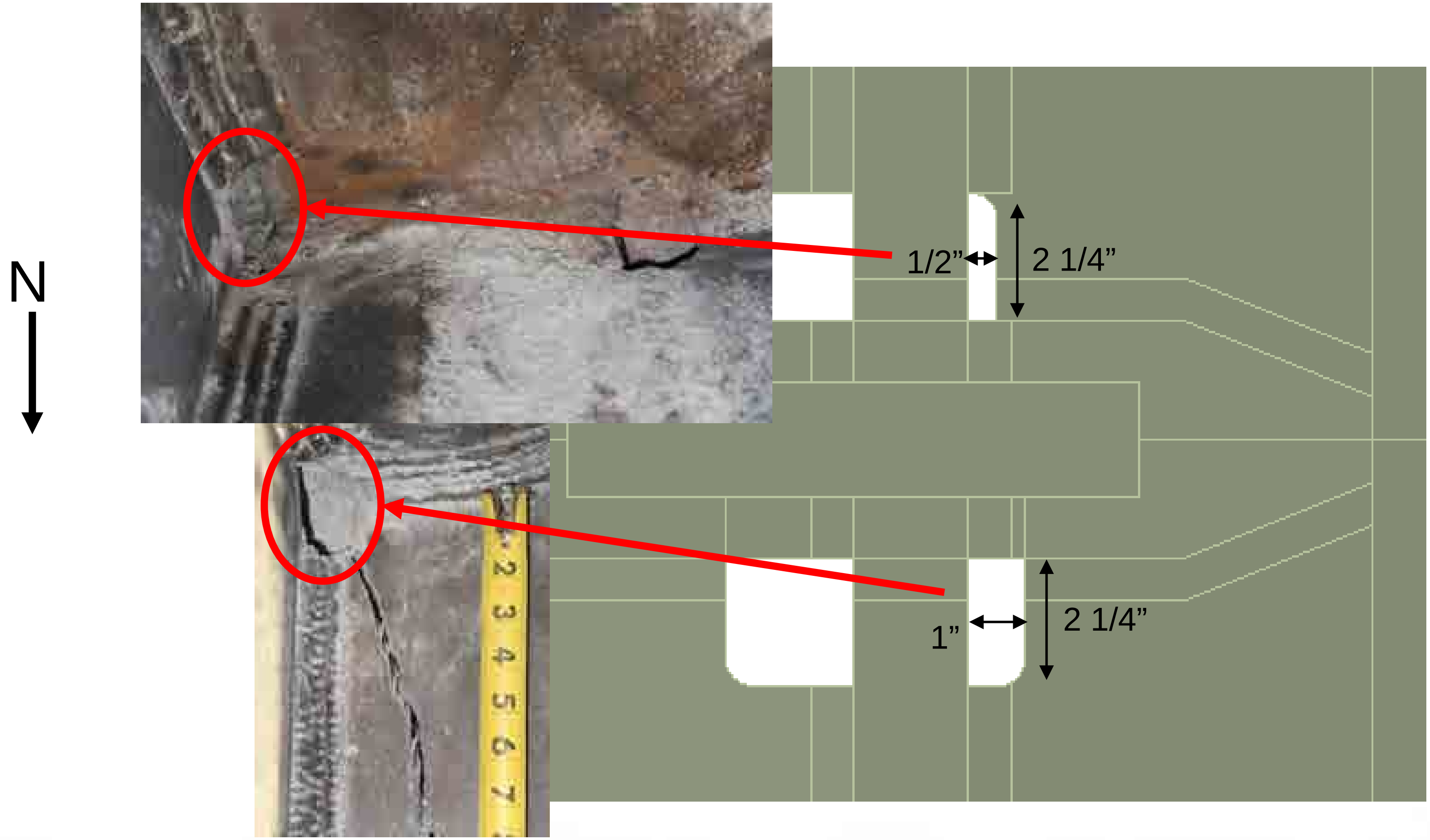


Fremont St D.4 and E.6 and First St D and F lines are similar

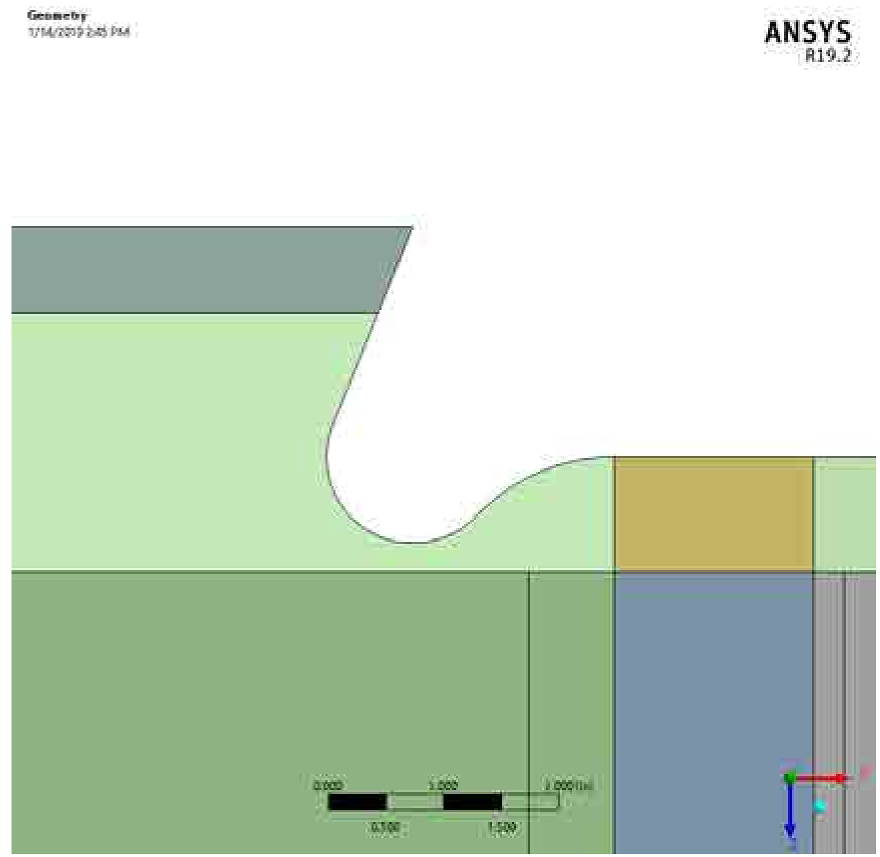
Fremont St Hanger Fillet Welds



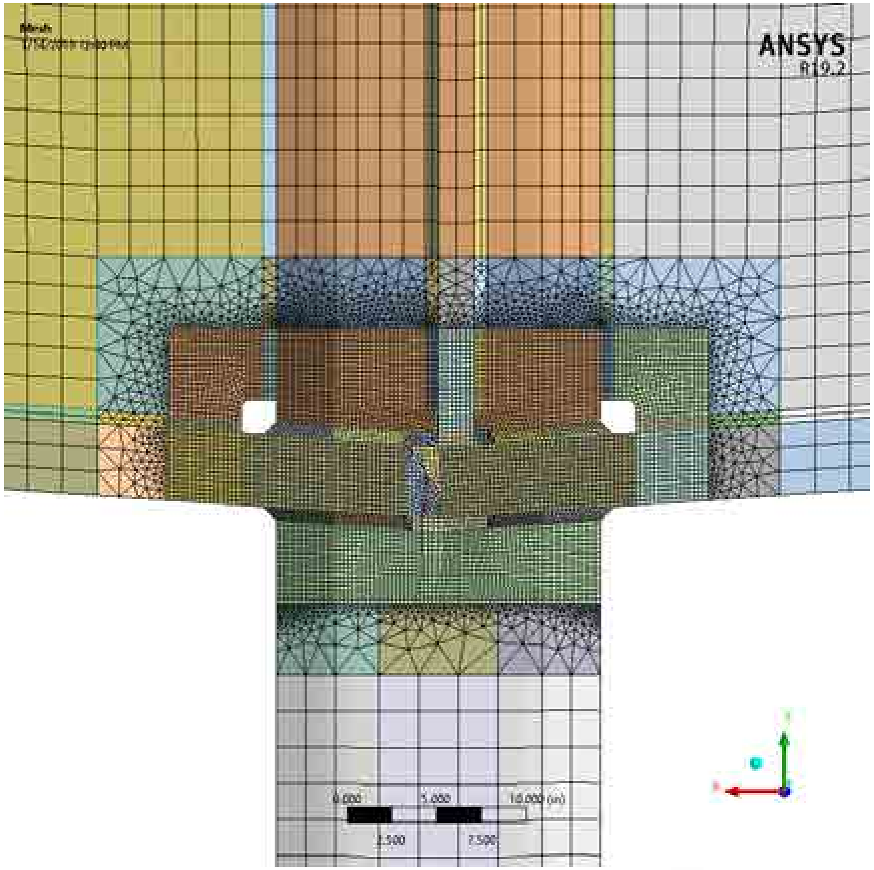
Fremont St D.4 (N) Access Holes

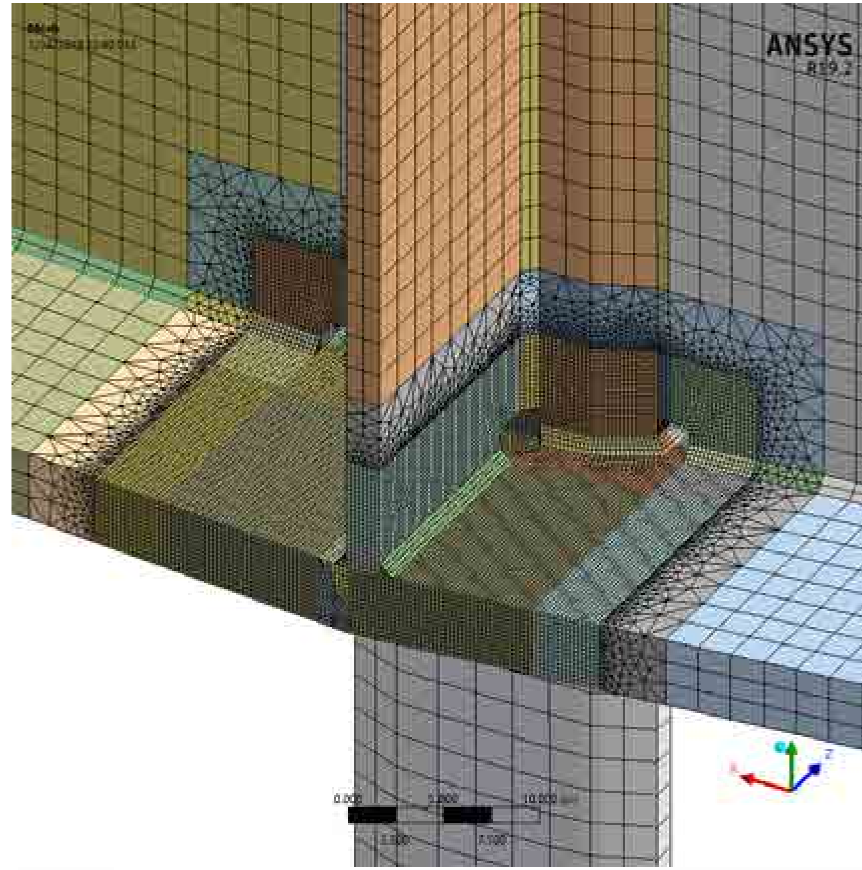


First St (S) – NE Access Hole



FE Mesh Overview





Timeline of Construction

Per Schedule Received from Webcor and Construction Cameras

Sep 2015 to Oct 2015	• Fremont St TPG3 girders erected
March15, 2016	• 10-in. slab placed on Bus-Deck level
April 4, 2016	• 10-in. slab placed on Roof level (loads are post-composite after this point)
April 26, 2016	• Additional 4-in. slab placed on Bus-Deck level
May 16, 2016	• Interior walls/curbs placed on Roof level
July 2016 to Feb 2017	• Ridge/Built-up slab, Drive Aisle, interior, and Central Island topping slabs at Bus Deck level
April 2017 to Aug 2017	• Roof protection slab
Oct 2017 to April 2018	• Tree/palm placement, concrete sub-slabs and finish grading at roof

Load Summary (per Thornton Tomasetti)

- Weights of construction, pre-composite:
  - Weight of TPG3 girders and other Roof steel framing members
  - Weight of Bus-Deck floor steel framing and hangers
  - Weight of 10-in. slab (7-in. NWC + 3-in. metal deck) at Bus-Deck level
  - Weight of 10-in. slab (7-in. NWC + 3-in. metal deck) at Roof level
- Weights of construction, post-composite:
  - Weight of 4-in. concrete structural topping at Bus-Deck level
  - Weight of Architectural toppings at Bus-Deck level
  - Weight of protection slab and drainage topping at Roof level
  - Weights of soil, tree and other landscape items at Roof level
  - MEP loads at Roof level
  - Weight of penthouse structure

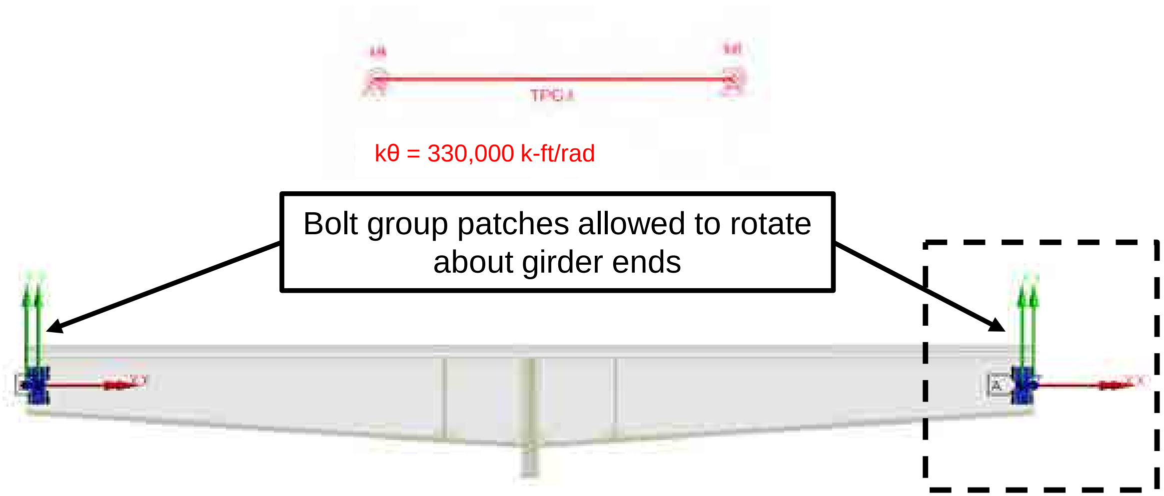
FE Analysis Load Sequence

1. Apply pre-composite **DL**
2. Apply post-composite **SDL**
3. Apply post-composite **LL**

End Restraint

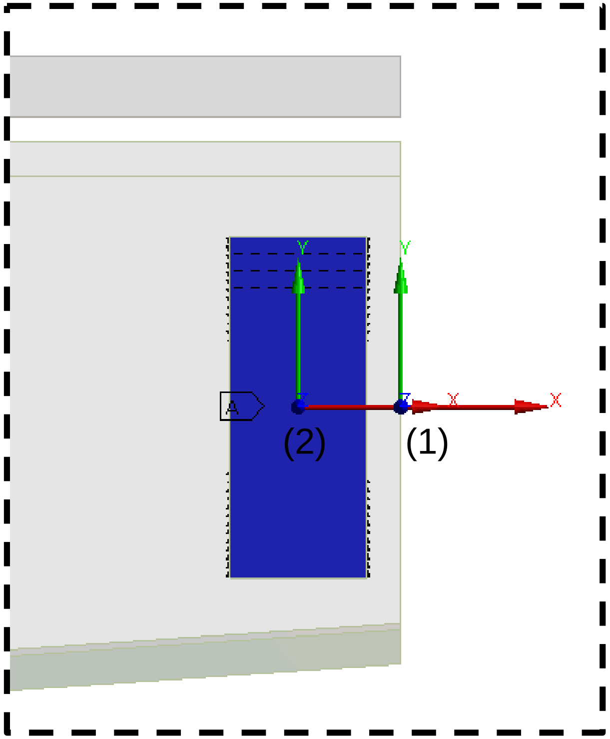
Fremont St D.4 (N)

BCs per TT:



Each End Pinned w/ Rotational Stiffness:

UX = UY = UZ = 0
RX = RY = 0
$K\theta,Z = 6.91 \times 10^{7}$ lbf-in./°

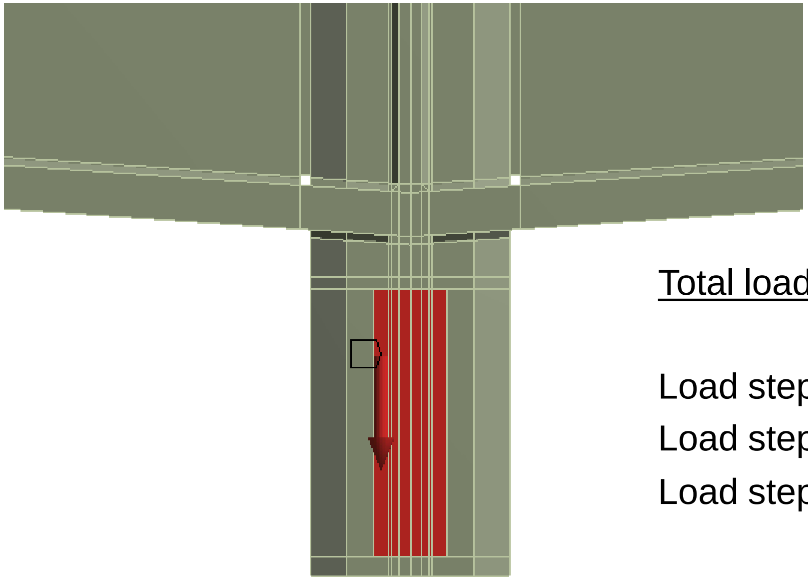


Rotation of patch (2) about girder end (1)

Fremont St D.4 and E.6 and First St D and F lines are similar

Hanger Loads on Girder

Fremont St D.4 Line (N)



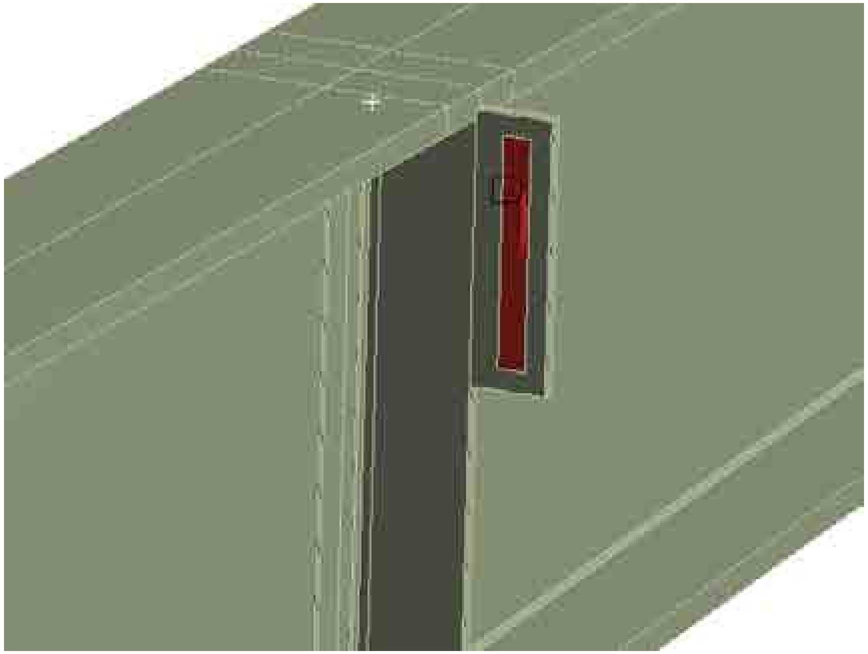
<u>Total load applied at each of the following load steps:</u>

Load step 1 (**DL**) =	174,000 lb
Load step 2 (**DL + SDL**) =	405,300 lb
Load step 3 (**DL + SDL + 0.1×LL**) =	418,980 lb

Fremont St D.4 and E.6 and First St D and F lines are similar

CL Stiffener Loads on Girder

Fremont St D.4 Line (N)



N

<u>Total load applied at each of the following load steps:</u>

Load step 1 (**DL**) = 58,000 lb

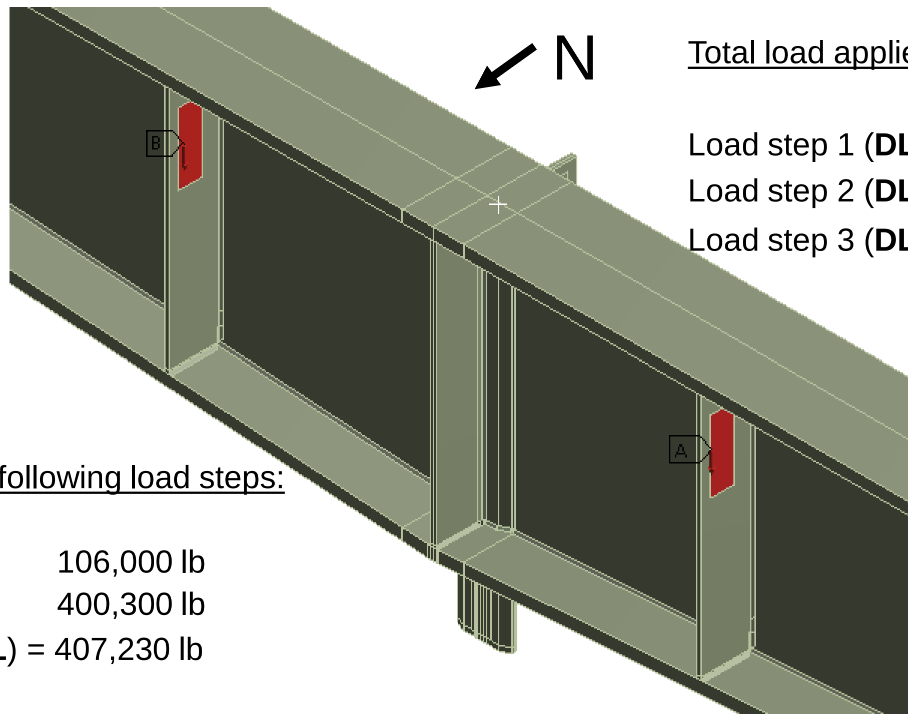
Load step 2 (**DL + SDL**) = 207,500 lb

Load step 3 (**DL + SDL + 0.1×LL**) = 211,270 lb

Fremont St D.4 and E.6 and First St D and F lines are similar

“7 ft” Stiffener Loads on Girder

Fremont St D.4 Line (N)



Total load applied at each of the following load steps:

Load step 1 (**DL**) = 116,000 lb
Load step 2 (**DL + SDL**) = 385,100 lb
Load step 3 (**DL + SDL + 0.1×LL**) = 391,850 lb

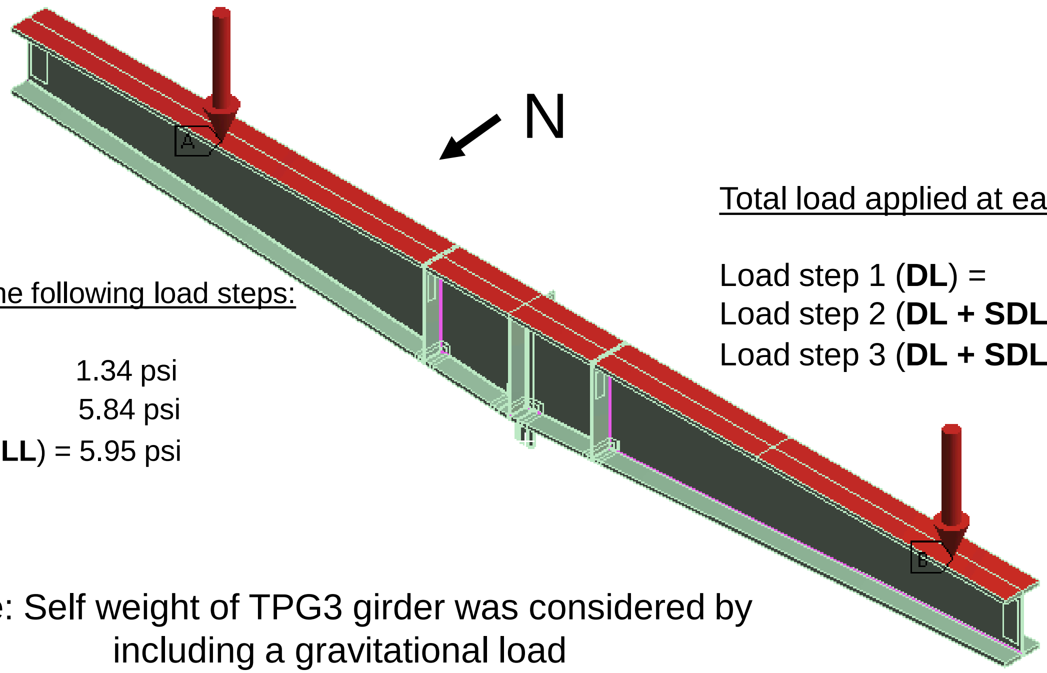
Total load applied at each of the following load steps:

Load step 1 (**DL**) = 106,000 lb
Load step 2 (**DL + SDL**) = 400,300 lb
Load step 3 (**DL + SDL + 0.1×LL**) = 407,230 lb

Fremont St D.4 and E.6 and First St D and F lines are similar

Line Loads on Girder

Fremont St D.4 Line (N)



Total load applied at each of the following load steps:

Load step 1 (**DL**) = 1.34 psi
Load step 2 (**DL + SDL**) = 5.84 psi
Load step 3 (**DL + SDL + 0.1×LL**) = 5.95 psi

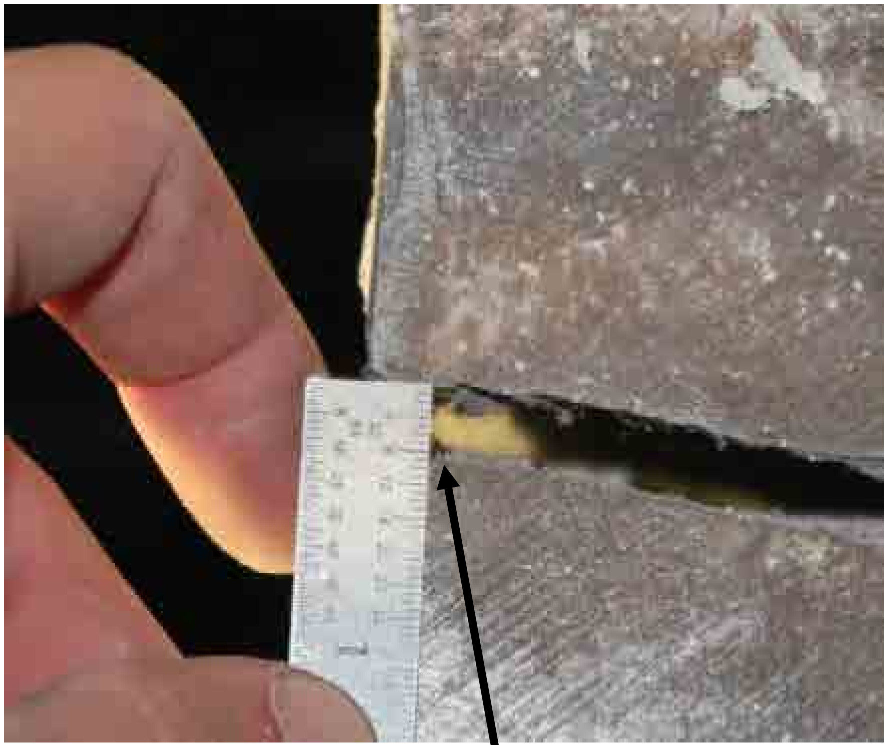
Total load applied at each of the following load steps:

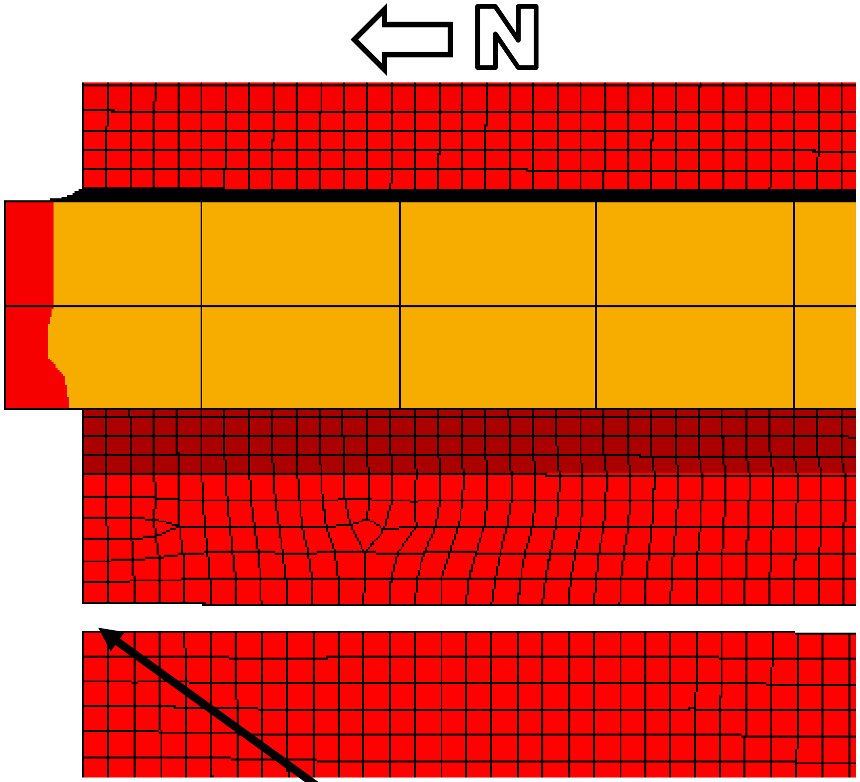
Load step 1 (**DL**) = 1.34 psi
Load step 2 (**DL + SDL**) = 5.34 psi
Load step 3 (**DL + SDL + 0.1×LL**) = 5.45 psi

Note: Self weight of TPG3 girder was considered by including a gravitational load

Fremont St D.4 and E.6 and First St D and F lines are similar

Fremont St Model Validation





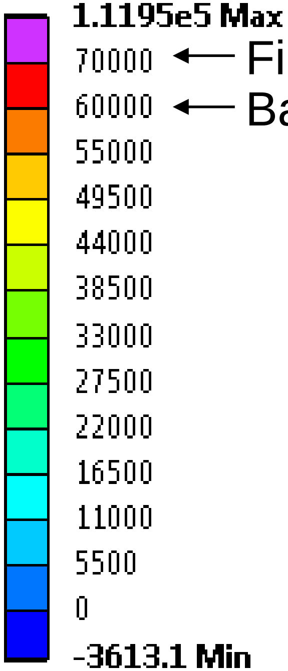
Actual Measurement ~ 0.25 in.

NW Fracture

FE Results ~ 0.27 in.

Fremont St D.4 Results

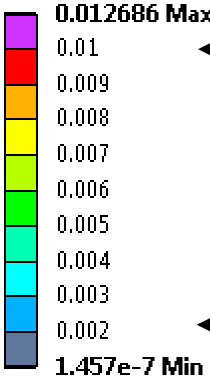
Stress (psi)



← Fillet weld yield strength

← Base metal yield strength

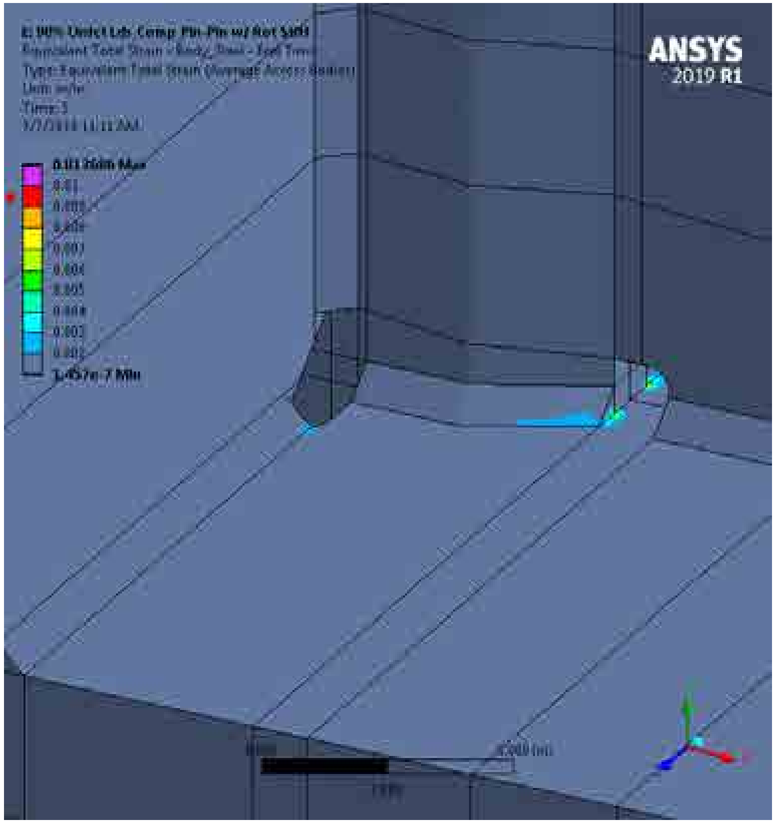
Total Strain (in./in.)



← 1%

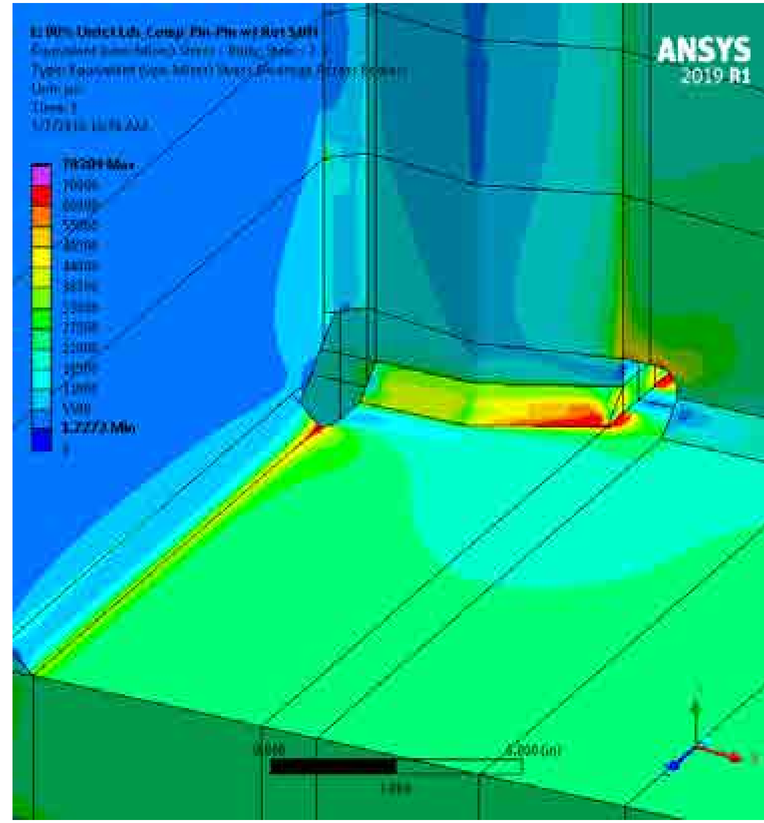
← 0.2% (Onset of yielding)

Fremont St D.4 (N) Results



Total Strain

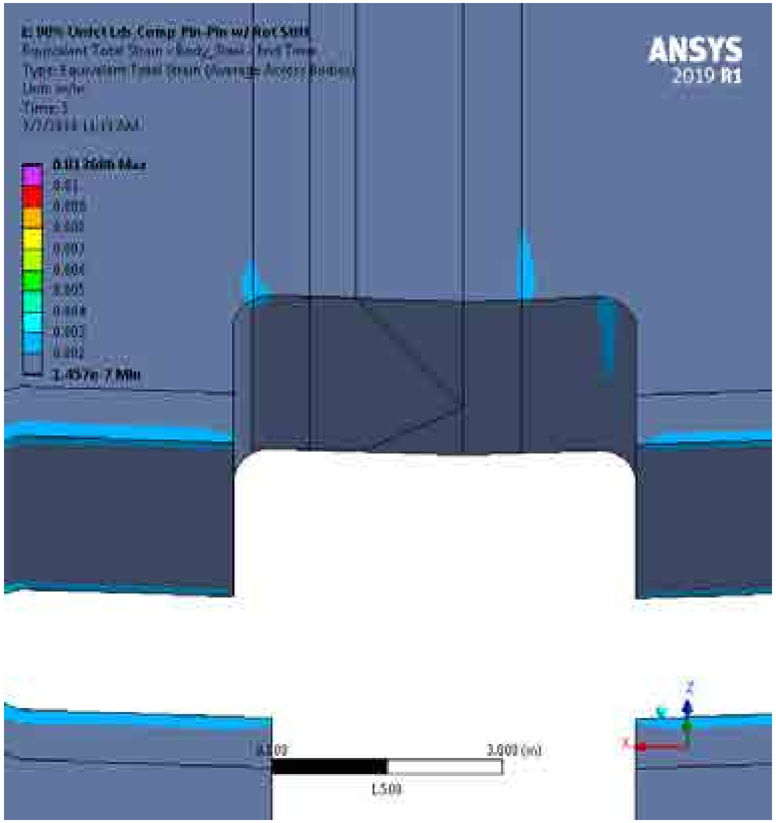
N



Maximum Principal Stress

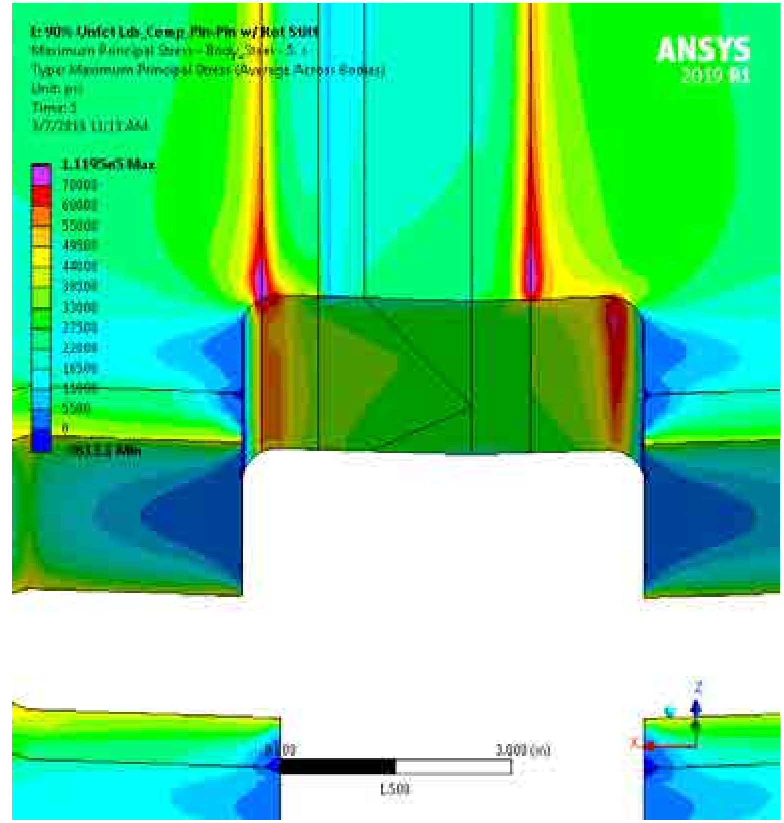
1.0(DL+SDL) + 0.1LL

Fremont St D.4 (N) Results



Total Strain

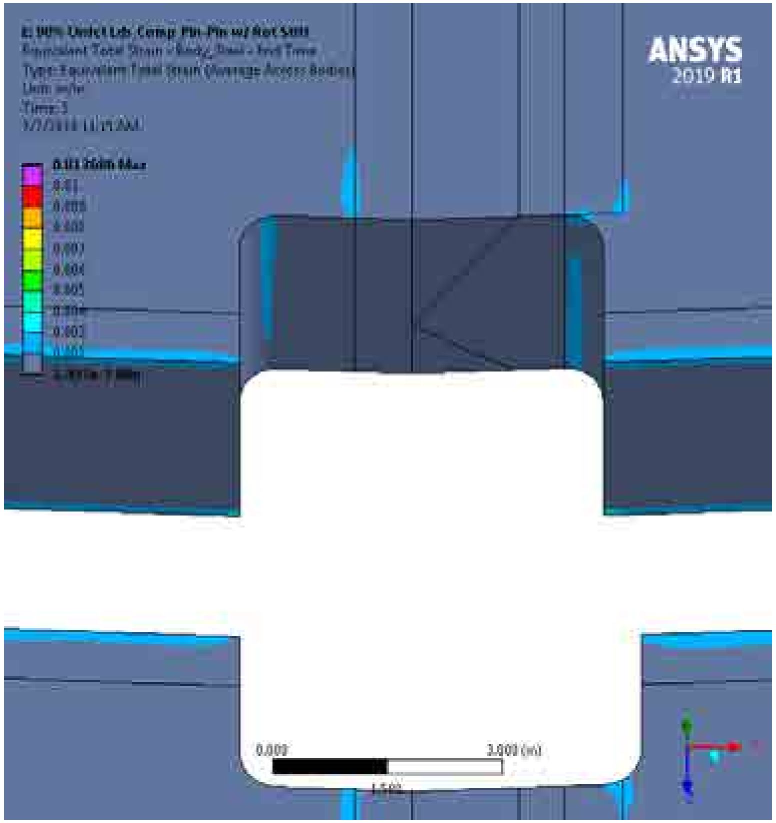
N

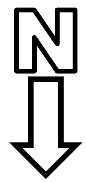


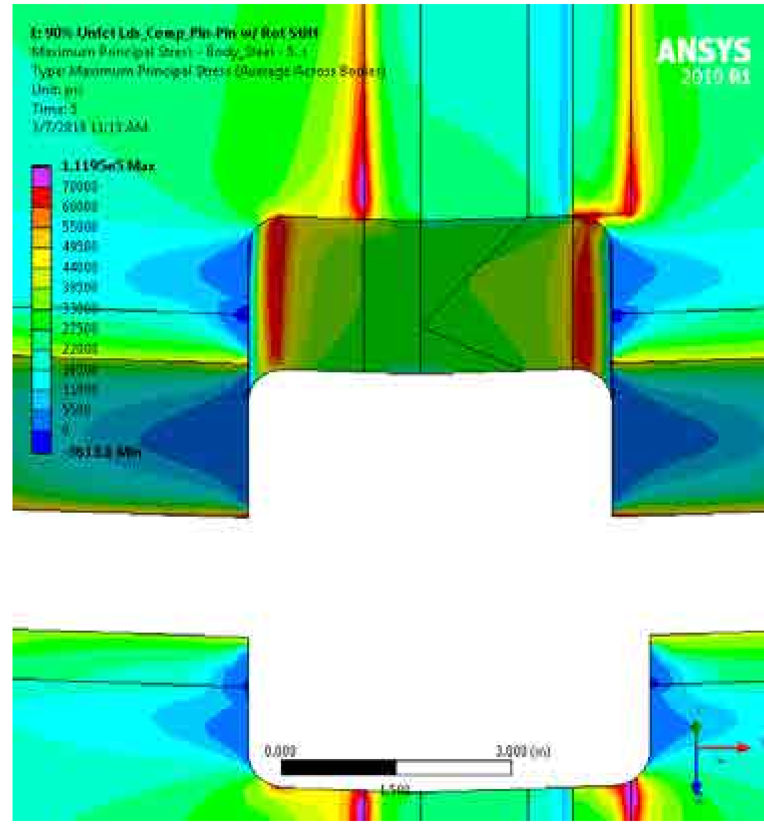
Maximum Principal Stress

1.0(DL+SDL) + 0.1LL

Fremont St D.4 (N) Results





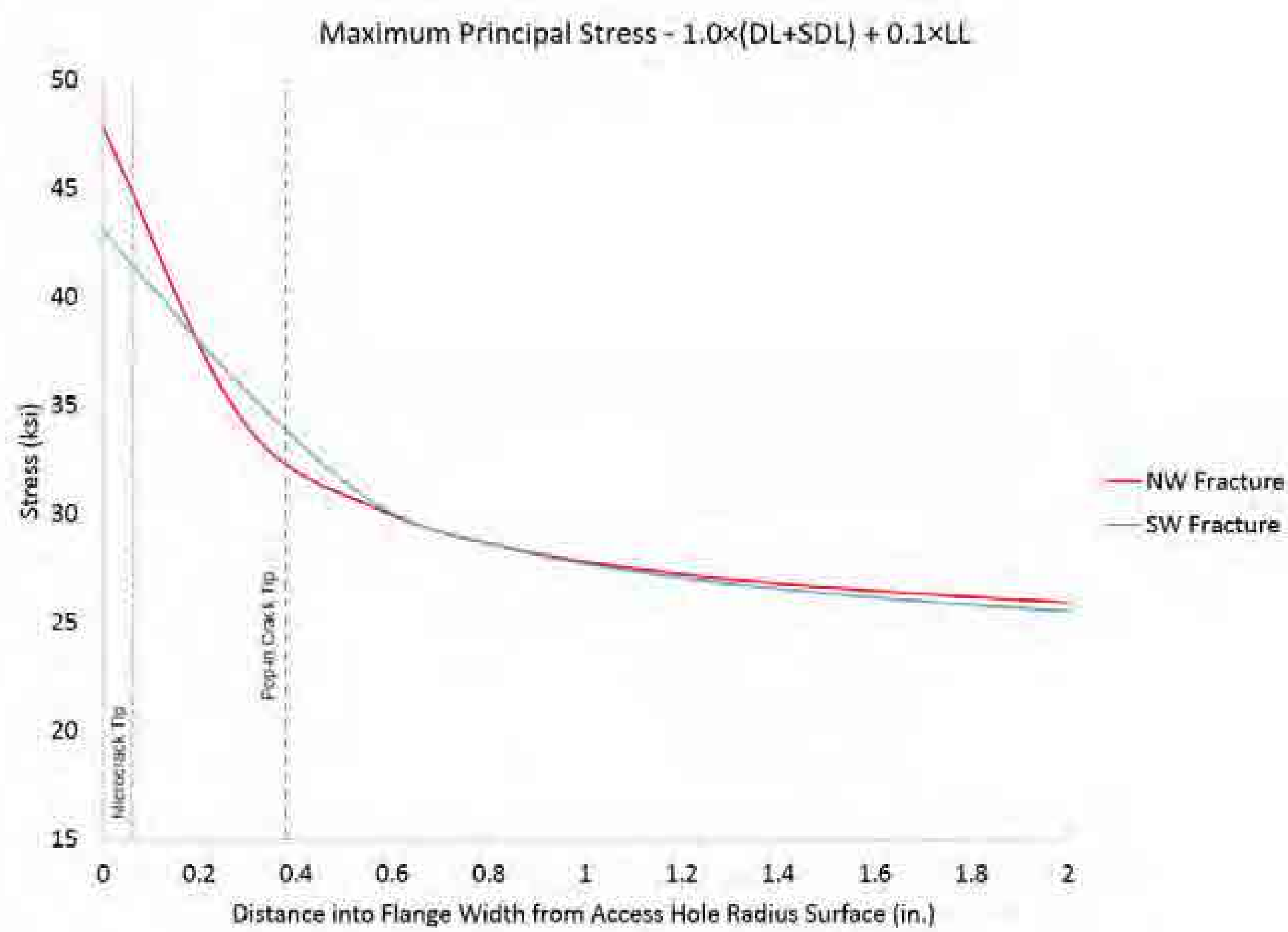


Total Strain

Maximum Principal Stress

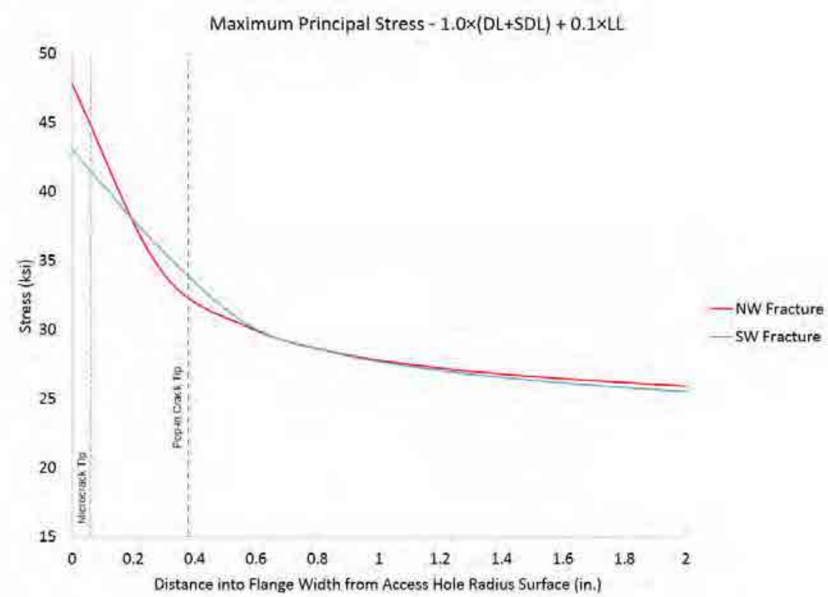
1.0(DL+SDL) + 0.1LL

Fremont St D.4 (N) Results



Fremont St Flange Fracture Initiation

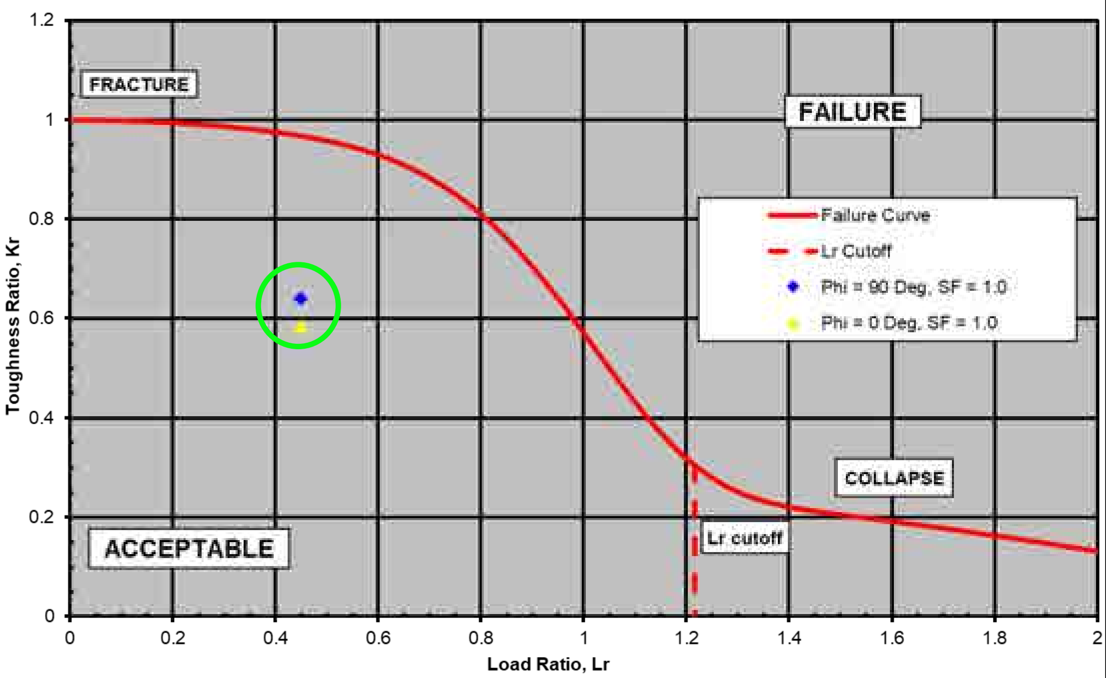
- Flange fracture (3) initiated from the Pop-in crack (2) under the combination of normal service-induced stresses and butt weld-induced residual stresses and extended across the width of the flange
- The Pop-in crack was 0.38 in. deep (a) with a surface length (2c) of 1.2 in. and located at mid-thickness (½-t) of flange, where the fracture toughness (K_{1c}) was approximately <u>55-60 ksi√in.</u>
- Service stresses were those due to 1.0DL + 0.1LL



Fremont St Flange Fracture Initiation

- For a crack 0.38 in. deep (a) x 1.2 long (2c) in., a fracture toughness of K_{1c} ~ 55-60 ksi√in., and service stresses only (i.e., no residual stresses), the following Fracture Mechanics (FAD) results were obtained

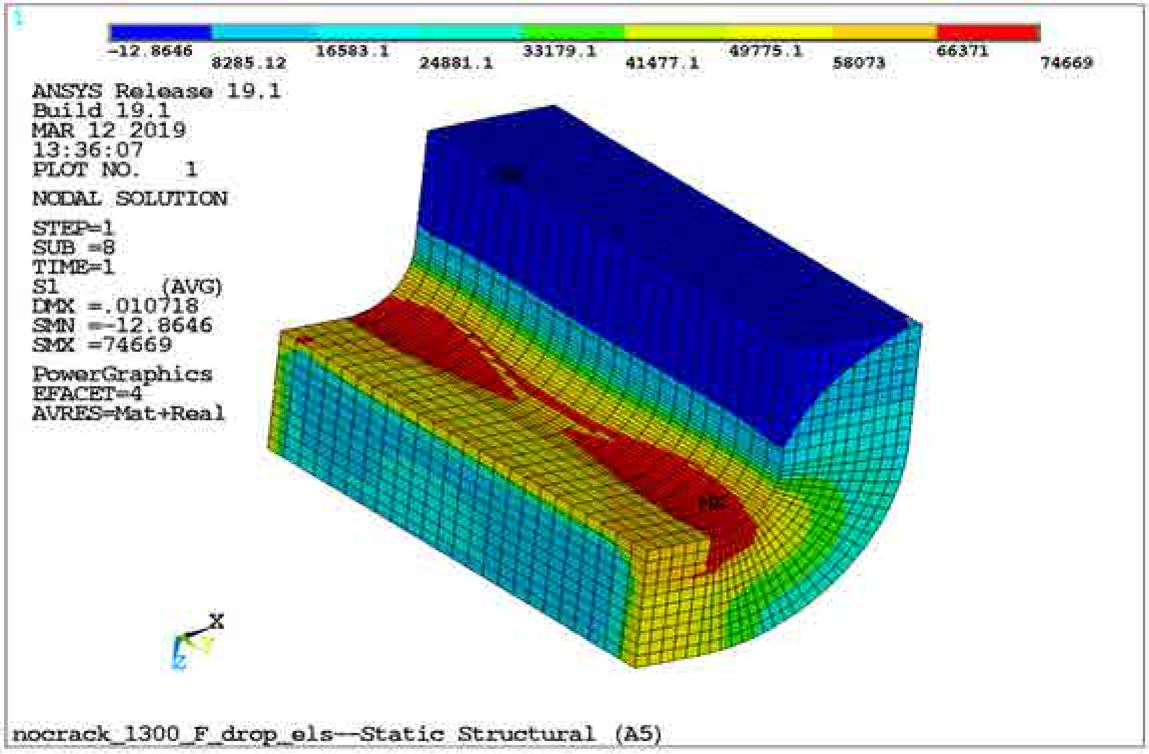
Failure Assessment Diagram (FAD) - Semi-Elliptical Surface Flaw in Plate Surface



- ***<u>From the Fracture Mechanics (FAD) calculations, flange fracture (3) from the Pop-in crack will NOT ( ) occur under normal service stresses alone</u>***
- **As such, a K contribution due to CJP butt weld-induced residual stresses is required to initiate flange fracture**
- **The contribution of residual stress necessary to initiate flange fracture can be "back-calculated" by incrementally increasing the residual stress K component of the FAD analysis until fracture is indicated by one of the assessment points ( ) intersects the FAD failure curve (left)**
- **The K due to service stress was <u>38 ksi√in.</u>**
- **Accordingly, the minimum additional residual stress-induced K required to initiate flange fracture is approximately <u>20-22 ksi√in.</u>**

Residual Stress - Fremont St

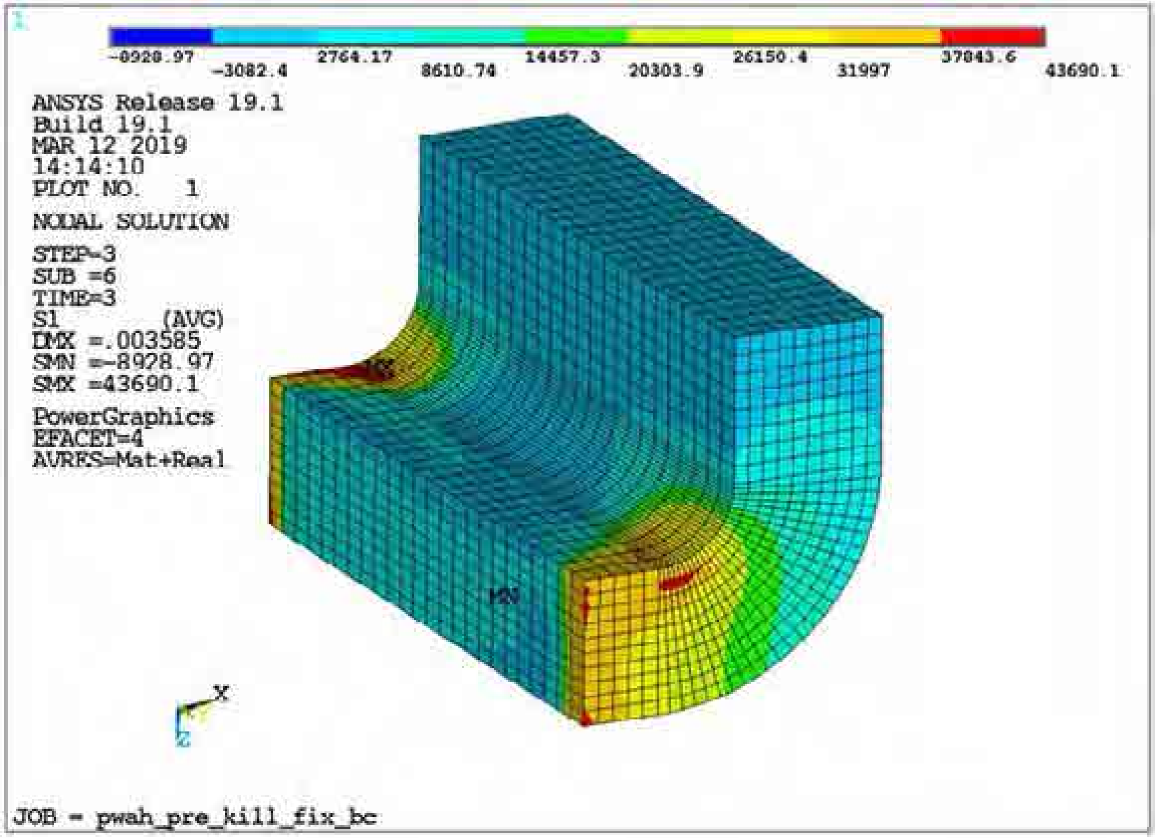
Weld access holes thermally **<u>cut before welding</u>**



Max Principal Stress

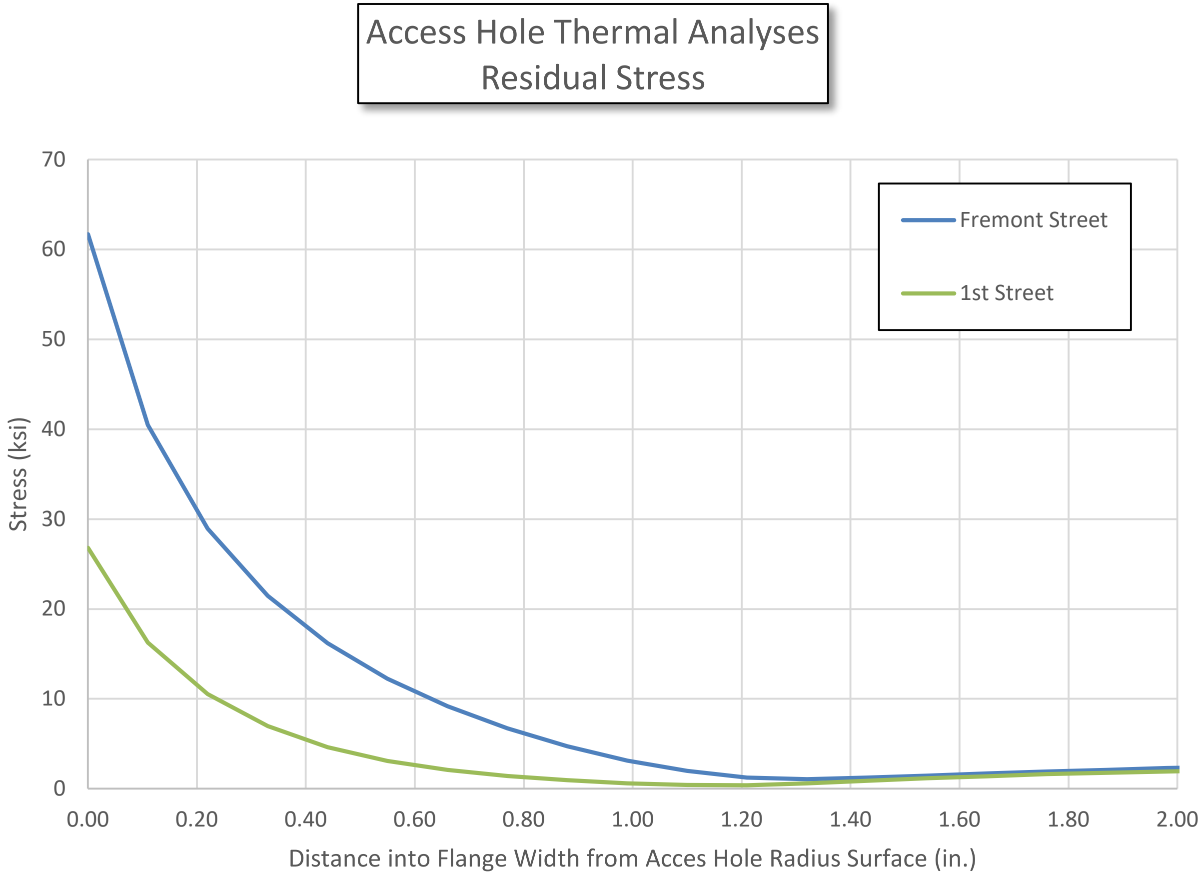
Residual Stress - First St

Weld access holes thermally **cut after welding**



Max Principal Stress

Residual Stress Comparison



Conclusions
Fremont St Flange Fracture

- Yield strength level residual stresses at the weld access hole radius surface (induced by CJP butt welding) were required to initiate the Pop-in crack from the 0.06 in. deep Microcracks

- Service induced stresses corresponding to 1.0DL + 0.1LL were NOT sufficient to initiate flange fracture from a 0.38 in. deep x 1.2 in. long Pop-in crack located at in the mid-thickness of the 4-in. thick flange, where the fracture toughness (K_{1c}) was considered very low at approximately 55-60 ksi$\sqrt{\text{in.}}$ at 50°F

- The girder design stresses were within expected and normal levels

- Service induced stresses corresponding to 1.0DL + 0.1LL, plus residual stresses associated with CJP butt welding, were required to initiate flange fracture from a 0.38 in. deep x 1.2 in. long Pop-in crack located at the weld access hole surface, in the mid-thickness of the 4-in. thick flange, where the fracture toughness (K_{1c}) was considered very low at approximately 55-60 ksi$\sqrt{\text{in.}}$ at 50°F

- Fracture did not initiate at First Street because the residual stresses were relieved due to the different fabrication sequences between First Street and Fremont Street

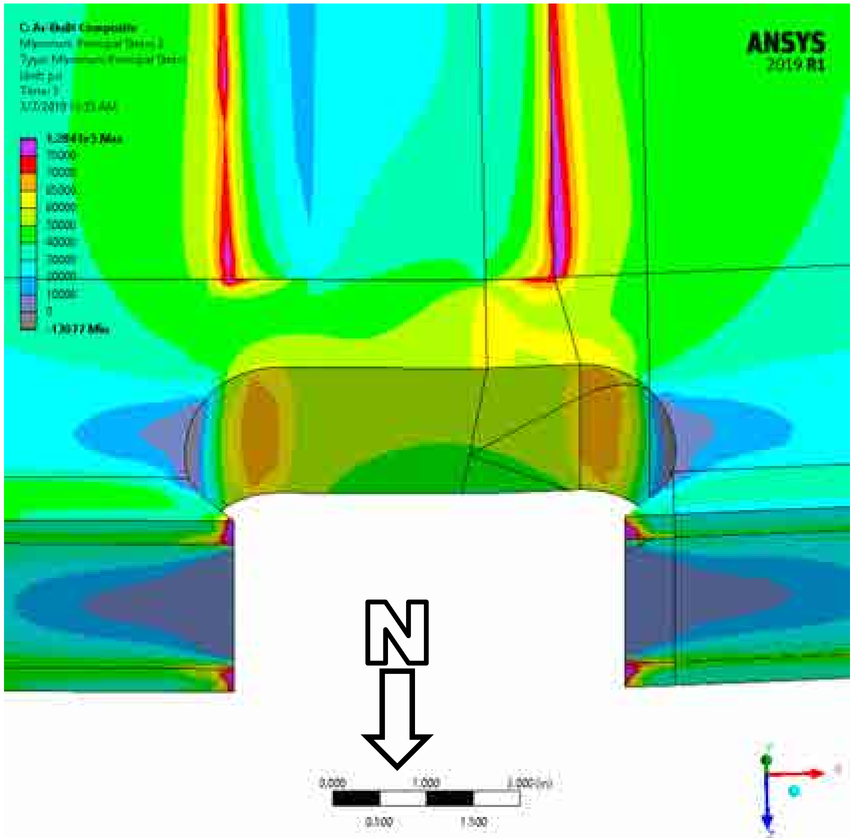
- The access holes were cut at Fremont Street prior to welding, whereas the access holes at First Street were cut after the CJP butt weld was completed

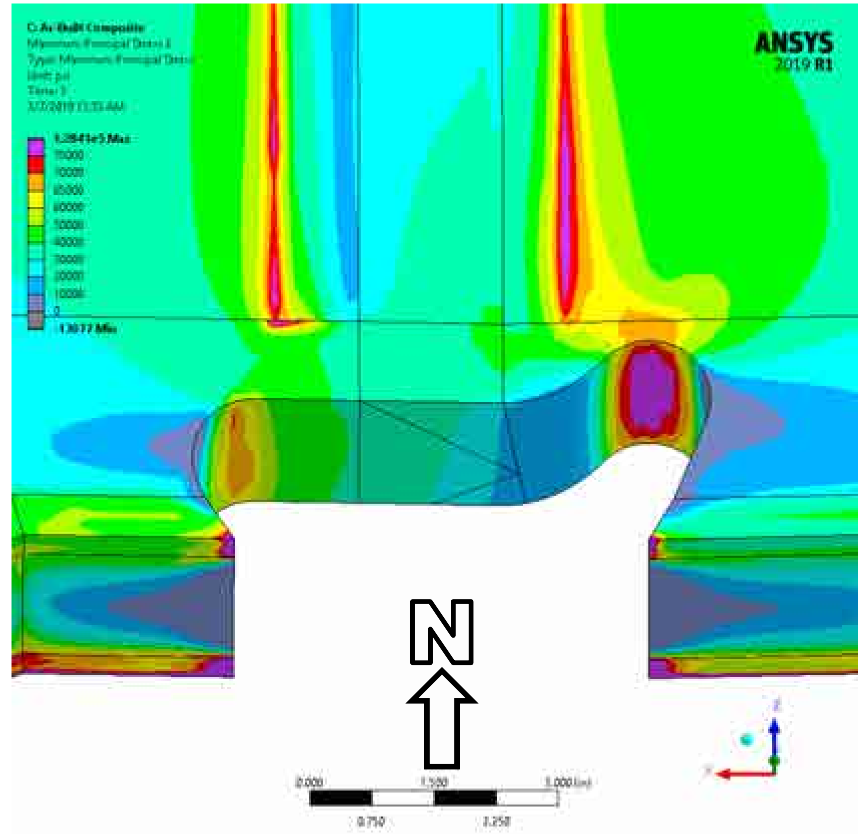
First St Repair

Fully Factored Loading

$1.2\times(DL+SDL) + 1.6\times LL$

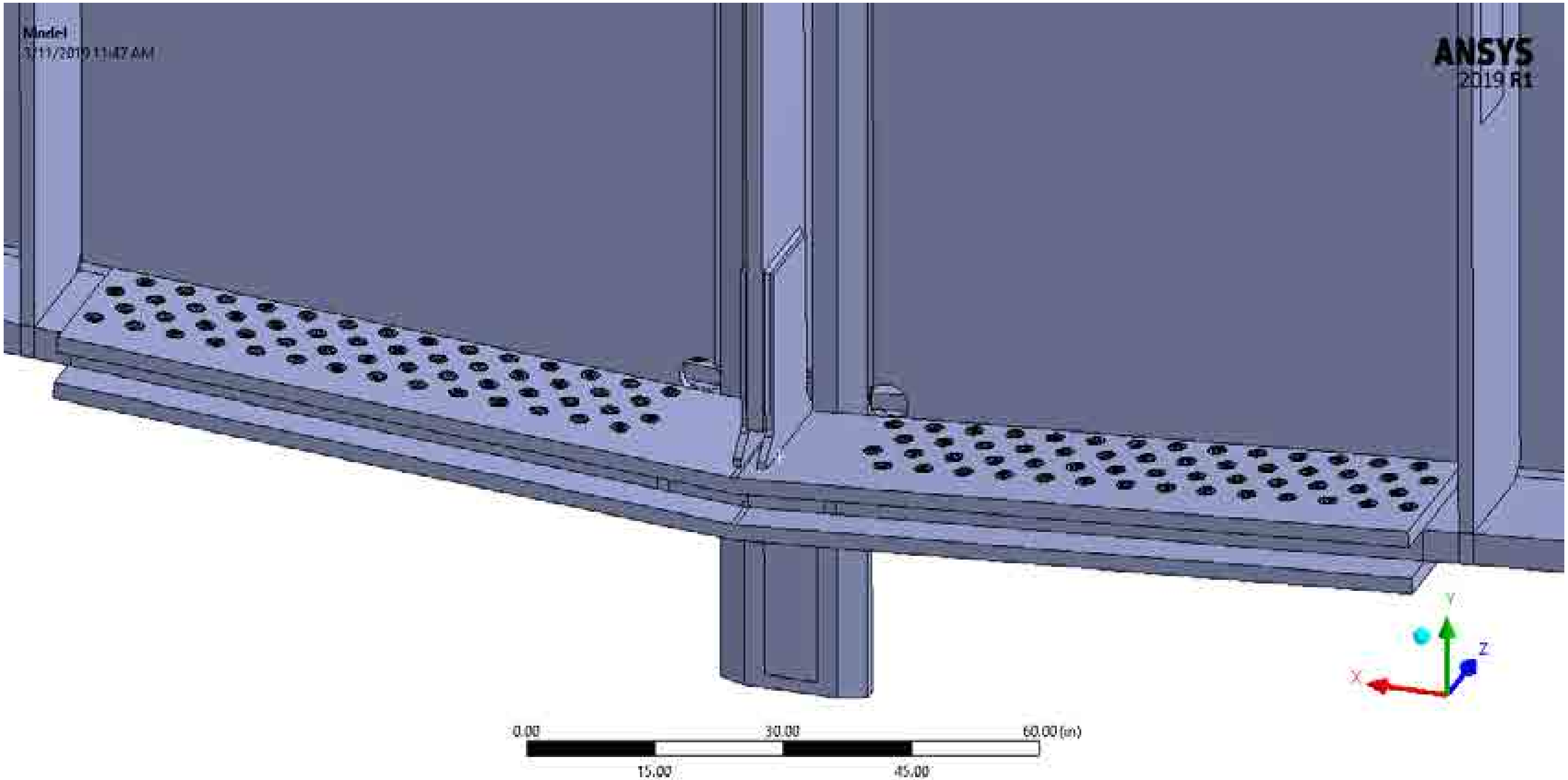
First Street F (S)
As-Built under 1.2DL + 1.6LL





Maximum Principal Stress

First St Repair



Conclusions – First St

- Stresses in the First Street girder under the fully factored load state are considered normal and acceptable prior to the bolted repair solution

- The bolted repair at First Street provides additional load carrying capacity beyond what is required

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Advanced Analysis & Fitness for Service
Failure & Materials Evaluation
Nondestructive Engineering

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Salesforce Transit Center - MTC Peer Review Panel (PRP)

Review Status Update

PRP Presentation for TJPA Board of Directors – March 14, 2019

Presented by: Andrew B. Fremier, Deputy Executive Director, MTC
Michael D. Engelhardt, Chair, PRP

MTC PRP: Status of Review

1. **Shoring capacity:** Reviewed and concur.
2. **Sampling and testing plan:** Reviewed and concur.
3. **Cause of failure:** General concurrence with findings; pending final report.
4. **Impact of fractures on adjacent elements:** Review nearing completion.
5. **Repair of Fremont girders (and retrofit at First Street):** Reviewed and concur.
6. **Search for other areas susceptible to brittle fracture:** Concurrence with criteria; review of TJPA project team’s work on-going.