LPI, Inc. Consulting Engineers

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

Est. 1885

Root Cause Assessment – Fractured Girder Flanges

Transbay (Salesforce) Transit Center, San Francisco

TJPA Board
December 13, 2018

Prepared by:
LPI, Inc.
Robert S. Vecchio, Ph.D., P.E.
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**: Expected completion of all metallurgical and mechanical testing
- **January 2019**: Expected completion of root cause assessment

Fremont Street and First Street Girders

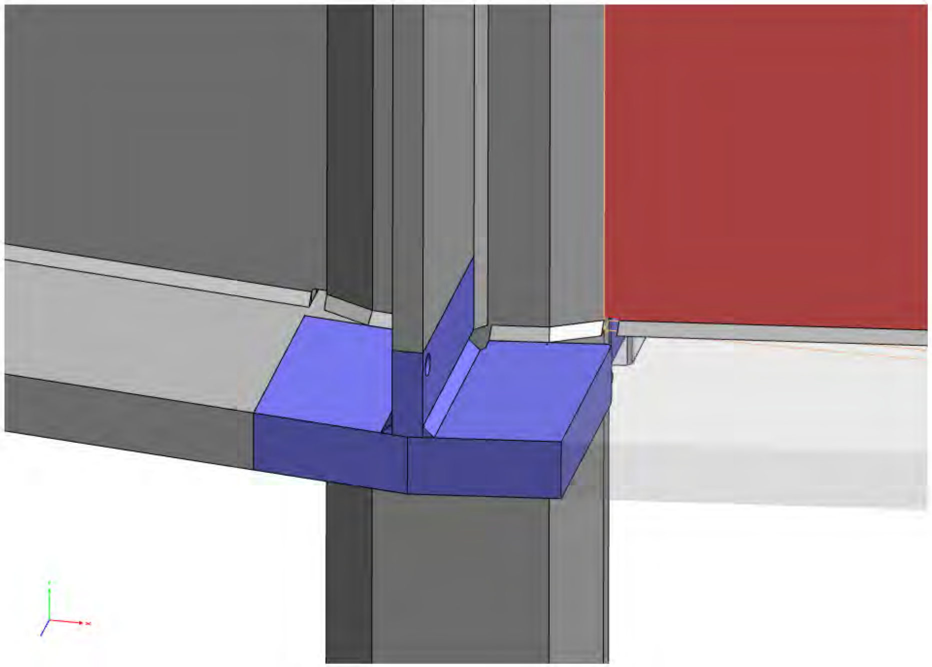
Fractured Fremont St Girder

Girder Sample Removal

- Four samples were removed from the fractured Fremont St. girders
  - North Girder, D.4-NE-NW (cracked)
  - North Girder, D.4-SE-SW (cracked)
  - South Girder, E.6-NE-NW
  - South Girder, E.6-SE-SW (cracked)

Girder Sample Removal

Typical Girder Sample



- Fremont St., south girder, E.6-SE-SW (cracked)

Girder Core Removal

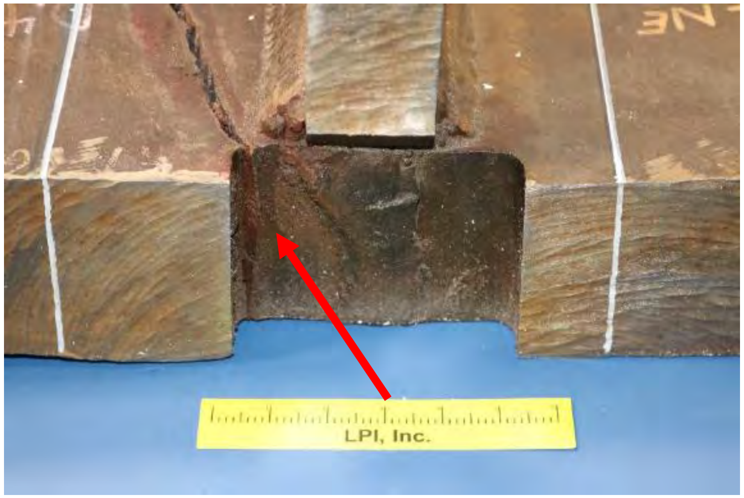
- Four 3-in. diameter cores removed from the girder flanges at First Street
  - NE-18
  - NW-18
  - SE-18
  - SW-18

Fracture Surface Examination

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

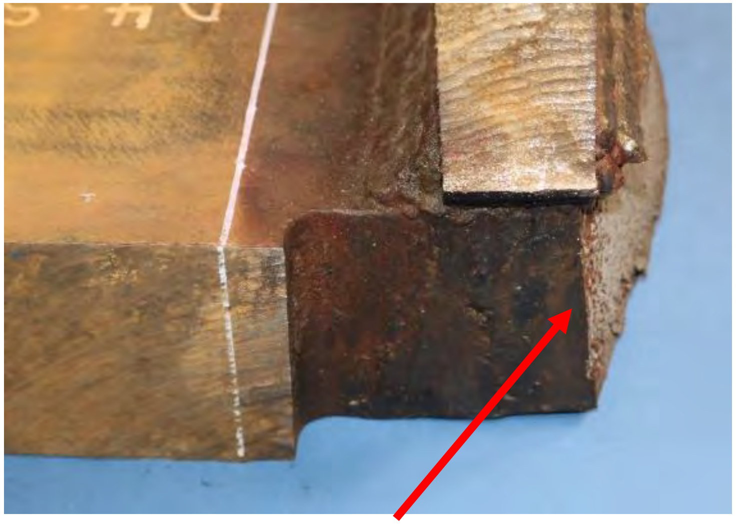
Fracture Surface Examination

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



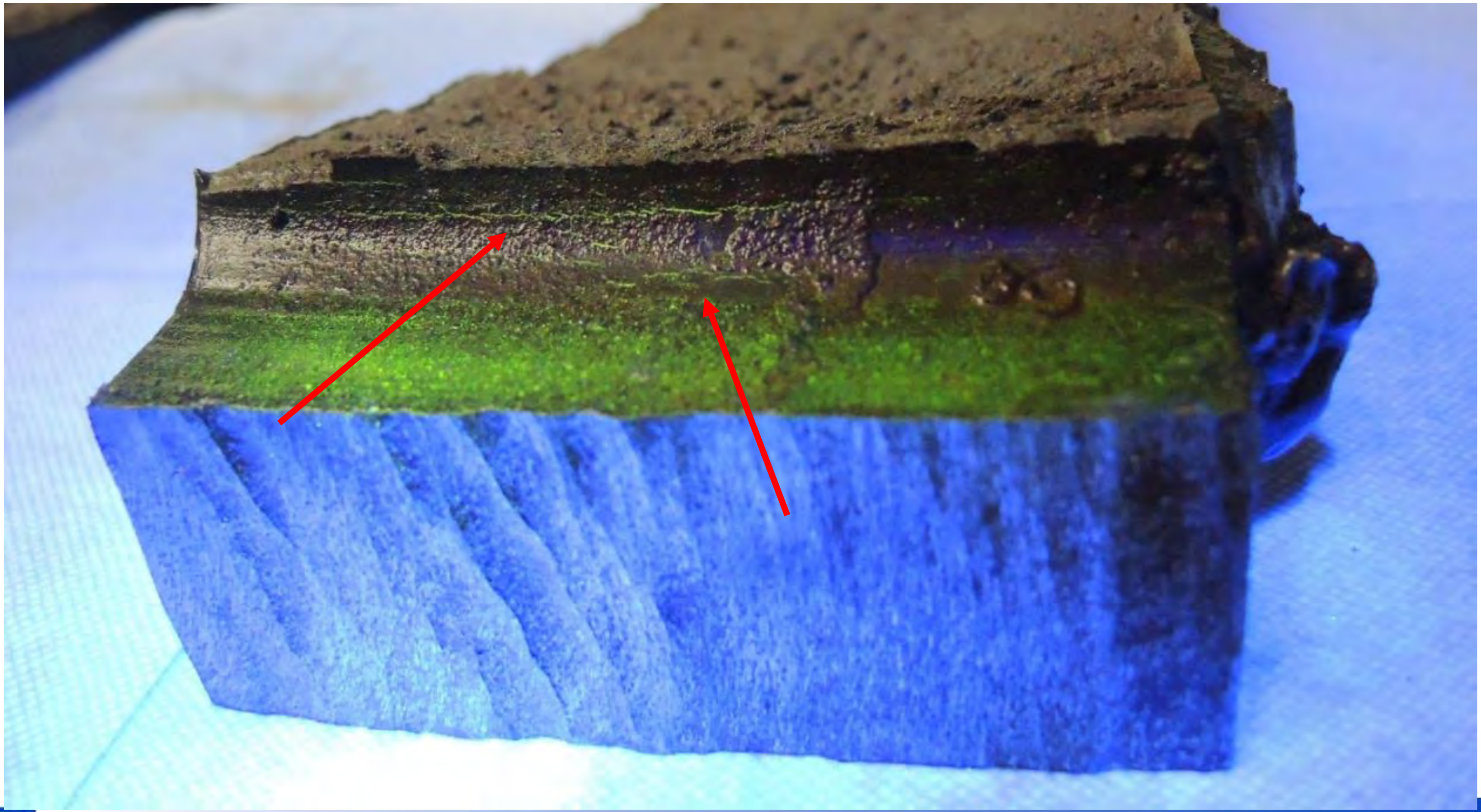
Fracture Surface Examination

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



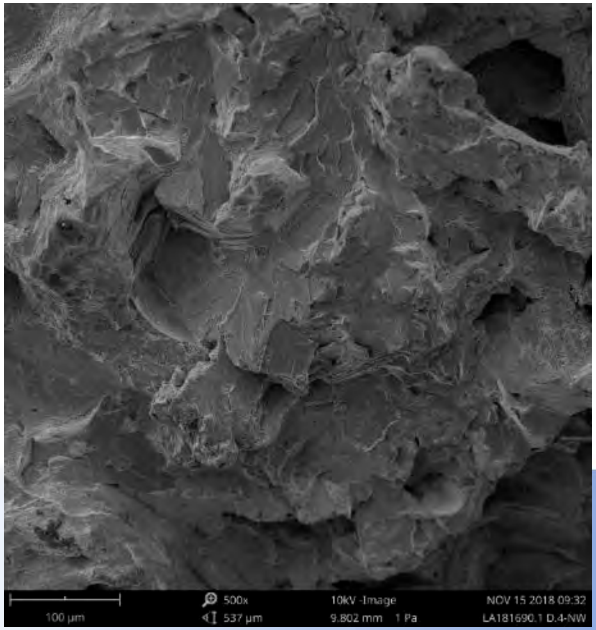
Fluorescent Magnetic Particle Testing

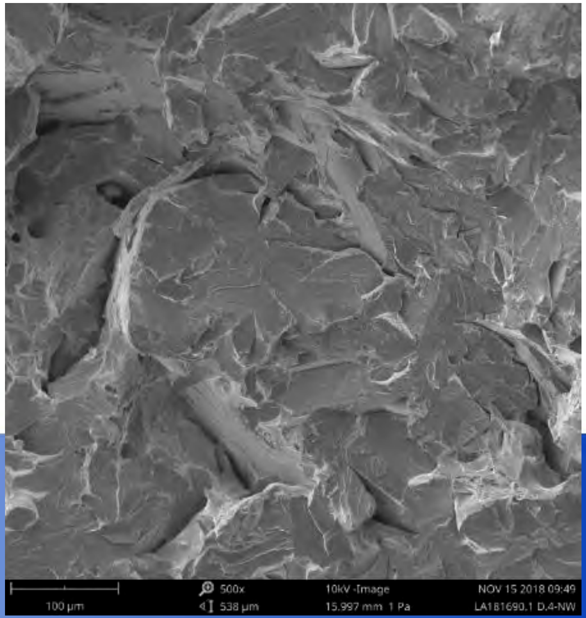
D.4-SW exhibited secondary cracking in the radius of the weld access hole.



Scanning Electron Microscopy (SEM)

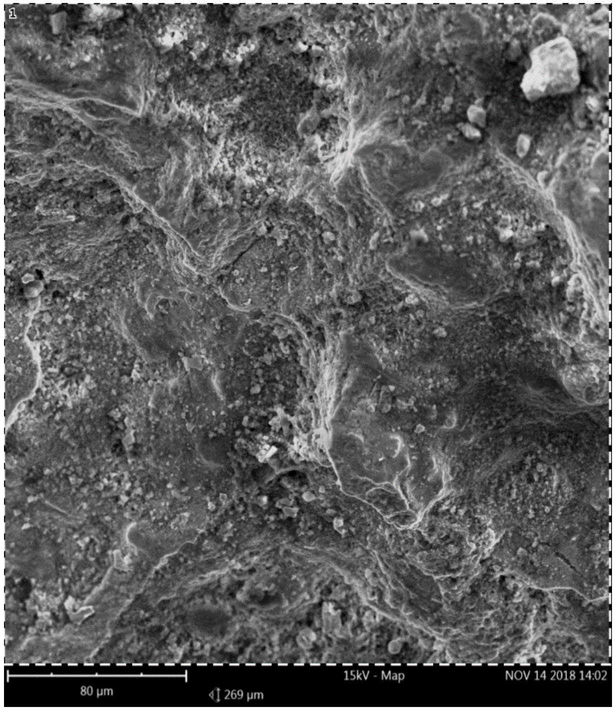
Initiation sites for all girder fractures exhibited tenacious dark oxide (high temperature) with underlying low-energy (brittle) cleavage fracture. The remainder of the fracture surfaces also exhibited a cleavage fracture morphology.



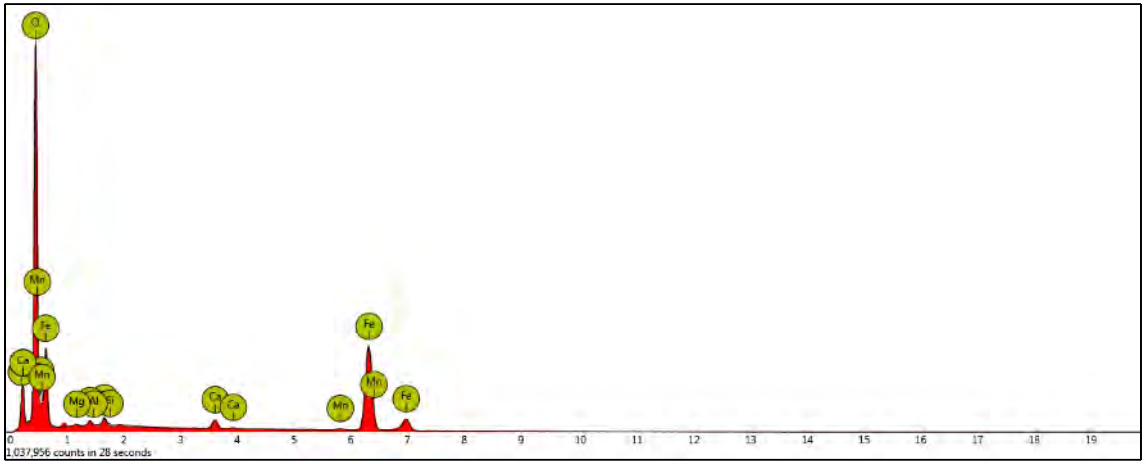


Energy Dispersive X-ray Spectroscopy (EDS)

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

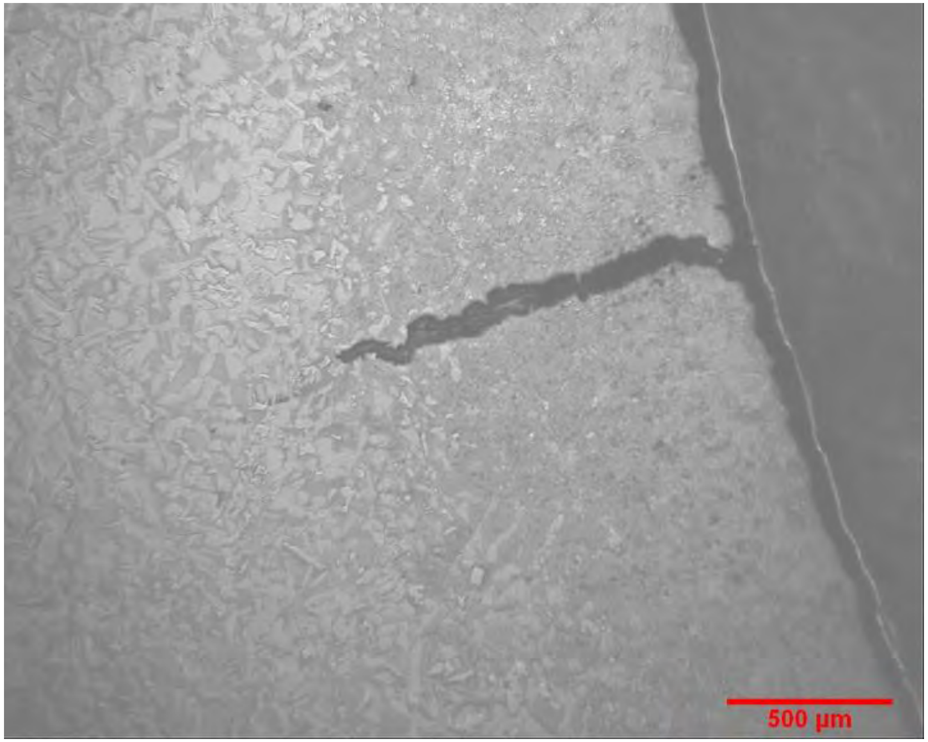


Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
8	O	Oxygen	74.92	48.85
26	Fe	Iron	20.61	46.91
20	Ca	Calcium	0.83	1.36
6	C	Carbon	2.25	1.10
14	Si	Silicon	0.49	0.56
25	Mn	Manganese	0.23	0.51
13	Al	Aluminium	0.42	0.47
12	Mg	Magnesium	0.24	0.24



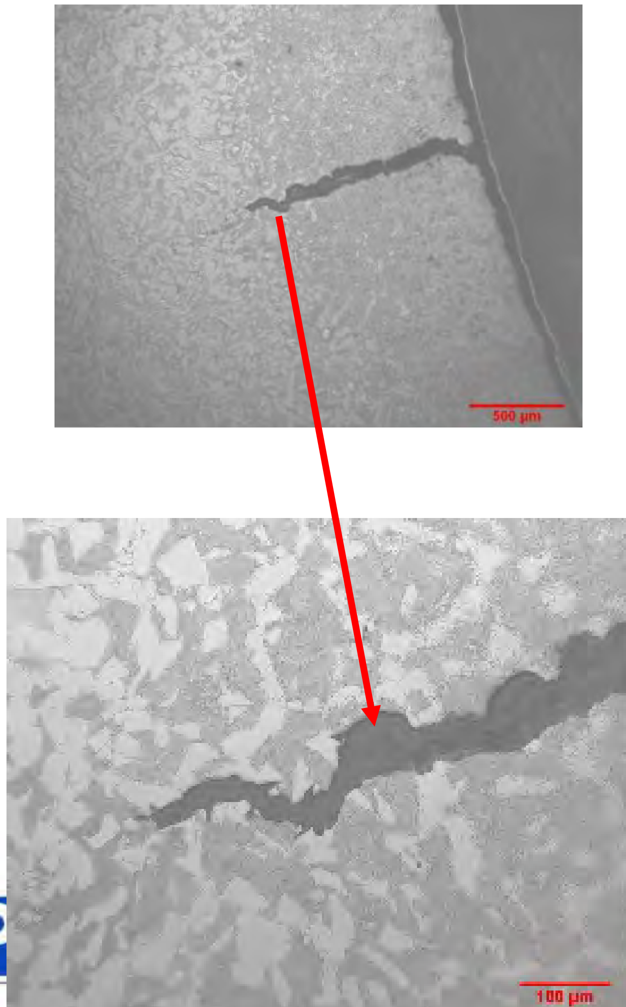
Metallography

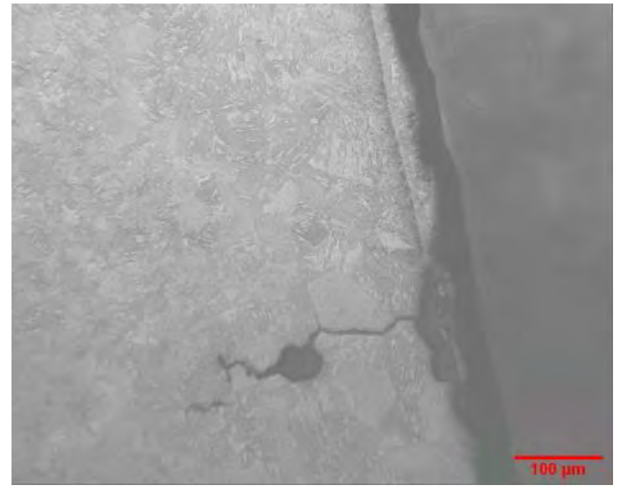
Metallographic cross-section specimens through weld access hole radii revealed a brittle martensitic surface layer from thermal cutting containing multiple shallow (micro) cracks.

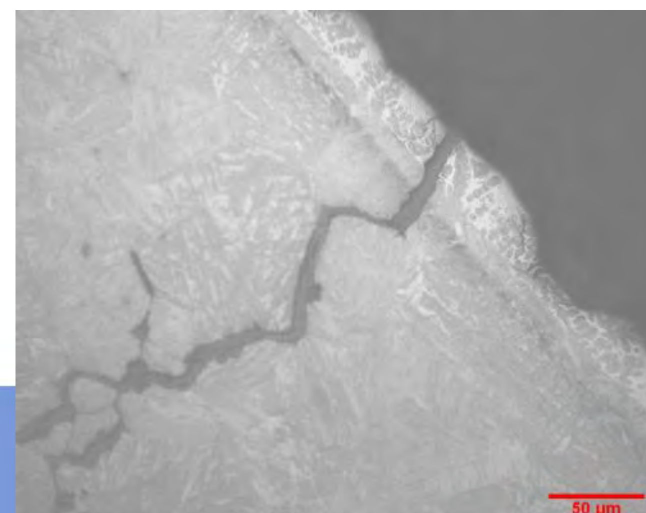


Metallography

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

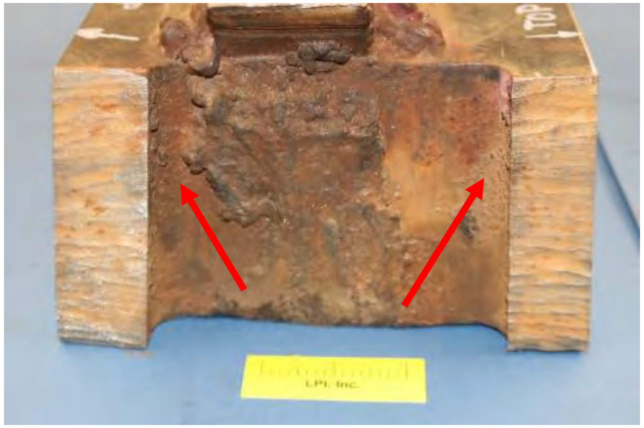






Surface Hardness Testing

Rockwell C surface hardness (HRC) measured in the radii of the thermally cut weld access holes revealed high surface hardness.

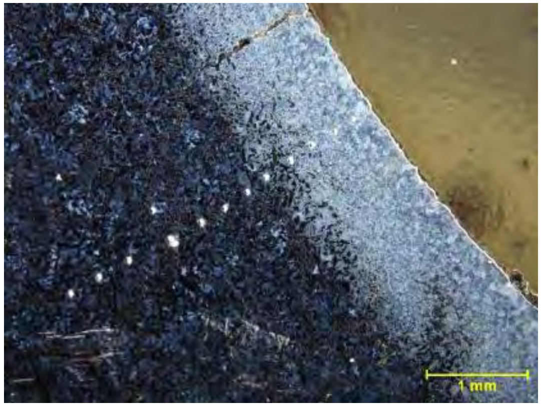


ID	D.4-NW	D.4-NE	D.4-SW	D.4-Se	E.6-NW	E.6-NE	E.6-SW	E.6-SE
1	41	50	37	34	42	42	37	21
2	39	47	35	35	59	31	42	39
3	36	54	47	35	40	41	33	50
4	46	40	37	47	31	46	52	33
5	36	37	33	38	40	28	48	44
Average	40	46	38	38	42	38	42	37

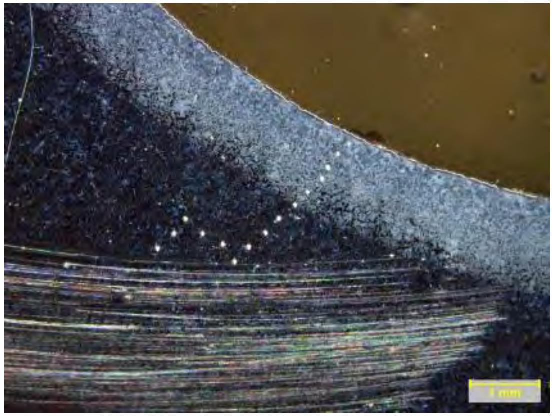
Microhardness Testing

Vickers Microhardness measurement locations, access hole surface to center

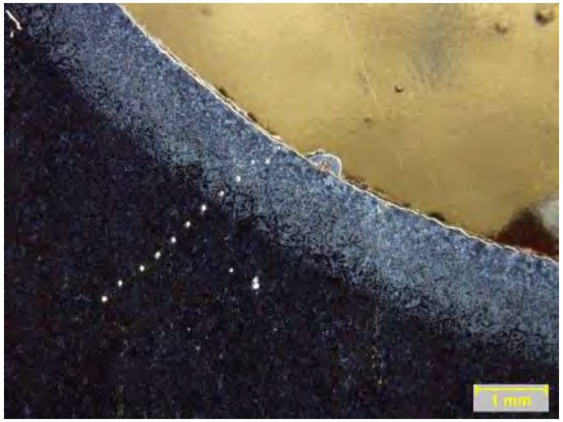
D.4-SW



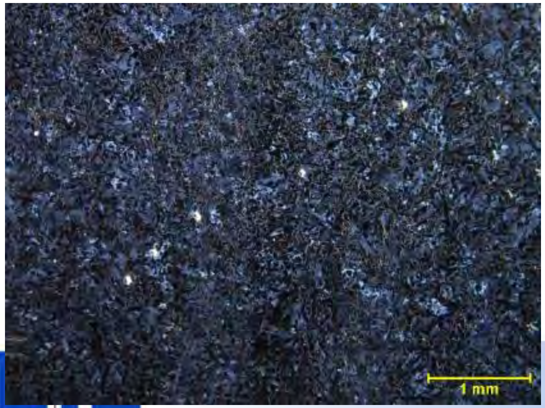
E.6-SW Sample 1

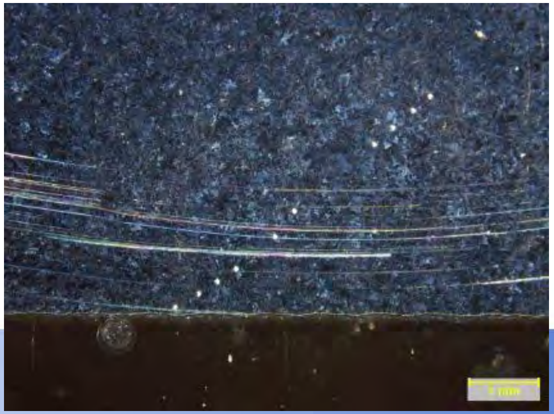


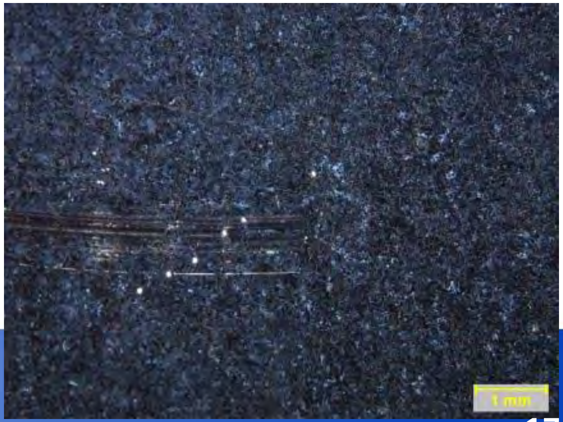
E.6-SW Sample 2



Vickers Microhardness measurement Locations, Specimen Center.







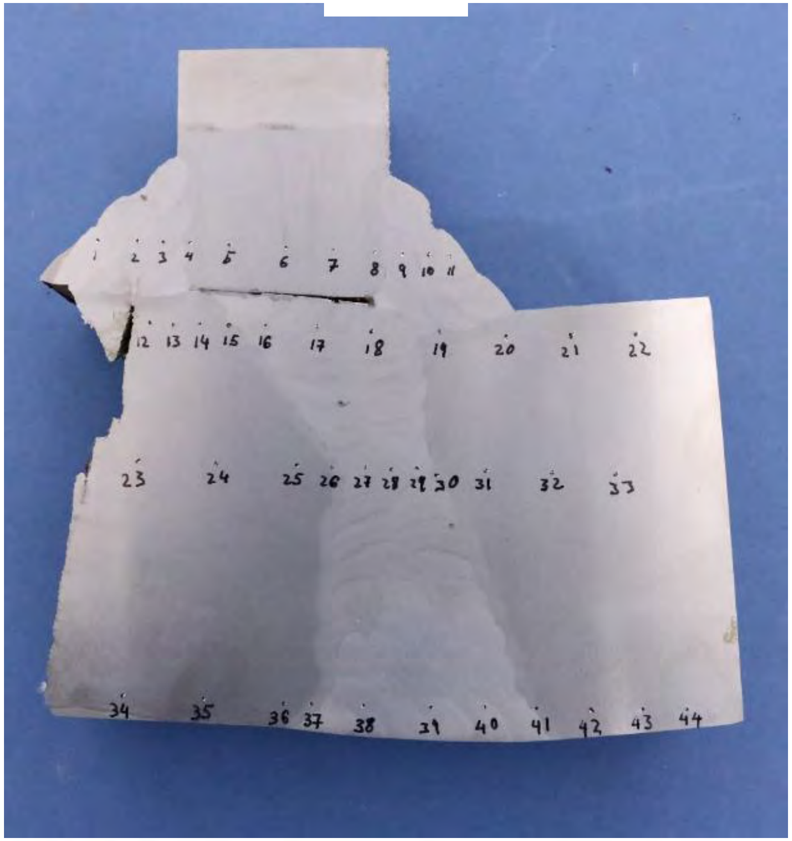
Microhardness Testing

Vickers Microhardness (HV) Testing									
ID	D.4-SW	E.6-SW Sample 1	E.6-SW Sample 2		ID		D.4-SW	E.6-SW Sample 1	E.6-SW Sample 2
1 (Surface)	406	443	458		**13**	(Center)	176	200	179
2	413	356	400		**14**		183	168	197
3	306	280	392		**15**		164	189	178
4	235	266	250		**16**		149	210	185
5	260	338	278		**17**		167	219	187
6	280	253	220						
7	235	238	203						
8	189	232	212						
9	216	202	201						
10	215	200	220						
11	220	198	215						
12 (Center)	213	200	202						

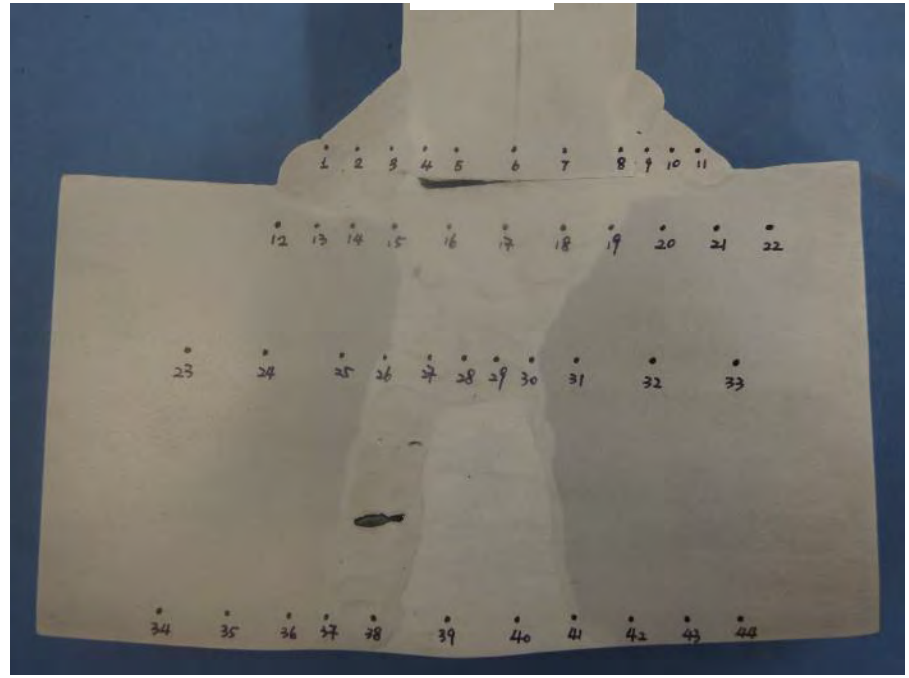
Hardness Testing

Rockwell B Hardness (HRB) measurements on girder cross-sections (~85-95 HRB).

D.4-S

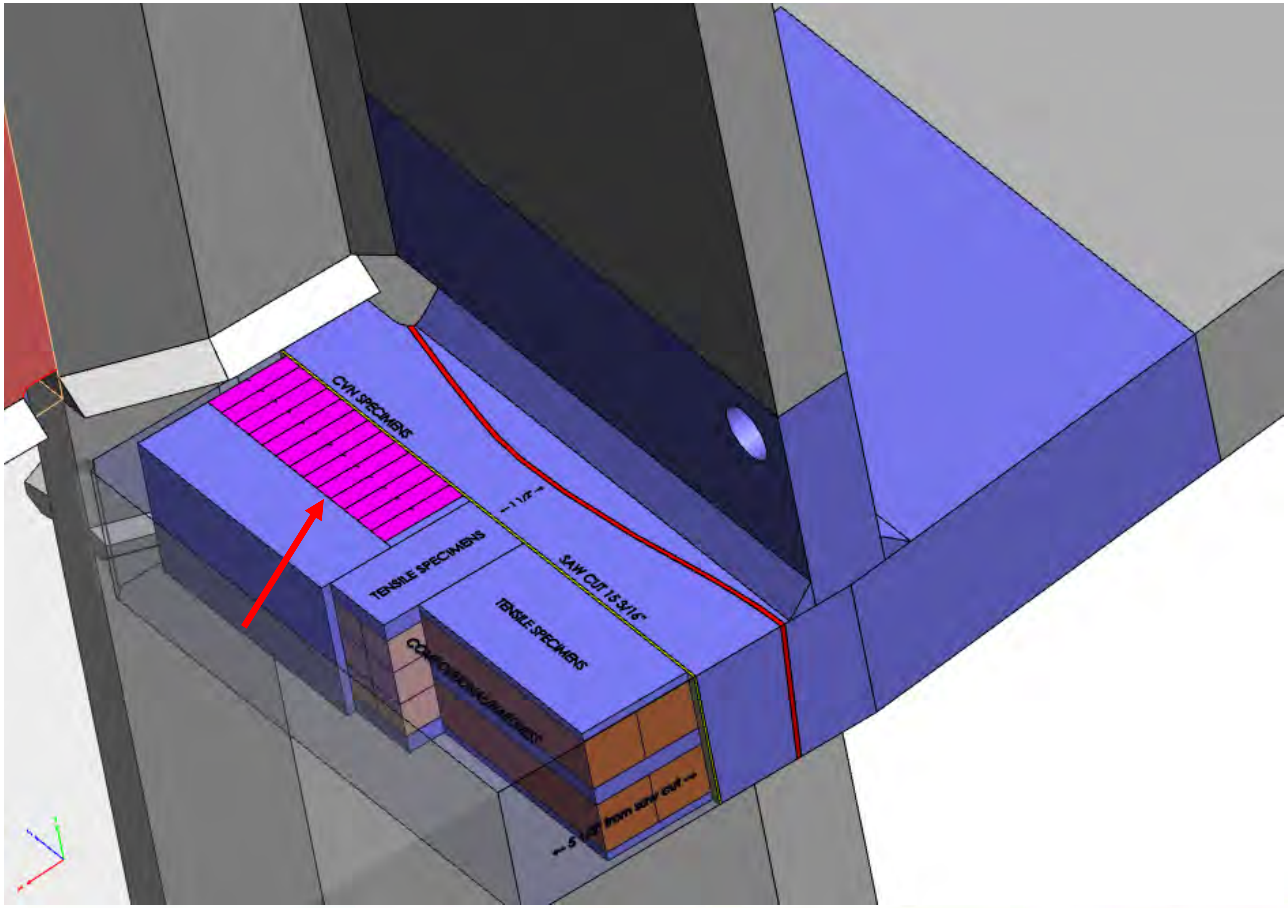


E.6-N



Charpy V-Notch (CVN) Impact Testing

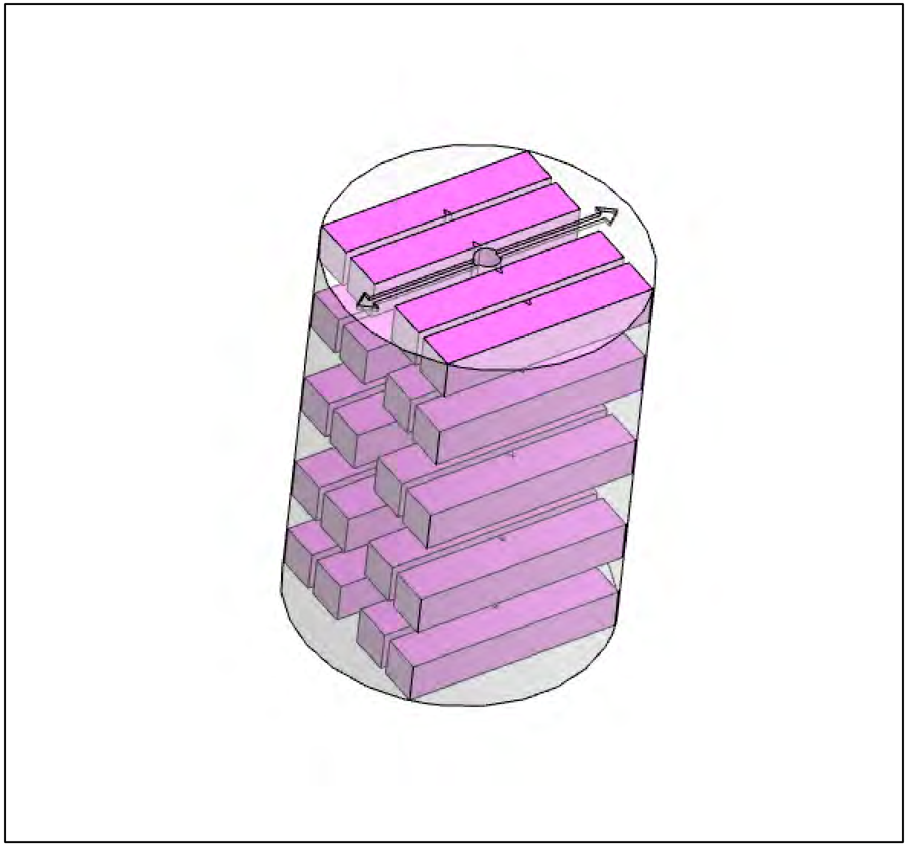
Fremont Street girder sample CVN specimen removal locations and orientation.



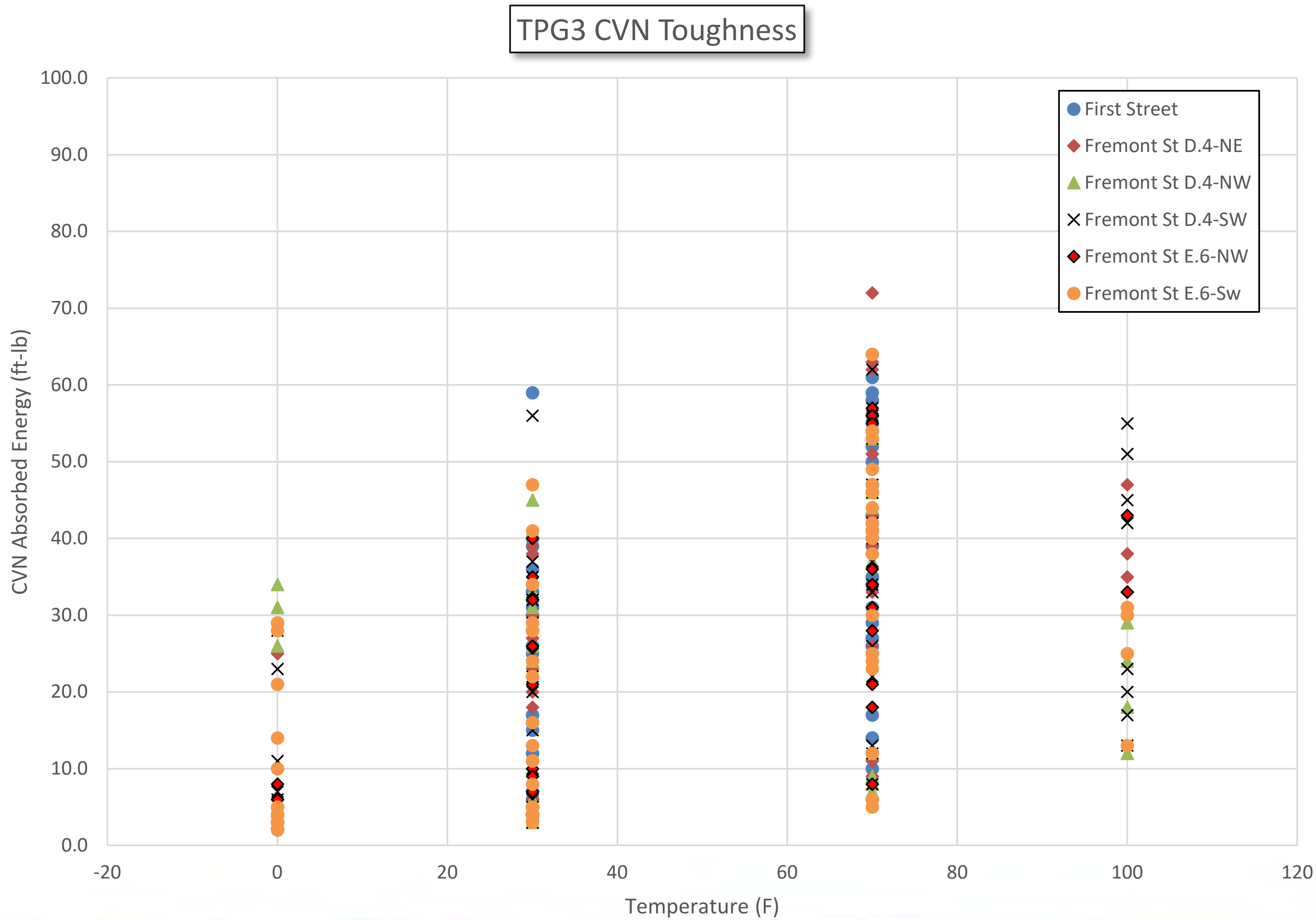
Charpy V-Notch (CVN) Impact Testing

First Street core sample CVN specimen removal locations and orientation.

.



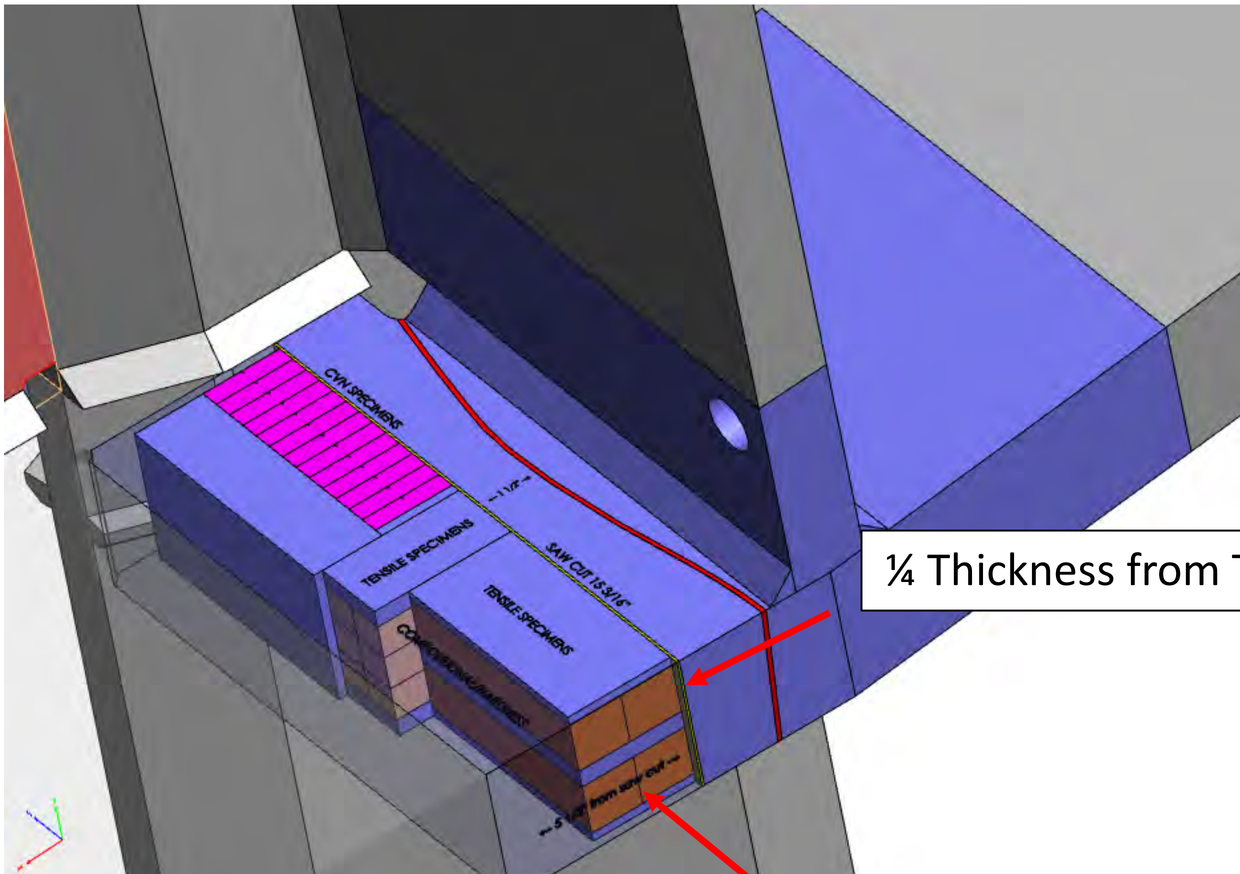
CVN Results



TPG3 CVN Toughness
CVN Absorbed Energy (ft-lb)
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-20
0
20
40
60
80
100
120
Temperature (F)
First Street
Fremont St D.4-NE
Fremont St D.4-NW
Fremont St D.4-SW
Fremont St E.6-NW
Fremont St E.6-Sw

Tensile Testing

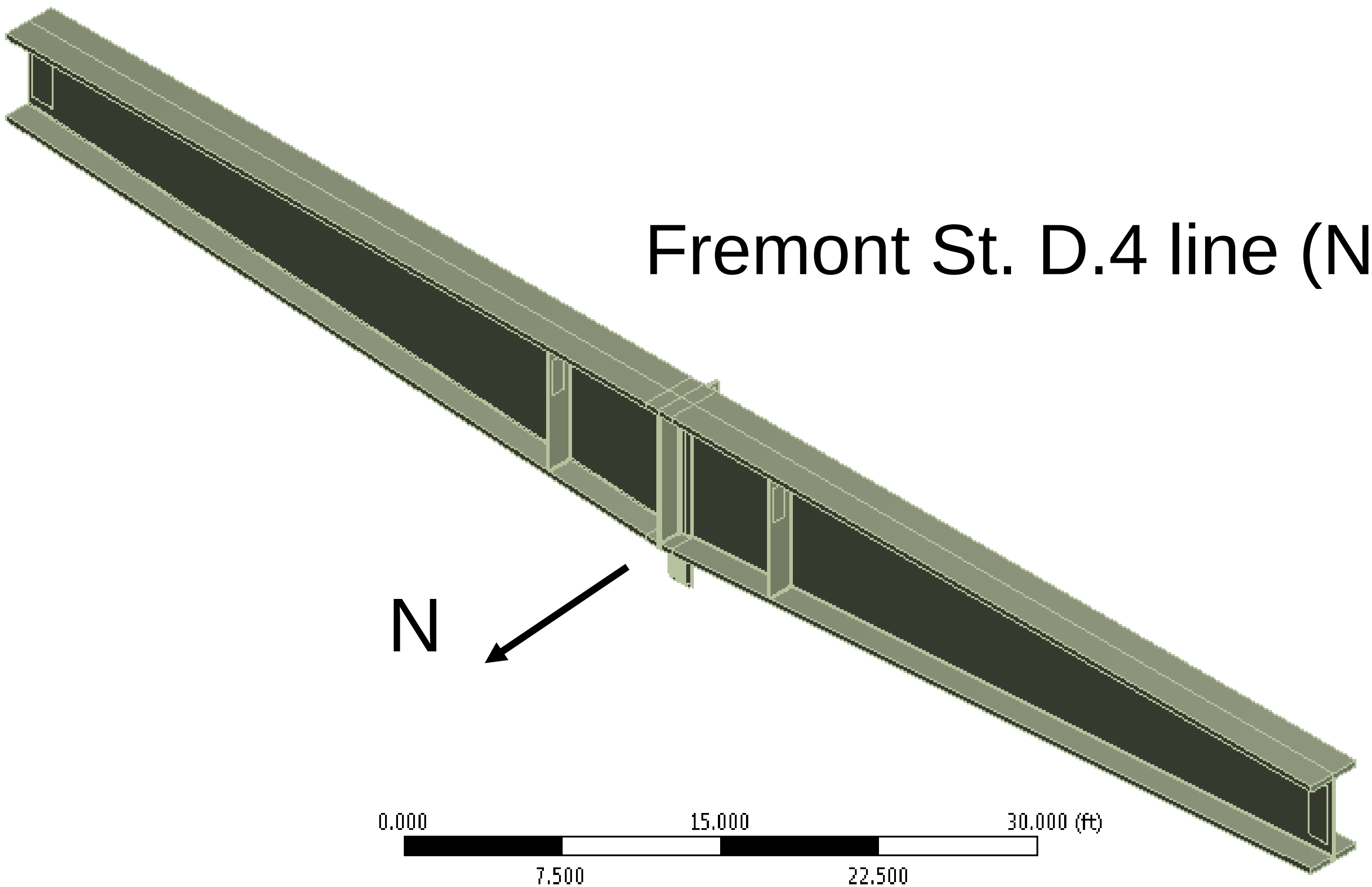
Tensile specimen locations



Tensile Testing

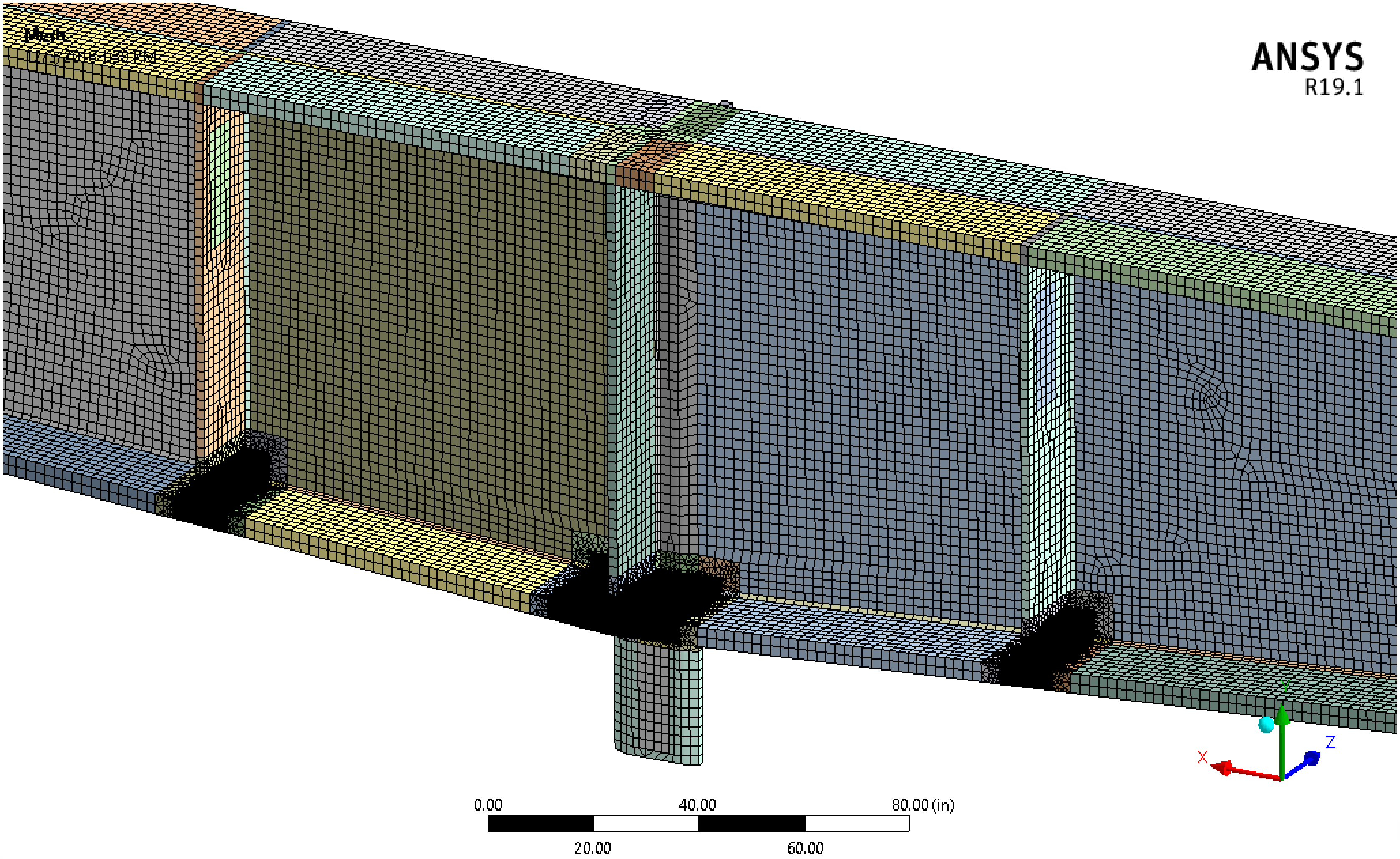
Girder Sample ID	Tensile ID	Tensile Direction	Tensile Location	Yield Strength, 0.2 % offset (ksi)	Ultimate Tensile Strength (ksi)	Elongation, 2 in. gage length (%)	Reduction of Area
D.4-SW	4-3-1	Transverse	¼ Thickness From Top	61	87	25.7	55.8
	4-3-2			61	87	26.6	54.8
	4-1-1		¼ Thickness From Bottom	60	87	25.0	56.1
	4-1-2			60	87	27.0	57.2
E.6-SW	6-3-1		¼ Thickness From Top	59	85	25.2	55.3
	6-3-2			60	86	23.3	55.8
	6-1-1		¼ Thickness From Bottom	59	86	23.1	54.3
	6-1-2			59	85	23.2	55.3

Global Girder Geometric Model

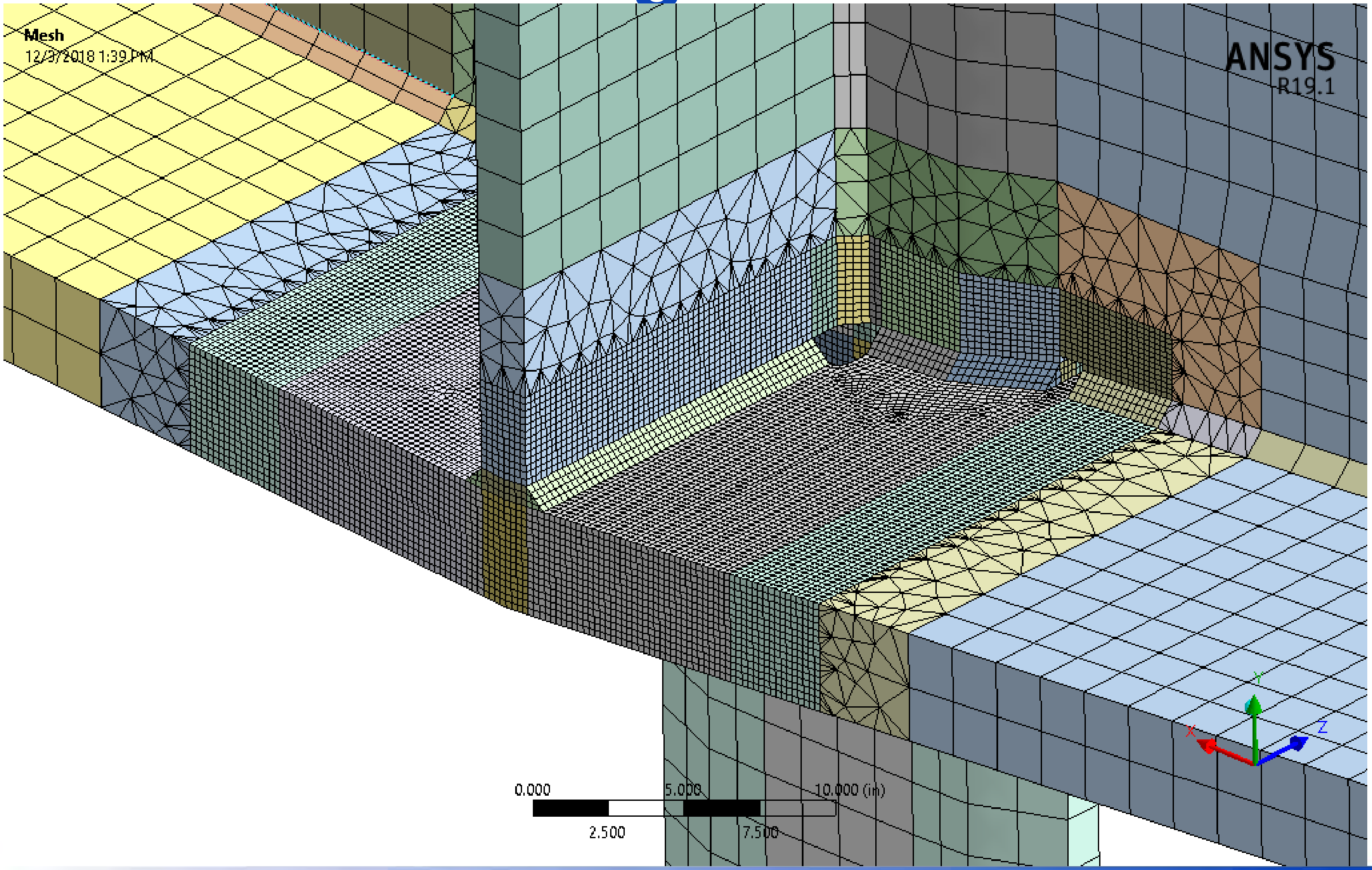


Fremont St. E.6 and 1st St. D.4 and E.6 lines are similar

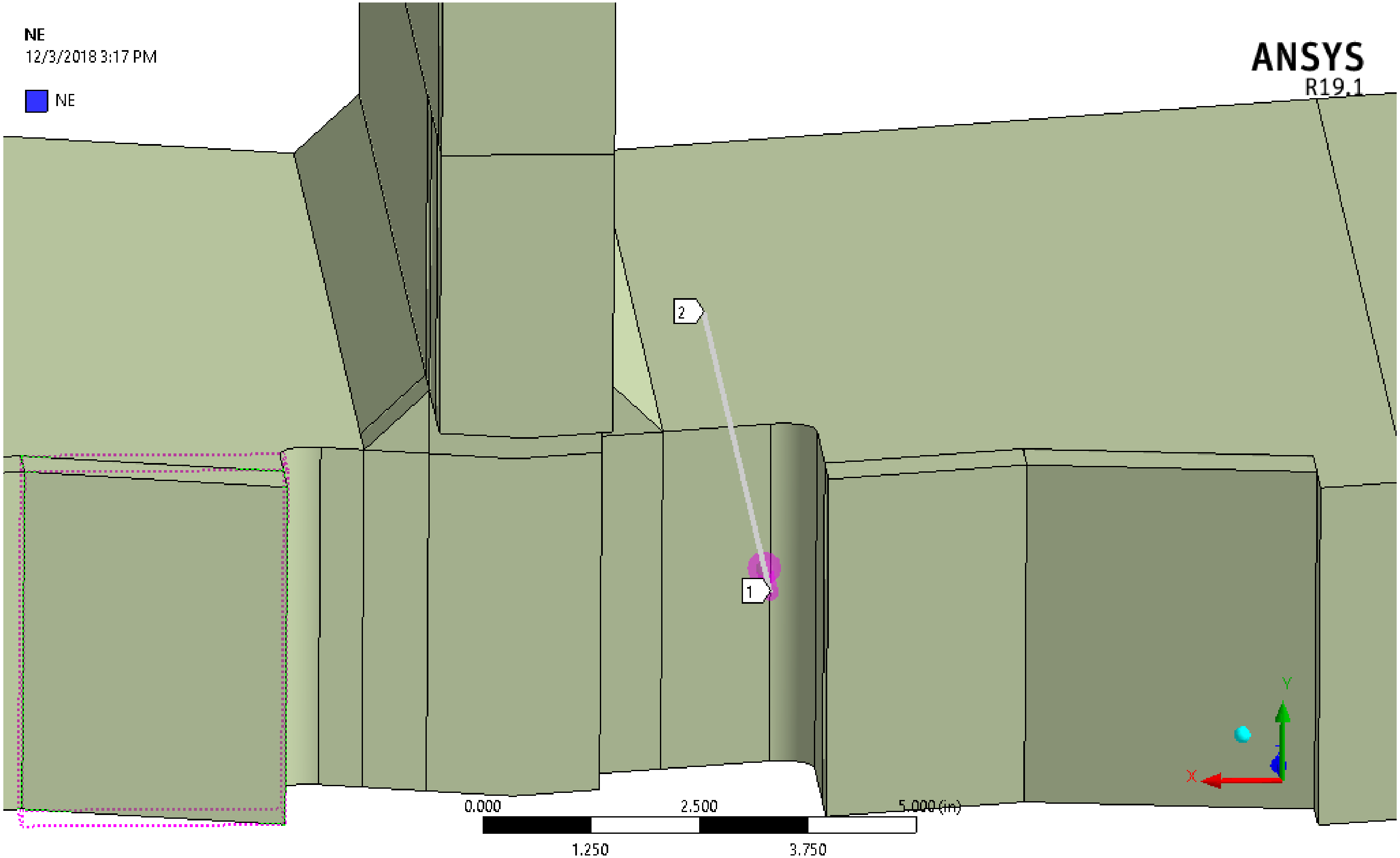
Mesh Overview



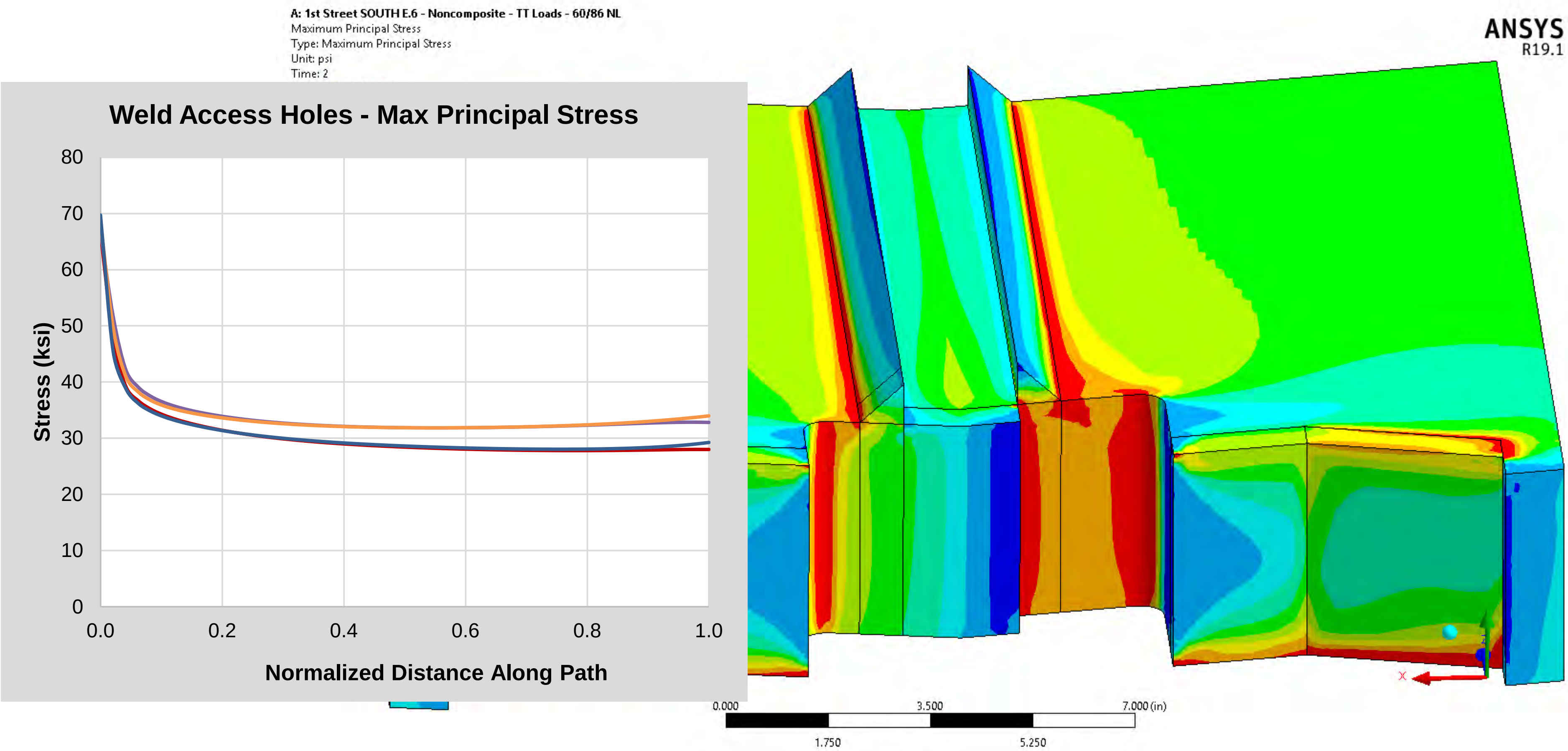
Mesh Detail at Weld Access Holes and Hanger Fillet Welds



Typical Access Hole Result Path



Access Hole – Max Principal Stress



Preliminary Findings

- Four girder flanges were sampled (2 per girder), three of which contained full flange width fractures.
- Analyses and testing performed, to-date, suggests the probable cause of the girder fractures at the TTC to be the formation of cracks in the girder weld access hole radii prior to service:
  - Initially, shallow (micro) surface cracks developed during thermal cutting of the weld access holes in the highly hardened and brittle martensitic surface layer.
  - Thereafter, larger pop-in cracks formed in two of the four flanges, potentially during butt welding of the flange plates.
  - Black, tenacious, high temperature oxide was present on both the shallow surface cracks and the larger pop-in cracks, confirming that both crack types formed at elevated temperatures.
  - The fracture origins were located in the mid-thickness of the flange where low fracture toughness, as confirmed by CVN toughness testing, provided little resistance to rapid, low-energy, brittle fracture.
  - CVN testing was performed on all flange samples at the top, ¼ depth, mid-thickness, ¾ depth, and bottom. ¼ depth CVN results were found to be consistent with the project specification and girder plate mill certifications.
  - Rapid, low-energy fracture of the flanges occurred as the girder was subjected to service loading on top of the normal residual stresses due to welded fabrication.
  - Further material testing and stress analyses are currently underway and will be considered in the final root cause assessment.

LPI Est. 1885

LPI, Inc. Consulting Engineers

Est. 1885

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

Thank You

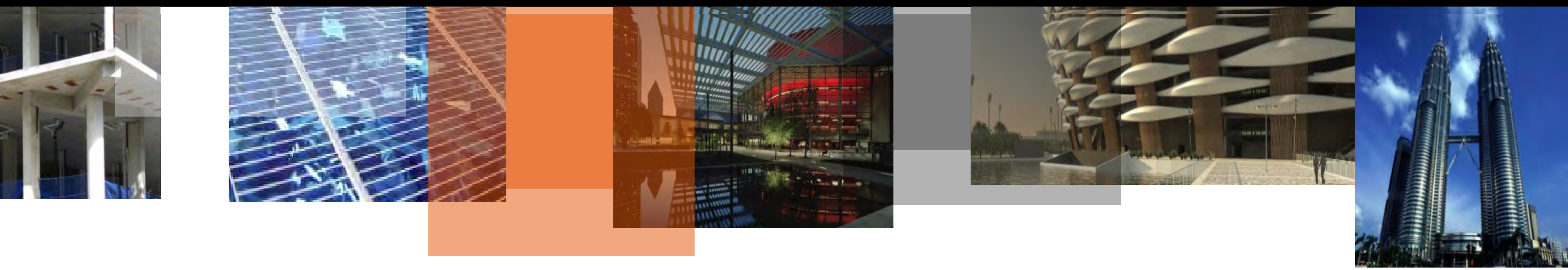
Lucius Pitkin – established 1885
304 Hudson Street • New York, NY 10013 • 212.233.2737

New York • Boston • Richland • Sydney • www.lpiny.com

Ensuring the integrity of today's critical infrastructure for tomorrow's world.

Thornton Tomasetti

Salesforce Transit Center
Girder Repairs



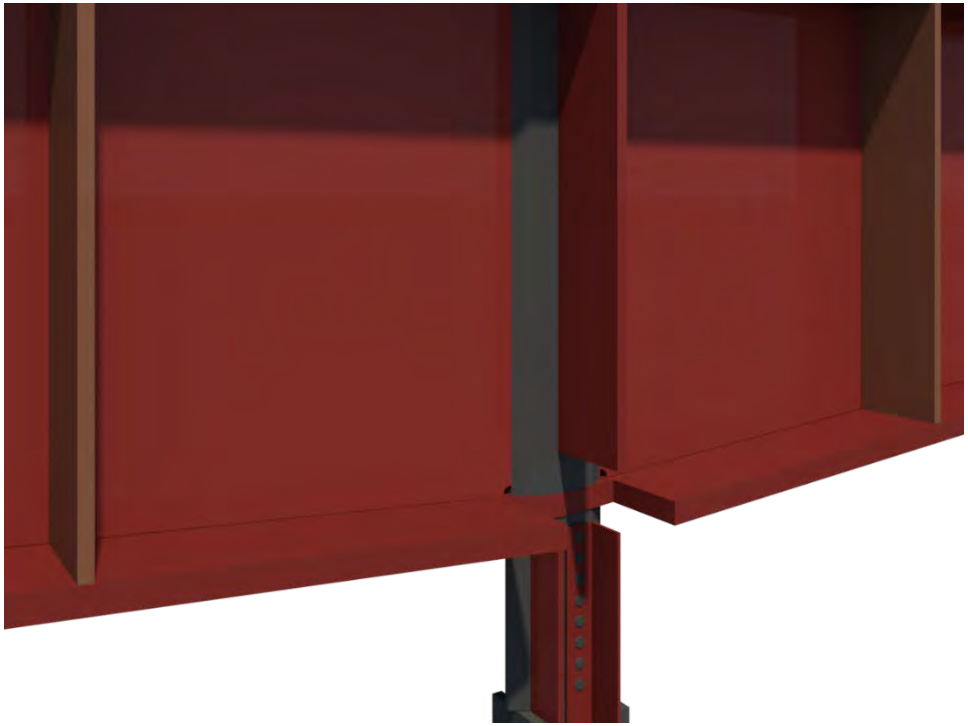
Bruce Gibbons, SE

December 13, 2018

Thornton Tomasetti

Fremont St. Girders - Repair

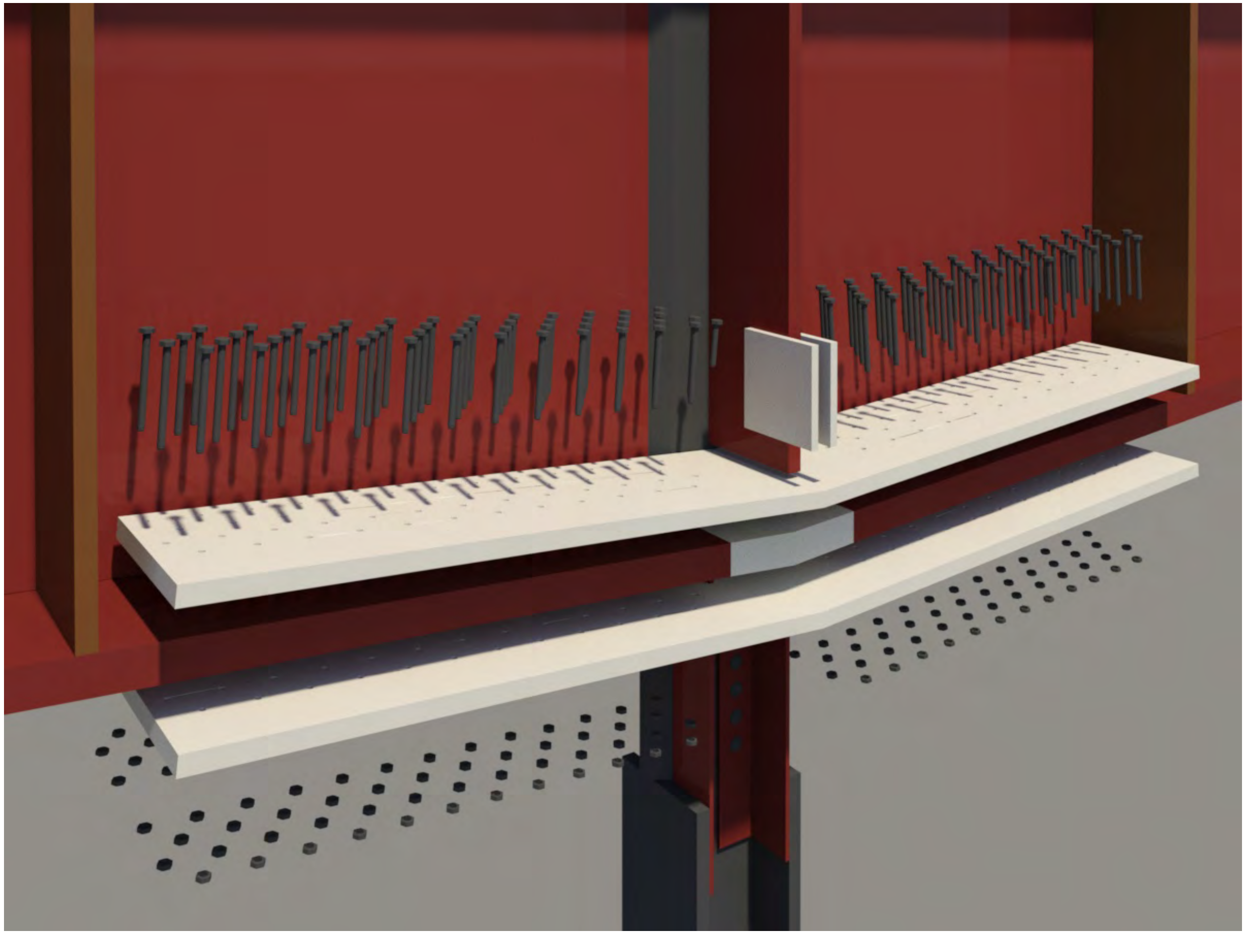
Objective: Restore the bottom flange to its original design capacity.



Grind the flame-cut surface of the web hangers to a smooth surface, and Magnetic Particle test.

Fremont St. Girders - Repair

Install bolted cover plates to replace flanges

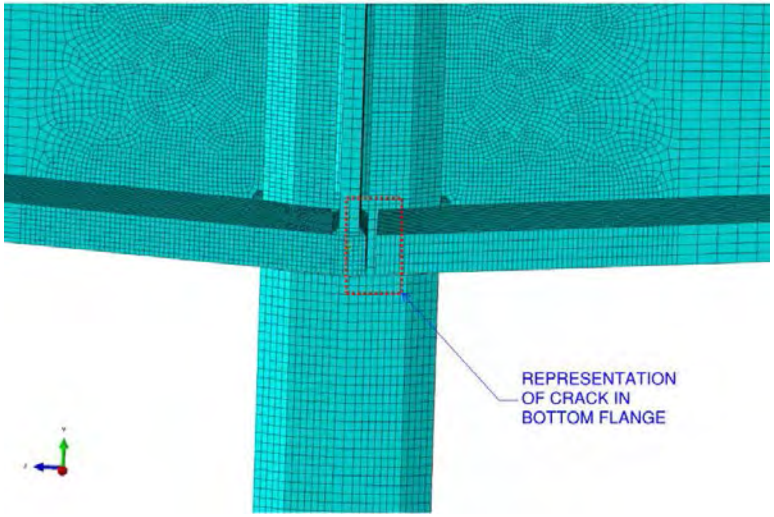


Fremont St. Girders - Repair

Extent of repair is localized to the fracture area

Load-Shedding Analysis

1. The cracked girders with reduced section had sufficient capacity to support the building dead loads and occupancy loads.



2. The actual forces in the girders were less than calculated using normal design procedures.

Load-Shedding Analysis

3. Analyze load paths after the Fremont St girders cracked, considering:
    a. Beam connection stiffness.
    b. Bus deck slab and roof slab stiffness.

4. Conclusions:
    a. Girders deflected 0.75” to 1” after cracking.
    b. Amount of load shed from the girder was up to 10%.
    c. Hanger loads reduced after cracking.
    d. Adjacent beams and columns were not overstressed.
    e. No indications of any damage, however we will test the integrity of girder bolted connections as a precaution.

Thornton Tomasetti

Thank You

Salesforce Transit Center - MTC Peer Review Panel (PRP)

- Background on PRP
- Scope and Status of Review

PRP Presentation for TJPA Board of Directors – December 13, 2018
Presented by: Andrew B. Fremier, Deputy Executive Director, MTC
Michael D. Engelhardt, Chair, PRP

Background on MTC PRP

- PRP created in response to request to MTC from San Francisco Mayor London Breed and Oakland Mayor Libby Schaaf.
- PRP membership established and PRP activities initiated on October 12.

Background on MTC PRP

Members of PRP:

• Michael Engelhardt, Ph.D., P.E. (Chair)	Professor – University of Texas at Austin, TX
• John Fisher, Ph.D., P.E.	Professor Emeritus – Lehigh University, Bethlehem, PA
• Brain Kozy, Ph.D., P.E.	Structural Engineering Team Leader – Federal Highway Administration, Washington, DC
• Thomas Sabol, Ph.D., S.E.	Principal, Englekirk Institutional—MBE, Los Angeles, CA
• Robert Shaw, P.E.	President, Steel Structures Technology Center, Howell, MI

Technical Support to PRP:

• Bill Mohr, Ph.D	Edison Welding Institute, Columbus, OH

MTC PRP: Process

- PRP has strived to provide an independent, expeditious, and thorough review.
- Progress through online and in-person presentations and meetings, site-visits.
- PRP has received excellent cooperation from TJPA.

MTC PRP: Scope of Review

1. Load capacity of the temporary shoring system
2. Sampling and testing plan for the material from the fractured steel girders
3. Cause of failure, as informed by the material test results and design analysis
4. Current condition of structural elements directly affected by the steel fractures
5. Repair solution, as informed by the cause of failure and current condition

MTC PRP: Status of Review

1. **Shoring:** Reviewed and concur with shoring approach.
2. **Testing and Sampling Plan:** Reviewed and concur.
3. **Cause of Failure:** General concurrence with preliminary findings; review on-going.
4. **Other Impacted Locations:** Review on-going.
5. **Repair:** General concurrence with design approach; review on-going.