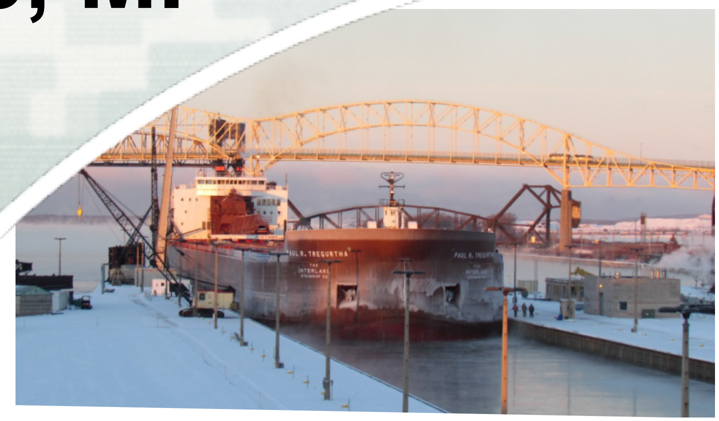
MITER GATE EMBEDDED ANCHORAGE
SOO LOCKS
Sault Ste. Marie, MI



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SOO LOCKS

• The Soo Locks are located on the St. Marys River at Sault Ste. Marie, Michigan, on the international border with Canada.

• There are two operating locks at the Soo, the MacArthur Lock, (1943) and the Poe Lock (1968).

• POE Lock - Approximately **70 percent** of the Great Lakes fleet carrying capacity can only pass.

• Approximately $160 million – 30 day unscheduled closure of the Soo Locks would have a **direct economic impact to the shipping industry**

• Half of all steel produced in the U.S. is manufactured with domestically mined ore and over **92% of the iron ore mined in the U.S**. traverses through the Soo Locks. Steel-dependant industries contribute more than 10% to the total U.S. Gross Domestic Product.

•The Soo Locks shut down from mid January to early April because of ice and extreme weather

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POE Lock General Information

- The POE lock was formally dedicated and placed into service on 26 June 1969 (47 years old).
- POE Lock chamber 110 ft x 1200 ft
- 32 ft depth of water over the sills at normal lower pool.
- Head of 21.5 feet
- Approx. 63 ft wide gate leaf between contact blocks
- Approx. 37 ft tall between CL gudgeon and sill
- Miter angle 1:3, or 18.4 degrees
- 1-Upstream Operating Gate, 2 Downstream Operating Gates, and 1 Downstream maintenance Gate
- ASTM A36 Steel

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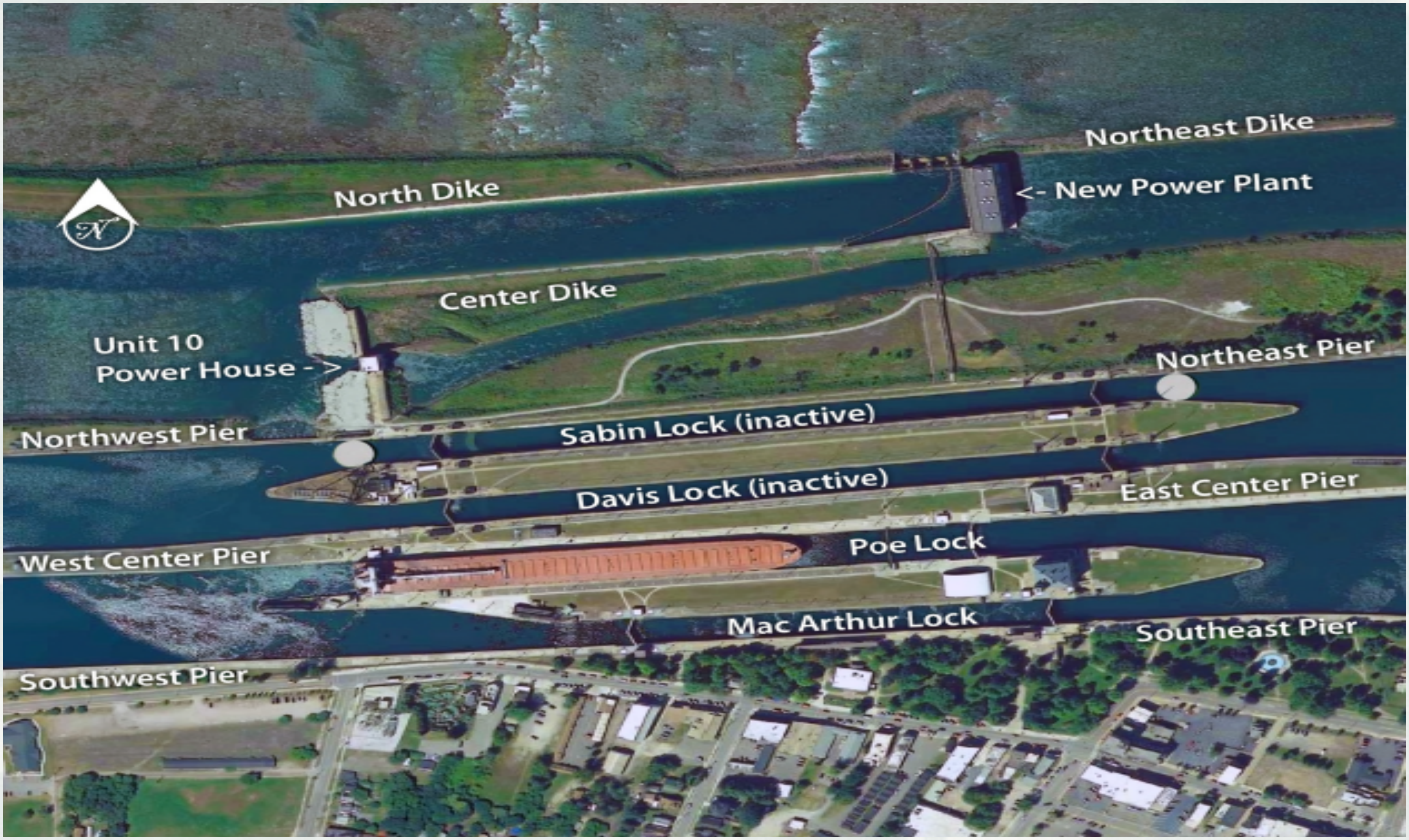

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Plan View No. 1,2,3,4

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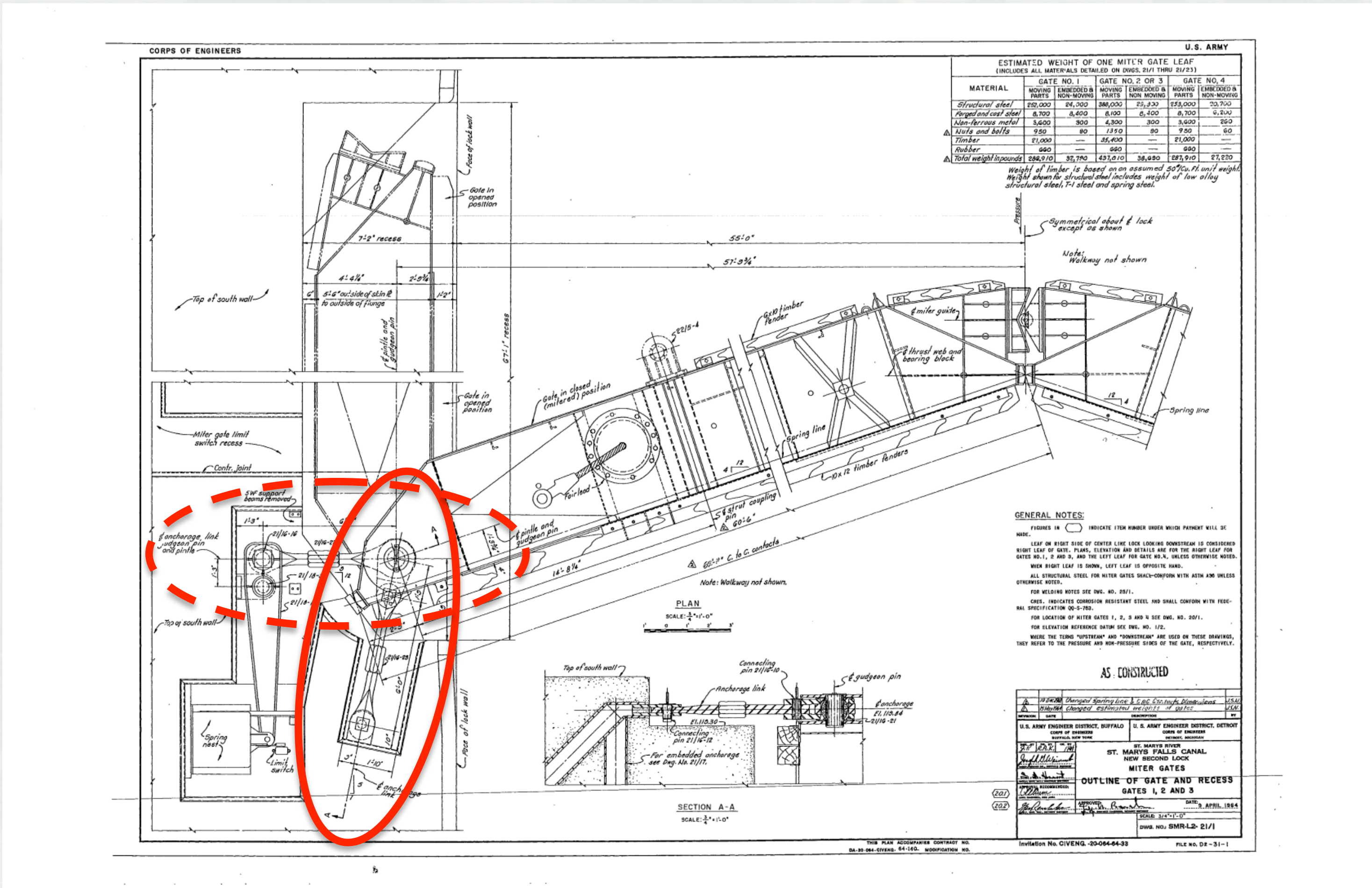
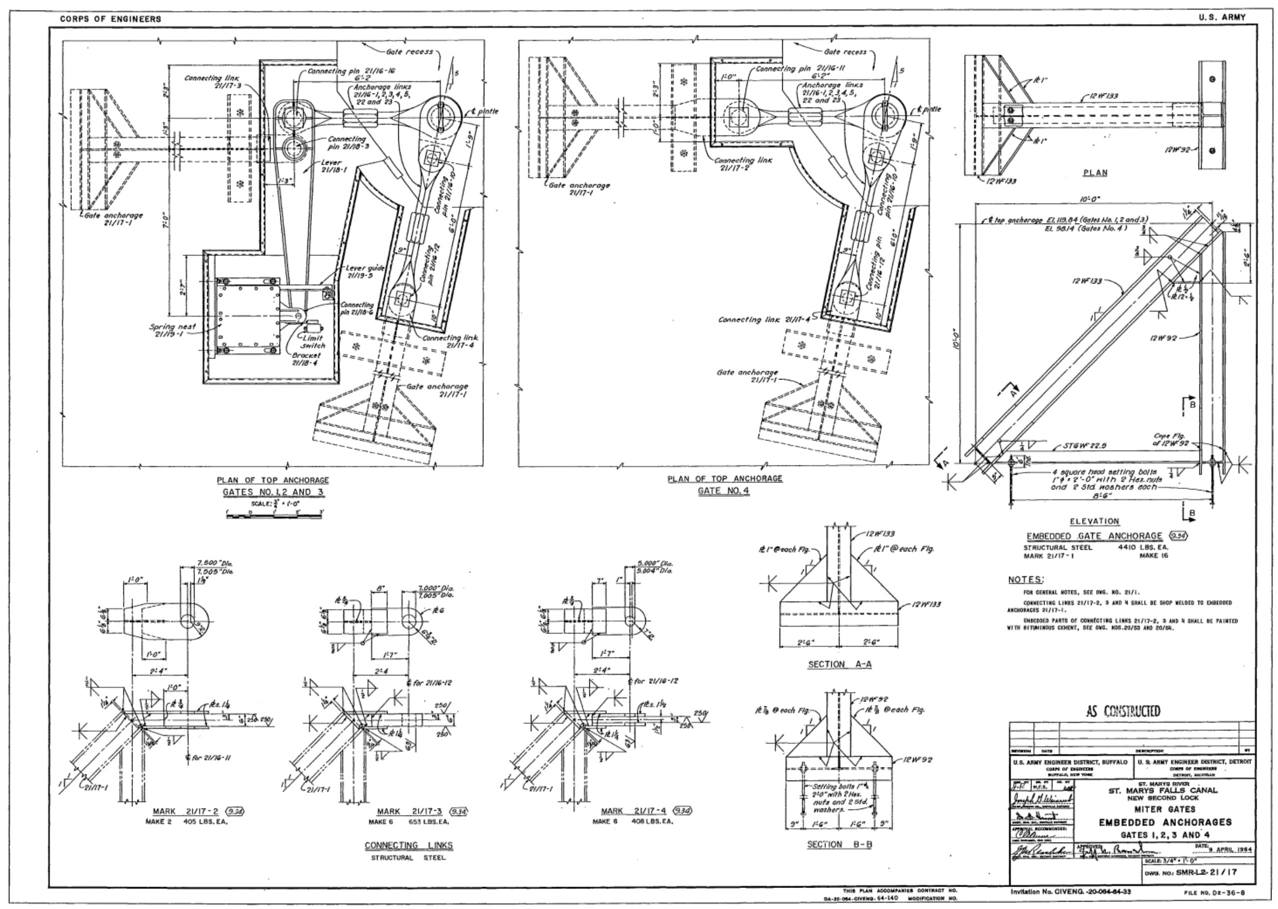
SOO LOCKS
Miter Gate Embedded Anchorage

1. The miter gate embedded anchorages were being studied in the Major Rehab Report (MRR)
2. The study had lead to a more detailed analysis with results that revealing that there is a potential near-term risk of failure in the upper region of the embedded anchorage.
3. The study concluded that Embedded Anchorages exceeded their life expectance and will likely perform until they experience a “SUNNY DAY” brittle failure with little to no outward signs of distress or warning.
4. The Miter Gate Leaf would most likely collapse into the chamber during a normal everyday operation.

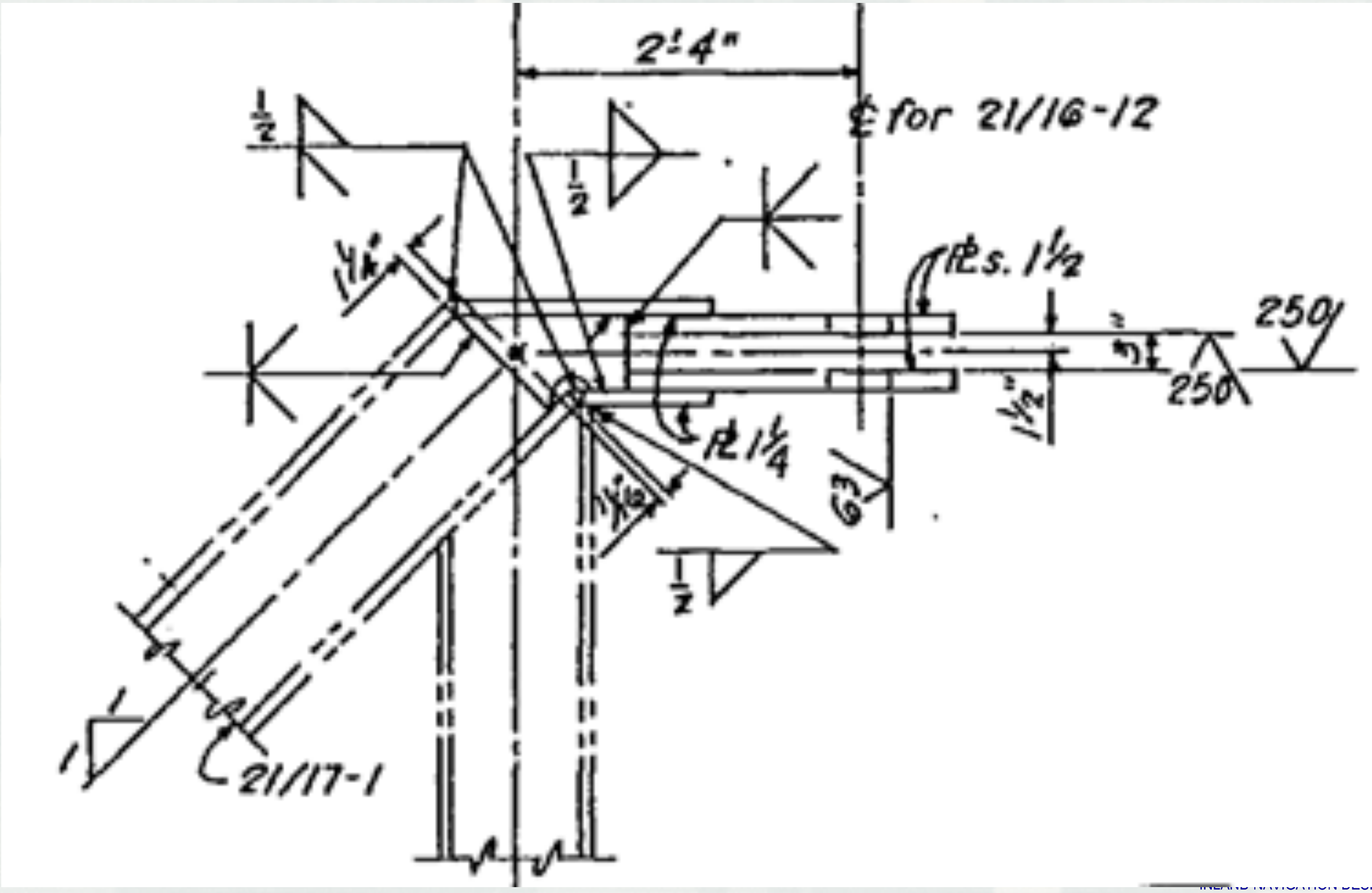
Miter Gates


CORPS OF ENGINEERS
U.S. ARMY
ESTIMATED WEIGHT OF ONE MITER GATE LEAF
Top of south wall
Gate in opened position
Gate in closed (mitered) position
Spring line
Note: Walkway not shown
PLAN
SECTION A-A
GENERAL NOTES:
AS CONSTRUCTED
ST. MARYS FALLS CANAL
NEW SECOND LOCK
MITER GATES
OUTLINE OF GATE AND RECESS
GATES 1, 2 AND 3

Embedded Anchorage



Embedded Anchorage



Sequence Of Actions, Steps

1. MRR Study
2. Stress Analysis with 3 Dimensional linear finite element analysis (FEA)
3. Fatigue Life Analysis base upon FEA results
4. Instrumentation to determine actual cyclic loading, Strain Gages. (BDI Report).
5. Concrete Removal and exposure of the upper embedded anchorage region of one leaf of gate 3S, for inspection.
6. Inspection (visual then NDT) followed with crack repair
7. Advanced Non-Linear Finite Element Analysis and Fatigue Life Analysis using actual load test data, concurrent with concrete removal.
8. Concrete Removal and exposure of the upper embedded anchorage region of gate all gate leafs for gates 1,2 & 3, for inspection.

9. Implement a Weld Crack repair process
10. Implement a structured inspection and monitoring program
11. Perform a “Design Charrette” to determine optional courses of actions for a permanent solution.
12. Perform a “Risk Assessment” to enable Senior Management to make a risk base decision on optional solutions with corresponding funding.
13. Develop Plans and Specifications for Permanent Embedded Anchorage Solution
14. Implement additional Risk Reduction Measures with the installation of a structural stiffener system.
15. Perform Fracture Mechanics Analysis to determine crack propagation period to sequence inspection and monitoring program pin plate inspection
16. Fabricate and erect permanent solution during FY 16 and FY 17

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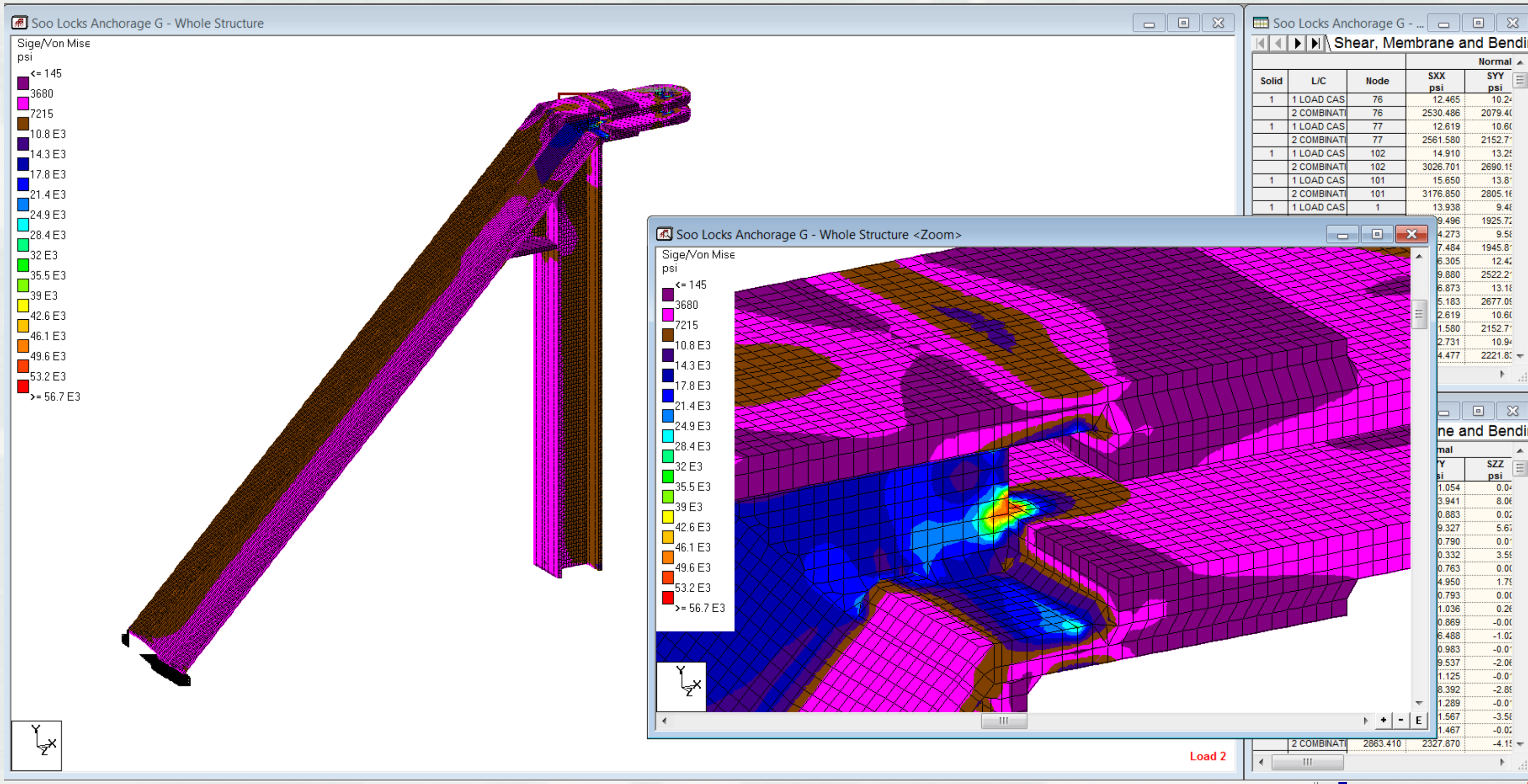
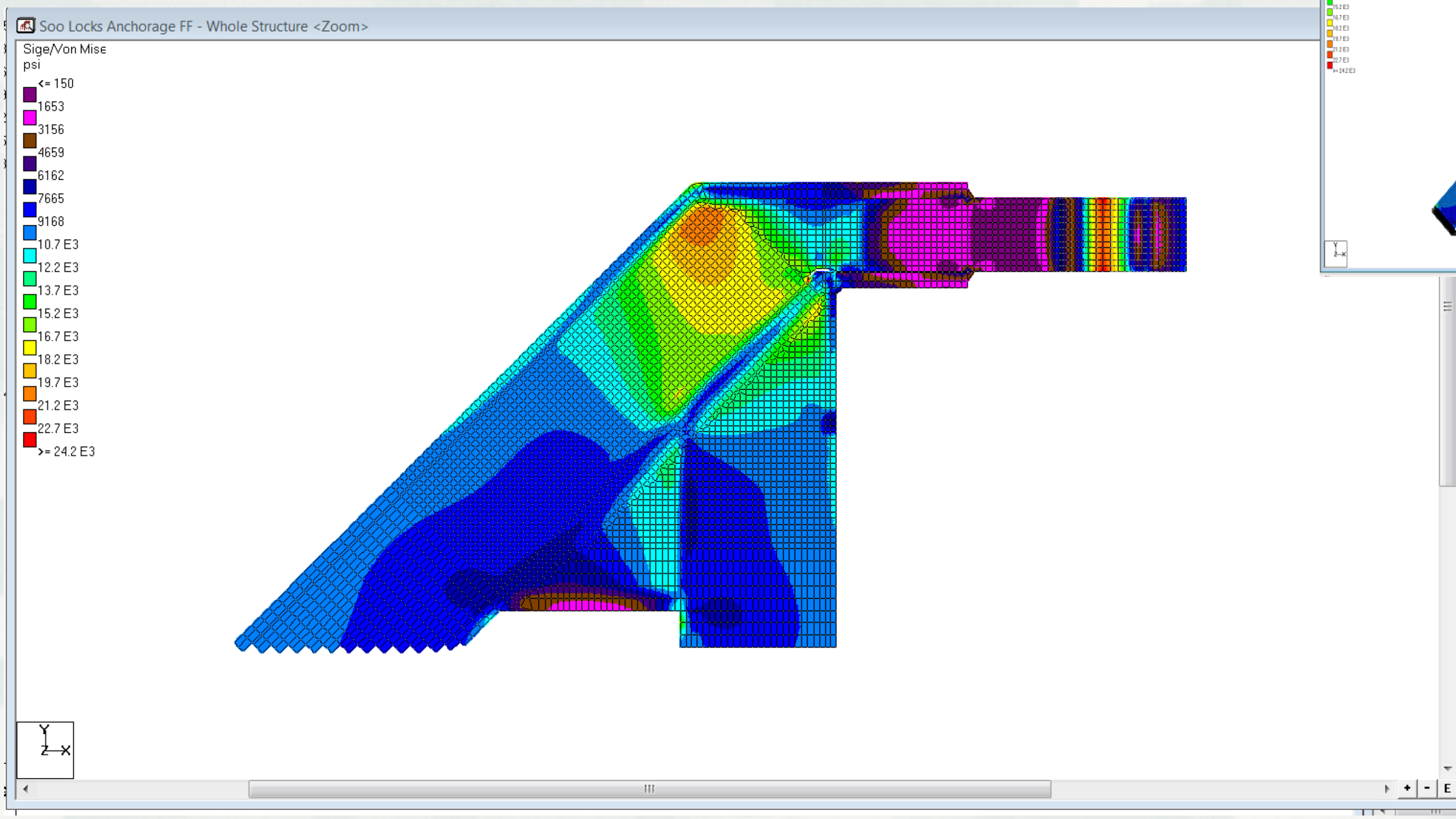
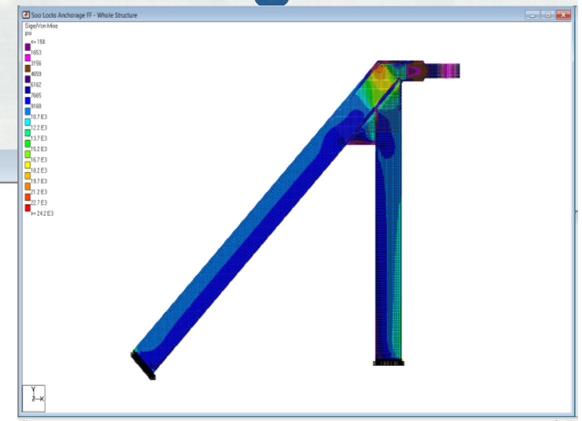
Step-2 Linear FEA Secondary Anchorage Sige / Von Mise Stress (psi)



Stress results of the secondary anchorage for gate #1 are shown to be 40 ksi to 49 ksi

Step-2 (continued) **Linear FEA Primary Anchorage**
Sige / Von Mise Stress (psi)





Stress results of the Primary anchorage for gate #1 are shown to be 20 ksi to 25 ksi

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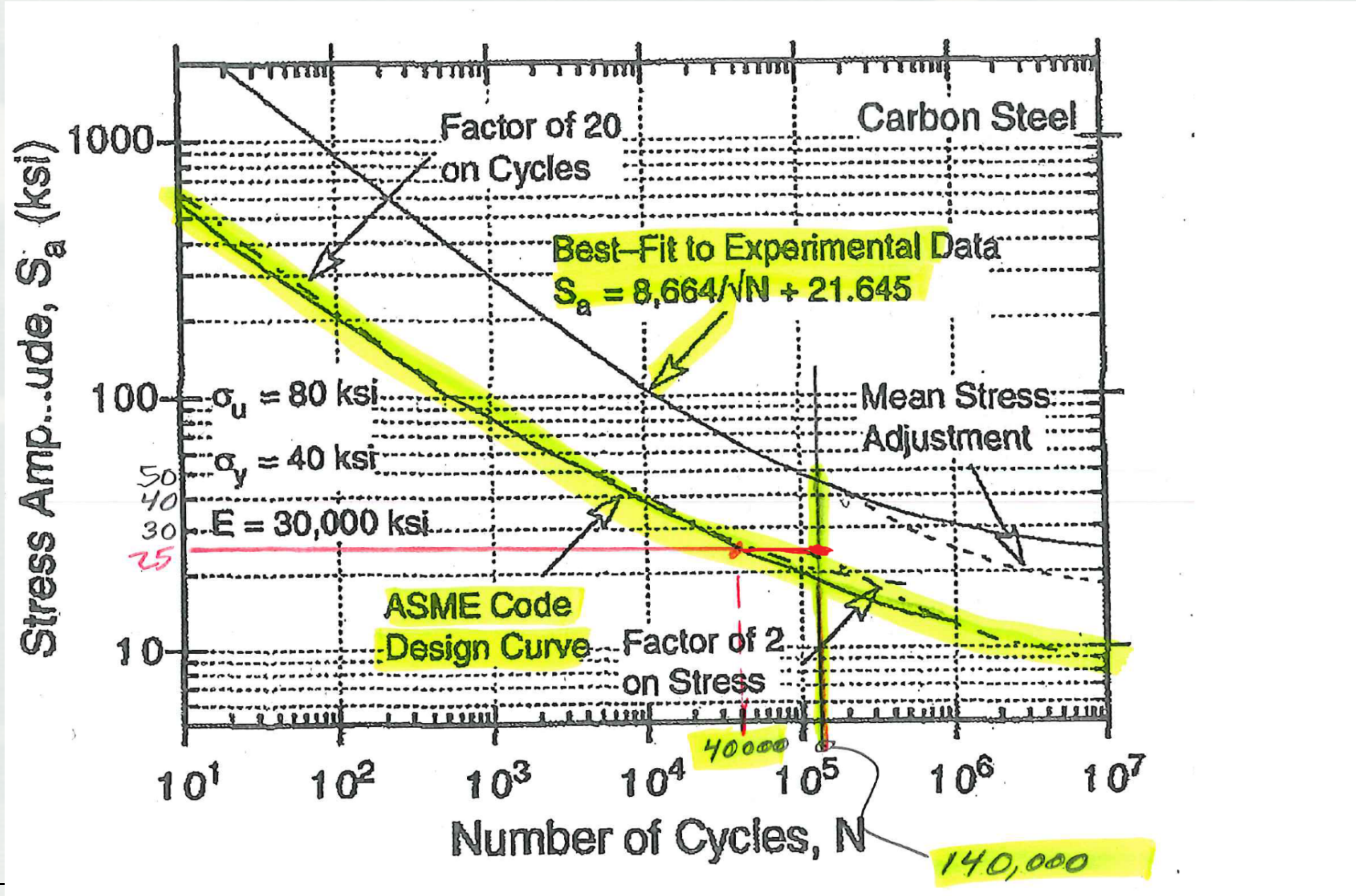
Step-3

Fatigue Life S-N CURVE



Step 4 Instrumentation to determine actual cyclic loads Strain Gage (BDI)

Foil strain sensors and string pot attachments

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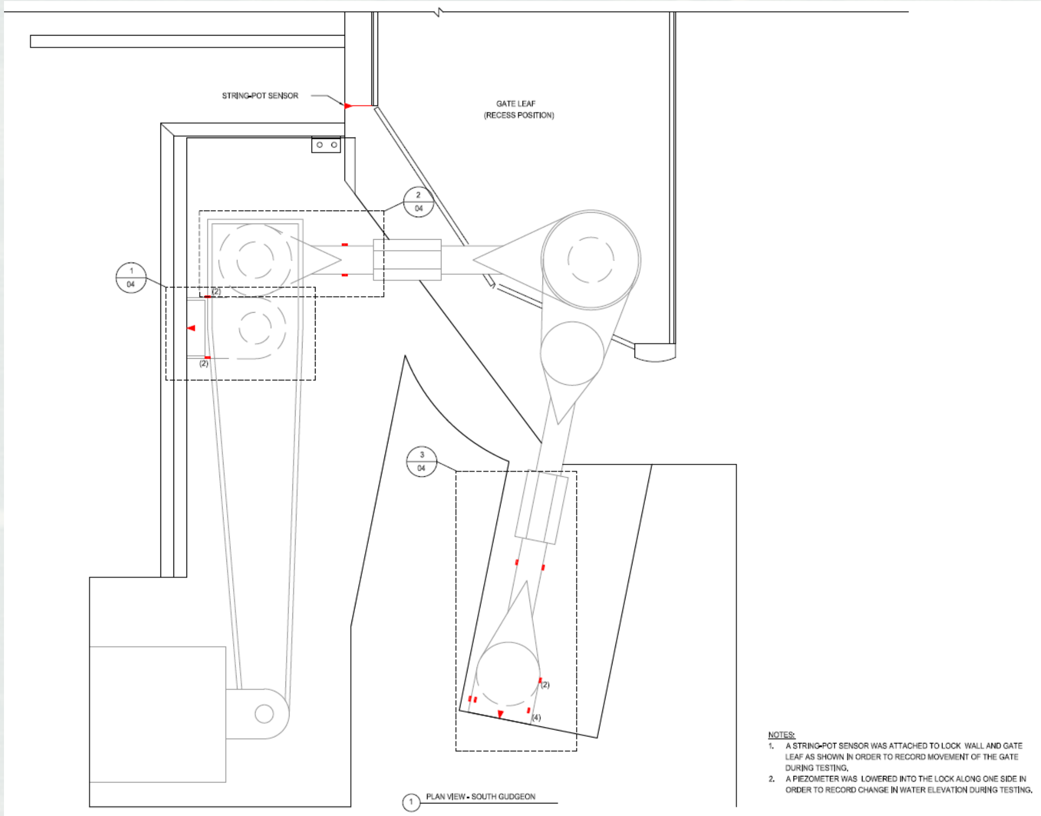
Step 4 (continued) **Strain Gage Layout**



Overall Instrumentation Locations – Plan View of South Gate Anchorage

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Step 4 (continued) ANCHOR BAR STRESS PLOTS (GATE 1 – NORTH ANCHORAGE)

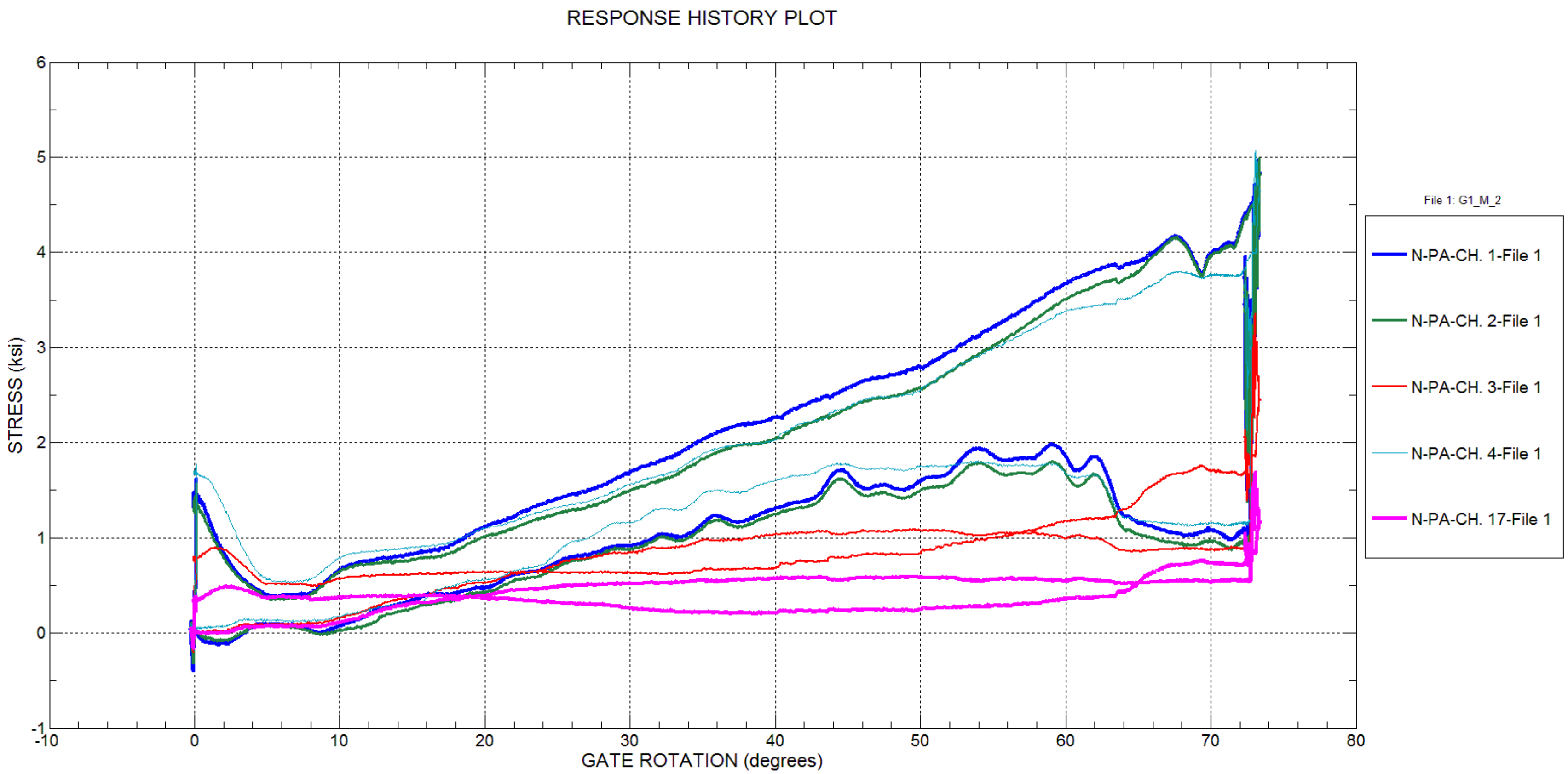

Figure 3.9 – Stress Plot – Gate 1 – North Primary Anchor – Miter Tests. (Blue = Ch. 1, Green = Ch. 2, Red = Ch. 3, Light Blue = Ch. 4, Pink = Ch. 17).

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Step 4 (continued) Gate 1 – Measured Strut Force and Anchorage Response Envelope Table

Member Label	Value Description	Measured Link Axial Force (kips)	Total Link Axial Force (kips)*	Measured Anchor Bar Displacement Value (inches)	Measured Anchor Bar Sensor Stress Value ** (ksi)	Measured Anchor Bar Stress Value - At Peak Link Force (ksi)	Extrapolated Anchor Bar Stress Value - At Peak Link Force (ksi)
North Primary Anchorage	Minimum	-21.48	--	-0.001	-0.35	2.42	0.93
	Maximum	326.33	--	0.017	5.01	5.00	6.16
	Range	**347.81**	**--**	**0.018**	**5.35**	**2.58**	**5.23**
North Secondary Anchorage	Minimum	-162.09	19.66	-0.001	-7.62	-7.92	--
	Maximum	9.75	191.50	0.000	1.38	-3.79	--
	Range	**171.84**	**171.84**	**0.001**	**8.99**	**4.13**	--
South Primary Anchorage	Minimum	-44.27	--	-0.003	-0.58	2.80	2.59
	Maximum	313.37	--	0.050	4.63	4.63	4.85
	Range	**357.64**	--	**0.053**	**5.21**	**1.83**	**2.26**
South Secondary Anchorage	Minimum	-163.90	--	-0.001	-8.75	-8.75	--
	Maximum	17.04	--	0.000	0.87	-2.29	--
	Range	**180.94**	--	**0.001**	**9.61**	**6.46**	--

Step 4 (continued) Stain Gage Results

- Secondary Embedded Anchorage measured load values were slightly higher than calculated values
- Primary Embedded Anchorage measured load values were significantly higher than calculated values
  - Values revealed an **88 kip** spike at point of gate mitering

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Step 5,8 - **Concrete Removal** to expose the upper embedded anchorage region of one leaf of gate 3S, for inspection

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Step 5,8 (continued)

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Embedded Anchorages Exposure, NDT, and IRRM Repairs Update

- Gates exposed to date:
  - Gate 3 South- Exposed 5 August
  - Gate 1 South- Exposed 27 August
  - Gate 1 North- Exposed 18 September
  - Gate 3 North- Exposed 13 October
- Gates to be exposed:
  - Gate 2 North- Exposure expected by 30 Oct
  - Gate 2 South- Exposure expected by 18 Nov

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Step 6 - Inspection (visual then NDT) followed with crack repair

Primary Embedment

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Step 6 (continued) - Gate 1S Secondary Embedded Anchorage Crack

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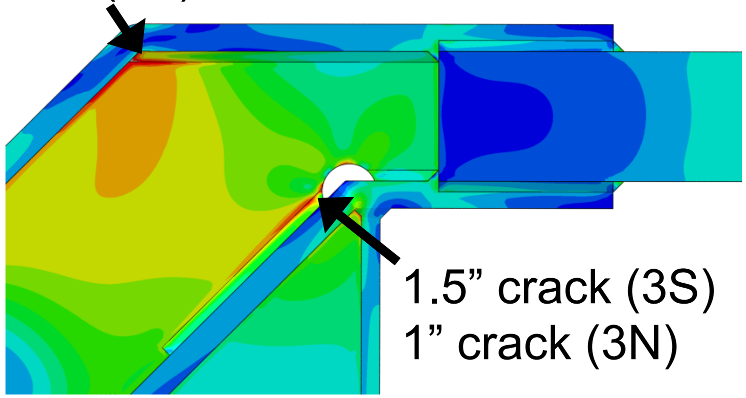
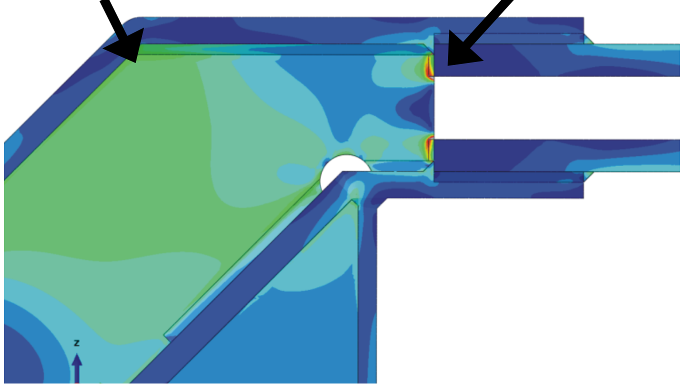
Step 7 (continued) NDT Results

- NDT has confirmed independent FEA model results
  - Majority of cracks and inclusions have been found in areas where model shows highest stress
- Poor Weld Fabrication- NDT shows porosity and non-fusion in welds
- Questionable Steel Quality- NDT shows de-lamination, pitting and corrosion



Primary Anchorage



Secondary Anchorage

Step 9,10 - Repairs

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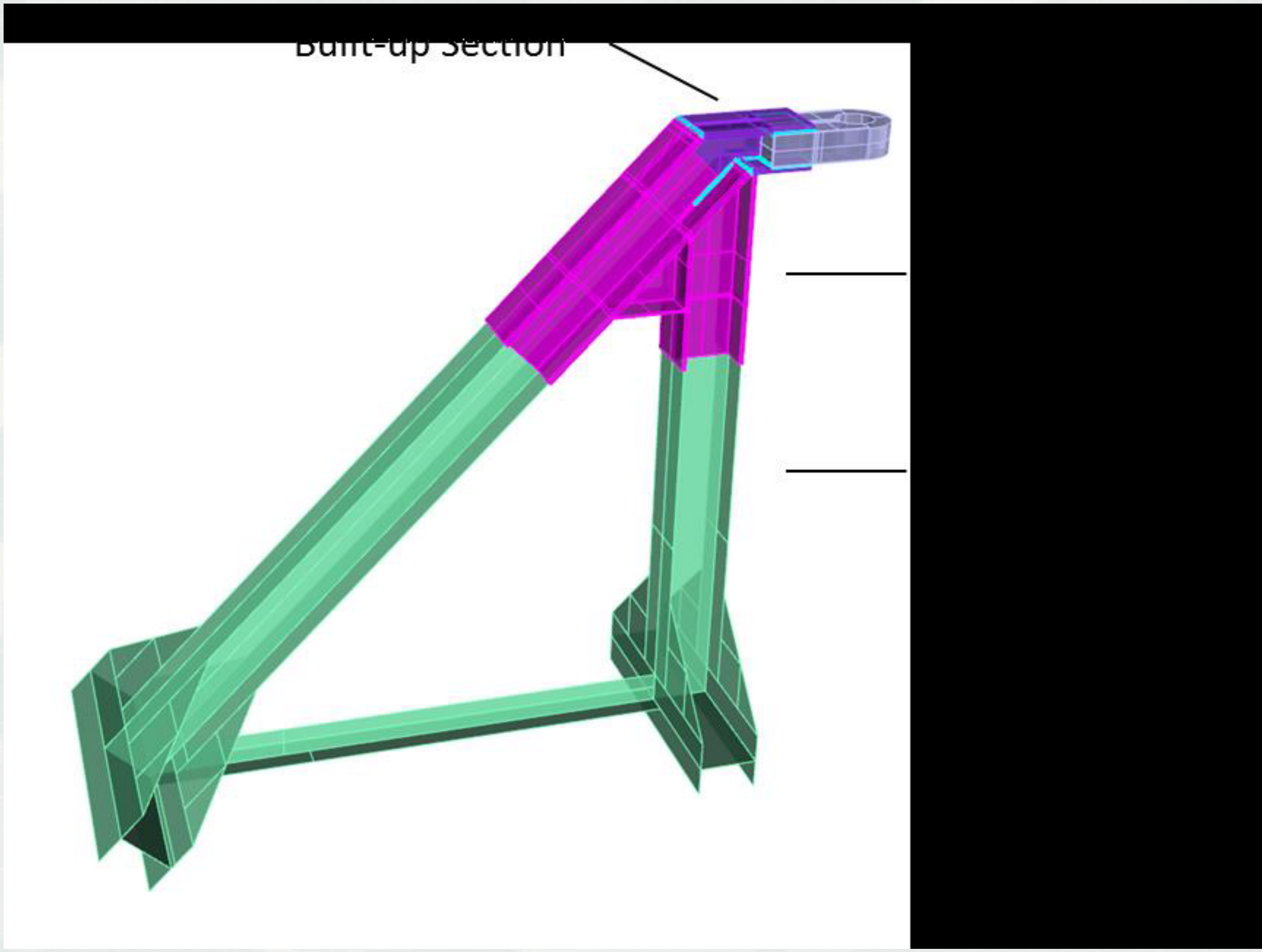
Step 7 Non Linear FEA and Life Cycle Analysis (ANATECH)



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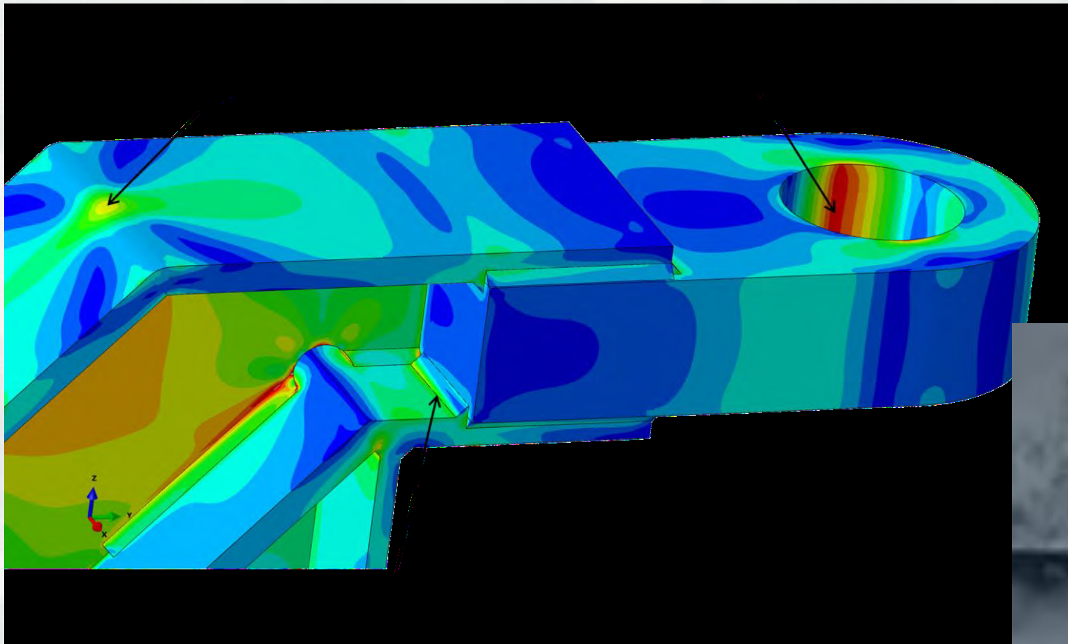
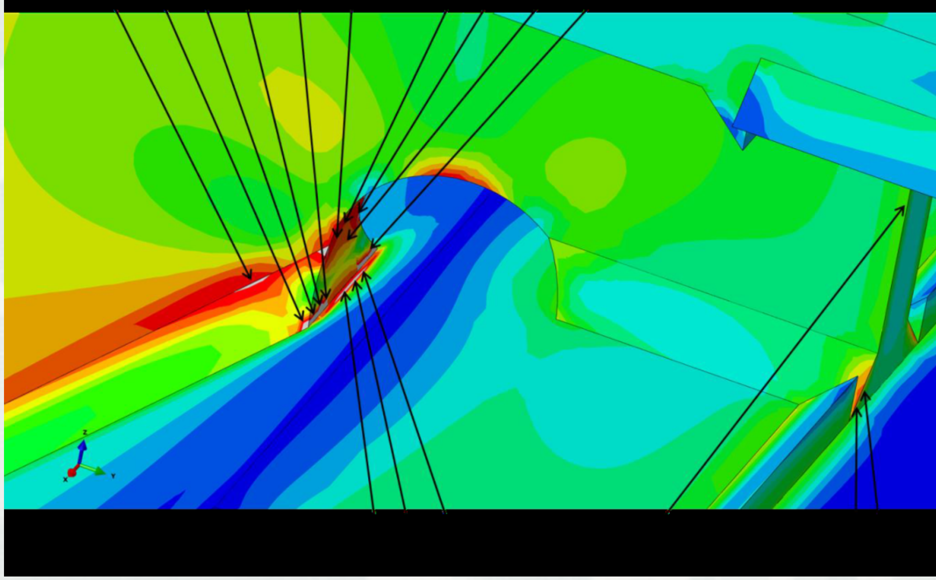
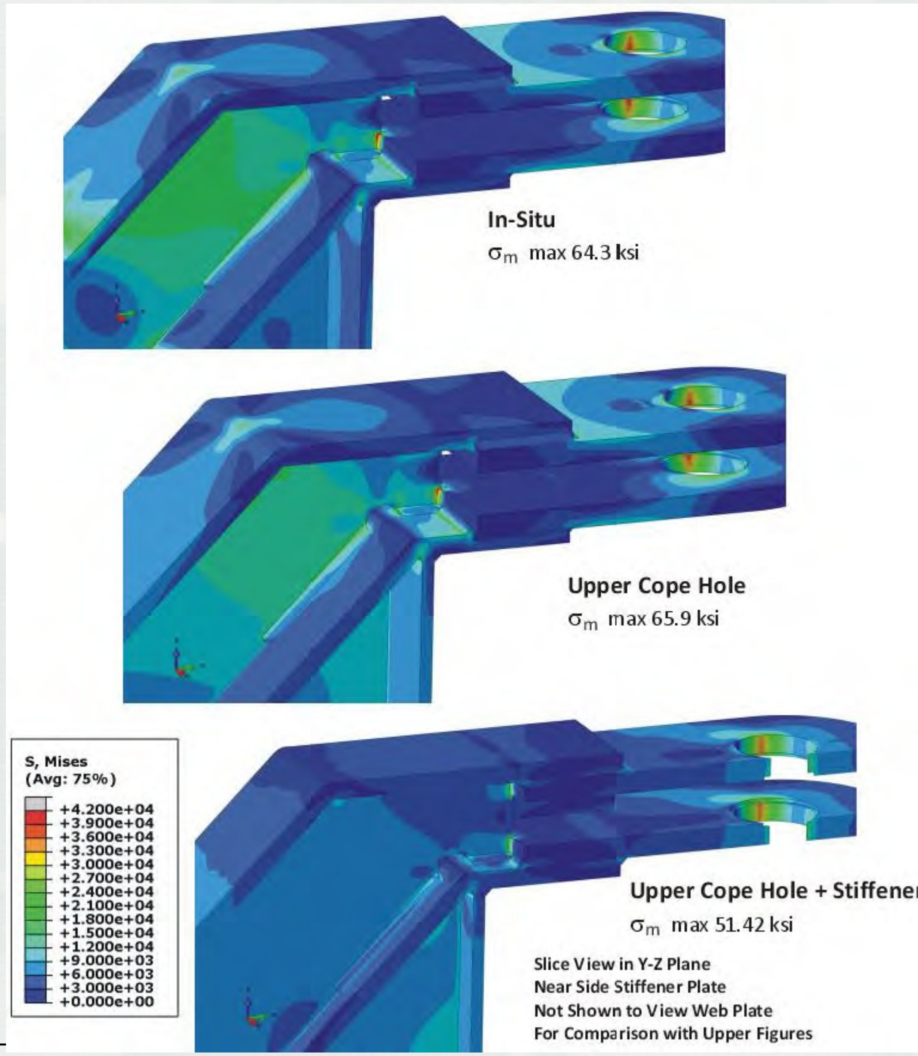
Step 7 (continued) **Primary Embedded Anchorage**





Step 7 (continued) Secondary Embedded Anchorage



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Step 7 (continued) Summary of Anchorage Components Cumulative Fatigue Design Life

	Traction Load Design Life (years)	Explicit Pin Design Life (years)
<u>Primary Embedded Anchorage</u>		
Upper Flange Joint	16	27
Lower Cope	8	3
Lower Flange to Vertical Flange	14	4
Horizontal Flange to Connection Plate - Lower	93	34
Horizontal Flange to Connection Plate - Upper	61852	infinite
Pin Hole	76	43
Bushing	n/a	31
Connecting Pin	n/a	> 1000
Secondary Embedded Anchorage		
Upper Flange Joint	371	366
Lower Cope	267	263
Vertical Web to Connection Plate - Lower	2	2
Vertical Web to Connection Plate - Upper	1	< 1
Pin Hole	41	762
Bushing	n/a	26
Connecting Pin	n/a	> 1000

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Step 11

Design Charette

- Goals/Scope:
  - Identify Criteria and Constraints for COAs
  - Brainstorm COAs for:
    - Permanent Repair
    - Interim Risk Reduction Measures (IRRM)
  - Develop Pros, Cons, and Costs for COAs
  - Create Risk Decision Matrix to Compare COAs
- Design Charette Team

Andy Harkness (INDC-RMC)
Paul Surace (INDC-EC)
Jeff Stamper (INDC-EC)
Rob Kelsey (MVS-EC)
Garett Fleming (MVS-EC)
Brian Holcomb (LRL-OP)
Rob Taylor (LRD-RBT)

Mike Ferguson (LRH-EC)
Brian Clouse (LRH-EC)
Brit Henderson (LRN-EC)
Daniel Hawk (LRL-ED)
Dave Wright (LRE-OTS)
Jim Tapp (LRE-OTS)
Mollie Mahoney (LRE-OTS)

Phil Ross (LRE-EC)
Andy Wadysz (LRE-EC)
Mike Bunker (LRE-SAO)
Jeff Harrington (LRE-SAO)
Allan Frappier (LRE-SAO)

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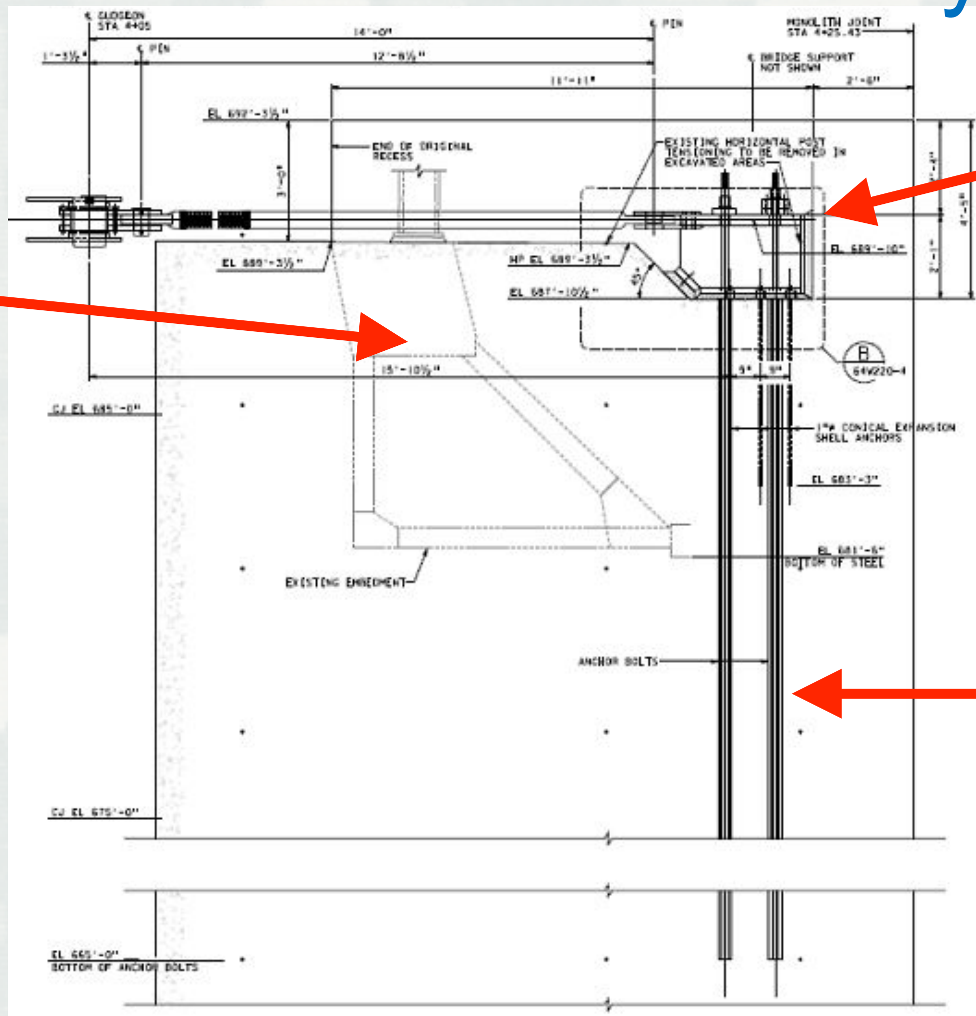
Step 11 (continued) Decision Matrix

	Constant Monitoring / Repair as needed IRRM	Do Nothing (Fix as Fails)	Replace Anchor Head In-Kind	Replace A Frame In Kind	Top Portion "A" Frame alterations (redesign and replace)	Top Portion "A" Frame alterations (Box Design)	Redesign and Replace entire "A" Frame	Kentucky Lock (new embedded anchorage beyond)	Add Buoyancy to Gate	Install new primary and secondary anchorage at shifted location
Meet Current Design and Performance Criteria	Red	Red	UNETHICAL TO PERFORM	UNETHICAL TO PERFORM	Yellow	Yellow	Green	Green	POSSIBLE SUPLEMENT TO OTHER COA'S	Green
Minimize Fracture Critical	Red	Red			Yellow	Yellow	Green	Green		Green
Impacts to navigation (industry)	Red	Red			Yellow	Yellow	Yellow	Green		Yellow
Resiliency	Red	Red			Yellow	Yellow	Green	Green		Green
Schedule (68 day max winter shutdown)	Green	Green			Yellow	Yellow	Yellow	Green		Yellow
Initial Cost	Green	Green			Yellow	Yellow	Red	Yellow		Red
Construction Risks	Green	Red			Yellow	Yellow	Yellow	Yellow		Red
Demonstrated/ Proven Success (lessons learned)	Red	Red			Green	Green	Green	Green		Yellow
Life Cycle Cost	Red	Red			Yellow	Yellow	Green	Green		Green
Weather Impacts	Yellow	Yellow			Red	Red	Red	Green		Red
Fabrication Impact	Yellow	Red			Green	Green	Green	Green		Red
Redundancy	Red	Red			Red	Red	Red	Red		Red
New loading (new hydraulic, ice fanning inpact)	Red	Red			Yellow	Yellow	Green	Green		Green
Standardization Efficiencies across all POE anchorages	Yellow	Red			Green	Green	Green	Yellow		Green
Compatibility with existing anchorage and gate	Green	Green			Green	Green	Green	Green		Red
Safety	Yellow	Red			Yellow	Yellow	Yellow	Yellow		Yellow
OVERALL DECISION TO PROCEED	Red	Red	Red	Red	Yellow	Yellow	Yellow	Green		Yellow

Step 11 (continued) COA 5 – Post Tension Anchor Rod System

Existing A-frame



Anchorage frame set further away from lock wall than existing frame

30’ long anchor rods transferring load to monolith

Step 12 Risk Assessment

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Step 12 Expert Opinion Elicitation

Issue Statement:

- Are expedited repairs of gate anchorages justified or can repairs be deferred?
- What are the risks of waiting?
- What risk reduction measures are feasible and how effective are they?
- What risk information is available to supplement decision making?

Expert Panel:

Dr. John Jaeger, P.E. (LRH, ret.) - Fracture mechanics expert
Travis Adams, P.E. (NWP) - Weld and fatigue expert
Dan Peters, P.E. (ANATECH)- Fracture Mechanics expert
Rob Kelsey, P.E. (MVS)- Poe anchorage design lead, design charette team
Cory DeLong, P.E. (MVR)- SOO SQRA & MRR PDT member
Bob Patev (RMC-INDC) – Risk Assessment Process and Facilitation

Expert panel observed by LRE Ops, E&C, and INDC to ensure objectives were met

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Step 12 (continued) Risk Decision Matrix

Criteria (Importance Scale 1-10)

Course of Action (COA)

	Impacts to Navigation	Reliability/ Resiliancy	Demonstrated/Previously Implemented Design	Impact to Nav during construction (Planned outage)	Life Cycle Cost	Initial Cost	Weighted Value Scores	Rank	Risk Weight	
	10	9	7	6	6	4				
COA-1, Constant Monitoring/IRRM	10	9	7	18	6	12	62	5	1	High Risk
COA-2, Redesign & Replace Top Portion A-Frame	20	18	14	12	12	8	84	3	2	Moderate Risk
COA-3, Install Reinforcing Box Around Top Portion of A-Frame	20	9	14	18	12	8	81	4	3	Low Risk
COA-4, Re-Design and Replace Entire A-Frame	20	27	21	12	18	4	102	2		
COA-5,Post Tension Anchor Rod System	30	27	21	18	18	8	**122**	1		

Step 12 (continued) Annual Probability of Failure (APF)

Annual Probability of Failure of Poe Gate 1 or Gate 3

Within the next year: 700/10,000 (7%)

Within the next five years: 3,500/10,000 (35%)

USACE Dam Safety Standard for Unacceptable APF: APF ≥ 1/10,000

[ER 1110-2-1156 (March 2014)]

Comparable Industry Standards for Unacceptable APF

- Bridges: APF ≥ 0.1/10,000 - 1/10,000
- American Concrete Institute: APF ≥ 1/10,000
- American Institute of Steel Construction: APF ≥ 1/10,000
- Nuclear: APF ≥ 0.01/10,000

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Step 12 (continued) Expert Opinion Elicitation Conclusions & Recommendation

- Likelihood of suffering extreme consequences is very high - Potential for catastrophic failure on either Gate 1 or 3 in the next year is 7%, 35% in 5 years.
- Dependent on severity of catastrophic failure, outage duration of up to 180 days
  - Direct shipping impacts up to $360M (180-day outage)
- Team recommend expedited permanent repairs.

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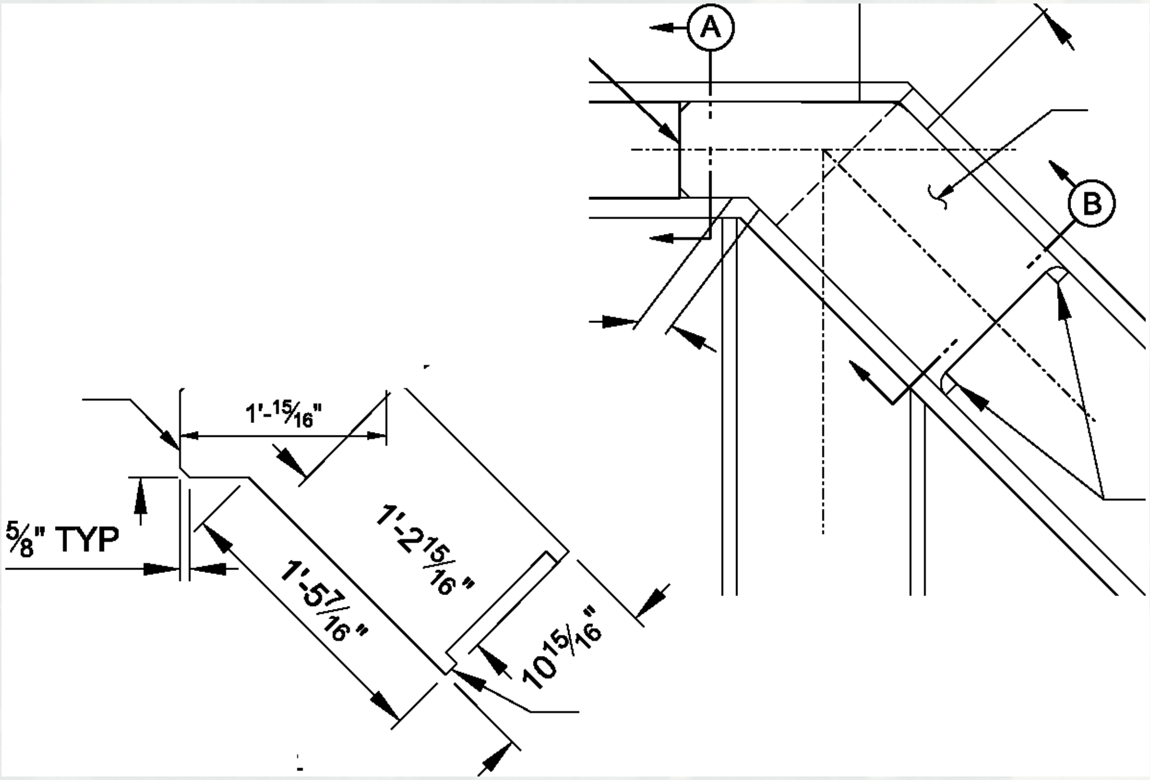
Step 14 Additional Risk Reduction- Structural Stiffeners



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Step 15 **Fracture Mechanics Analysis**

- Material test were conducted to determine properties necessary for fracture analysis
- Currently a fracture analysis is being performed on the anchor pin plates to determine the rate of crack growth
- Determine inspection cycle time of pin plates based upon rate of crack growth

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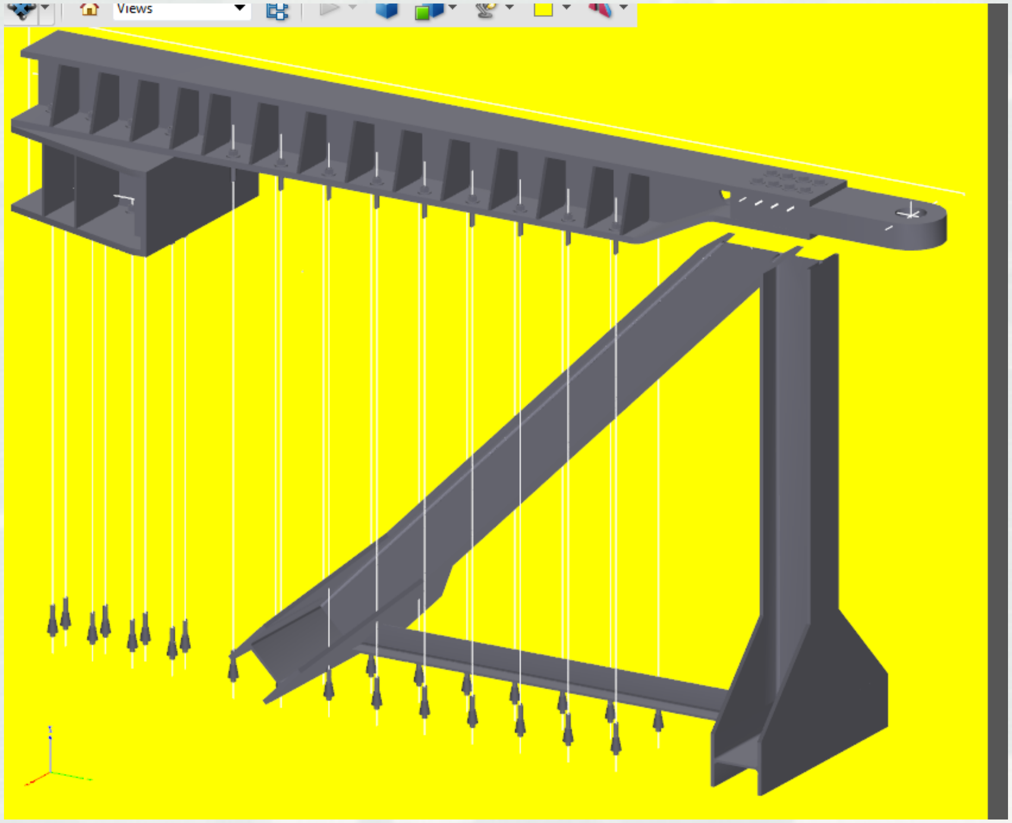
Permanent Design Features

- Embedded frame can be installed prior to winter shutdown
- Pin Plates are a bolt up feature
- Demolition of existing anchor frame top and installation of pin plates can be completed in winter shutdown

Permanent Design Solution



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NATION EXPERT TEAM

- INDC work interactively with LRE DISTRICT management assemble an EXPERT TEAM to find a solution to the embedded anchorage problem and provide the necessary information to LRD and LRE Command and Senior Management decision makers.
- Nation Team experts contributed as was needed to work towards a solution
- Team members included persons from:
  1. LRE – Project Management, O&M, Engineering, SOO Locks O&M, and Contracting
  2. LRH, LRL, LRN, MVS and MVR Engineering, RMC
  3. NWP Weld Center, NWW Cost Center
  4. AEs- ANATECH, FISH & Associates, Mid American Inspection Service, Bridge Diagnostics (BDI)

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QUESTIONS?

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