

The Development of the AASHTO/AWS Fracture Control Plan How it Relates to Historic Bridges

Karl H. Frank
Hirschfeld Industries

Outline

- History
 - What prompted the concern
 - The reaction
- The Old Bridges
 - What is different
 - Older bridge steels- Wrought Iron
- Comments on Gusset Plates

Point Pleasant Bridge Collapse



- Eye bar chain suspension bridge
 - Designed as cable suspension bridge
- Built in 1929 collapsed 1967

Total Bridge Collapse

Eye Bars
Chain- Pin
Connected



- Bridge Reassembled on Land to Determine Cause of Fracture
- Note Eye Bar Chain
- One Lane of Bridge Backed Up at Time of Collapse

Eyebars



- Pin Connected
- Two Bars per Chain
- Thickness varied along bridge
- Heat Treated 1060 steel
 - High Carbon (0.60%)
 - Low Toughness
 - Relatively High Strength

Failure Events

Ductile Failure

Brittle Fracture

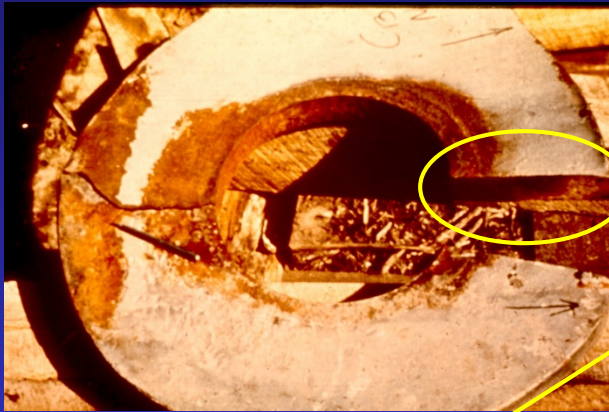
1. Brittle Fracture of One Side of Eye
2. Remaining Ligament Under Axial + Bending Due to Eccentricity
3. Ductile Failure of Ligament Causing Force Transfer to Intact Eyebar
4. Eccentricity of Force From One Eyebar on Joint Causes Joint to Rotate and Unfractured Eyebar Pulls Off of Pin

Fractured Eye Bar



- Left Side Ductile Bending Fracture
 - Paint Spalling Due to Large Plastic Strain
 - Almost Full Section Plastified
- Right Side No Ductility
 - Low Toughness Brittle Fracture

Fracture Surface



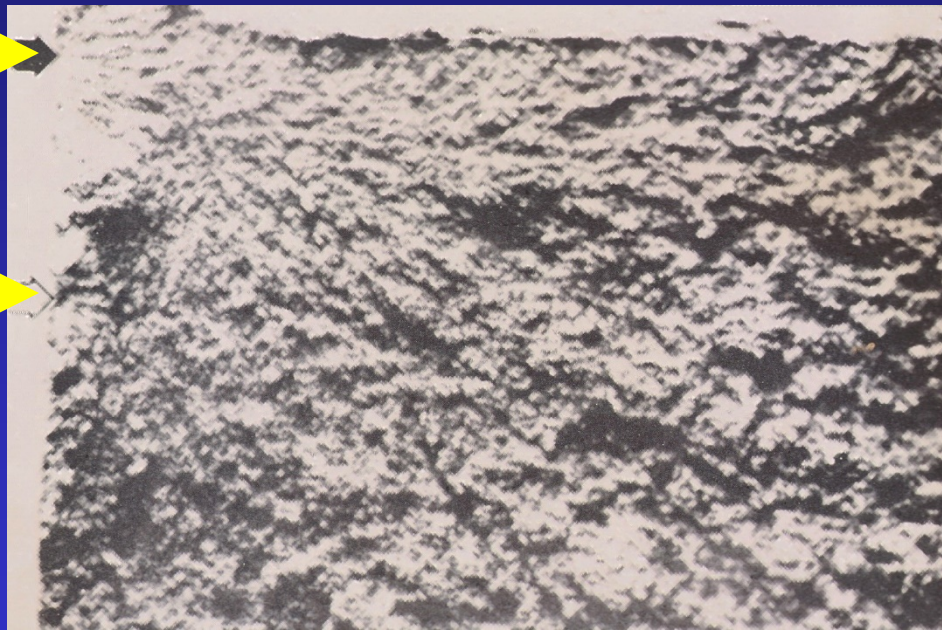
Origin



No Evidence of Ductility

Cleaned Fracture Surface

0.15 in.



- Fracture Initiated from Semicircular Cracks at Pin Hole of Eyebars
- Two Small Cracks
 - Growth Mechanism Most Likely Stress Corrosion
 - Fatigue Stresses Extremely Low in Eyebars Chain
 - Cracks Slowly Grew During the Approximately 40 year Service Life

Conclusions and Dilemma

- Collapse Caused by Unstable Crack Propagation in One Eye Bar
- Small Semicircular Cracks at Pin Hole Initiated the Fracture
- What to Do About the St. Mary's Bridge?
 - Identical Bridge
 - About the Same Age
 - Same Material
 - More Traffic

Solution

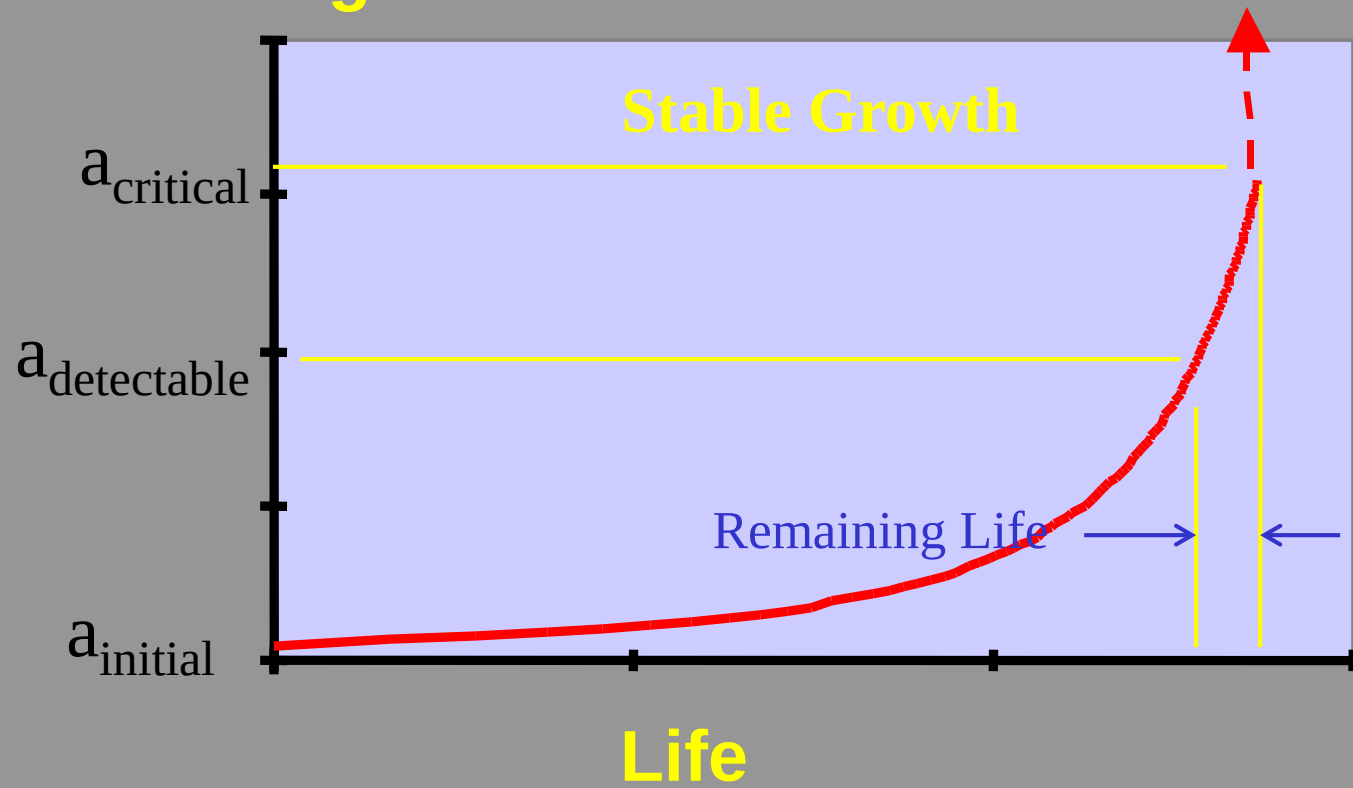
- Inspect Eyebars on St. Mary's Bridge
- Ultrasonic Inspection from Edge of Bar



- Difficult Access in Winter with Ice on Eyebars
- Inspectors Quit Due to Fear of Falling
- Unable to Differentiate Between Corrosion Pits on Pin Hole and Shallow Cracks
- Result: Bridge Taken Out of Service and Torn Down

Inspection

Crack Length- a



Eyebar was defined as Fracture Critical



New Term

- Failure of Single Eyebar Caused Failure
These Types of Member Labeled as ***Fracture Critical!***
 - These members are required to be “hands on” inspected at least every 2 years.
 - More Stringent Toughness Specifications
 - Enhanced Welding and Shop Inspection Requirements
- Truss Lower Chords are Typically Fracture Critical

The Fracture Control Plan



Enhanced Welding
and Shop
Inspection- Reduce
Initial Flaw Size

Field Inspection-
Looking for Fatigue
Cracks

Toughness Specifications for
Steels – Provide Inspect Ability

Older Bridges



Enhanced Welding
and Shop
Inspection- Reduce
Initial Flaw Size

Field Inspection-
Looking for Fatigue
Cracks

Low Stress, No Welds

Toughness Specifications for
Steels – Provide Inspect Ability

Toughness???

Piano Bridge in Texas



WEAK BRIDGE
.6 MI. AHEAD
NO
TURNAROUND

Lower Chord and
Diagonal are
Eyebars!

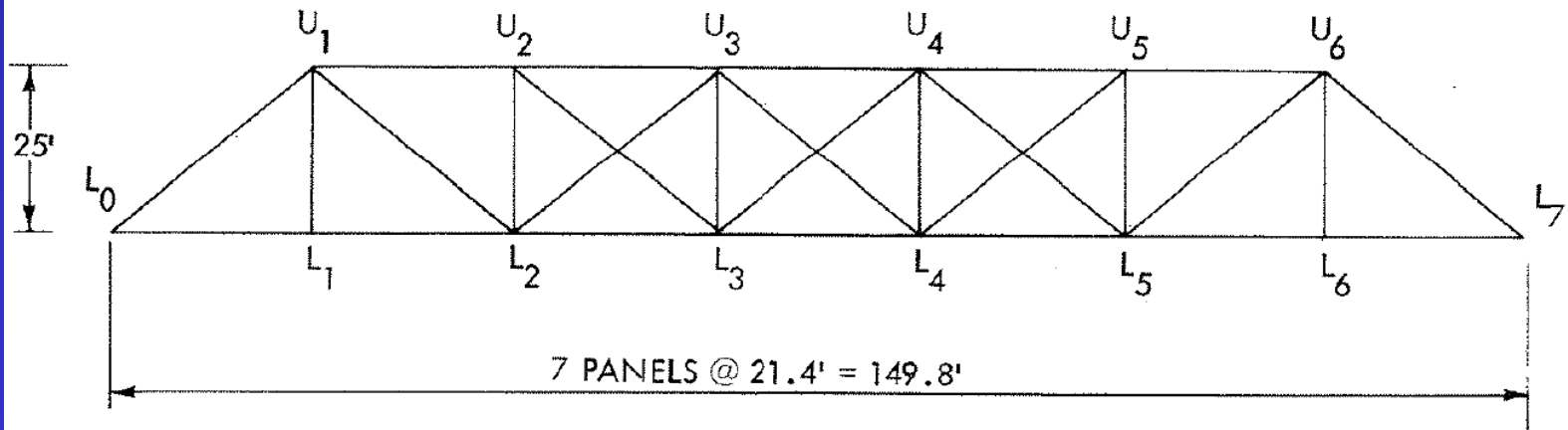


Experimental Studies of Eyebars

- “Ultimate Load Behavior Full-Scale Highway Truss Bridges”- Sanders et al, Iowa, 1975.
- “Mechanical and Chemical Properties of Selected Steels used in Bridge Structures”, Frank, FHWA, 1974.



Chestnut Ford Bridge



Wrought Iron Eyebars

Element	Wrought Iron- Hubby Bridge	Wrought Iron- Chestnut Ford Bridge	FHWA Wrought Iron 1-3	FHWA Wrought Iron #4
Carbon	<0.03	<0.03	0.01	0.10
Manganese	<0.05	0.25	<0.05	<0.05
Phosphorus	0.29	0.13	0.32-0.39	0.39
Sulfur	0.042	0.036	0.018	0.018
Silicon	0.22	0.12	0.76-1.5	1.50

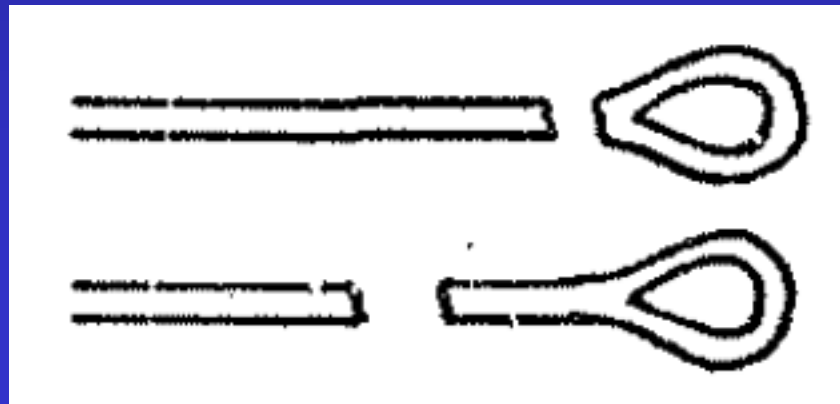
Wrought Iron Coupon Strengths

Bridge/Material	Yield Strength (ksi)	Ultimate Strength (ksi)	Modulus (ksi)
Hubby/Wrought Iron	35.5	49.1	28,000
Chestnut Ford/Wrought Iron	34.9	48.6	25,300
FHWA 1-3	24.7-28.5	42.6-47.9	na
FHWA #4	36.5	52.0	na

Tensile Tests of Eyebars

Type of Eyebars	Location of Failure	Average Yield Strength (ksi)	Range in Ultimate Strength (ksi)	Average Ultimate Strength (ksi)
Round	Bar	35.5	44.6-50.0	49.1
Rectangular	Forging	35.5	28.9-49.4	42.7
Square	Bar	32.7	44.7-58.4	50.3
Square	Forging	34.5	43.9-47	45.7

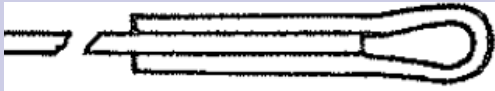
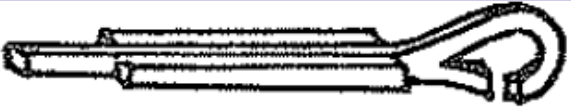
1949 AASHO Allowable Stress= 14 ksi



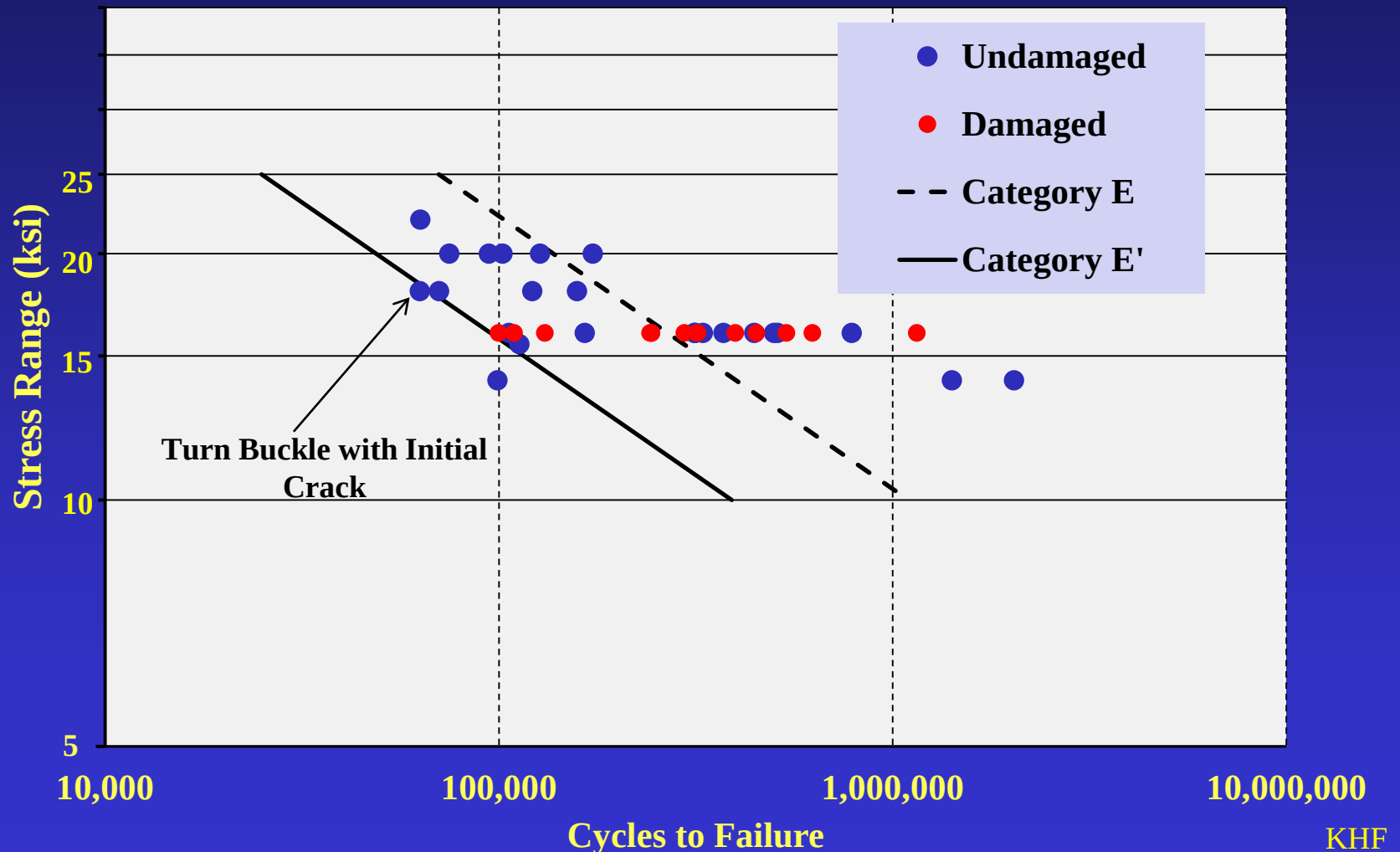
Forging

Bar

Static Tensile Tests on Damaged and Repaired Eyebars

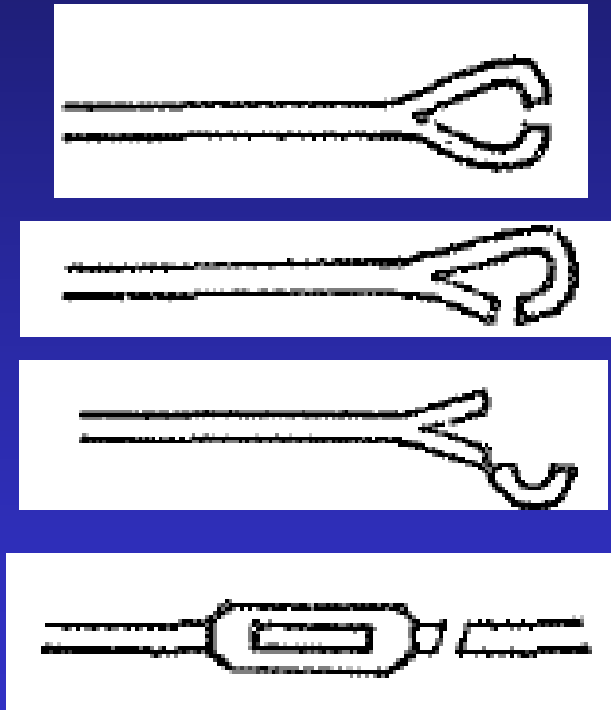
Size (in.)	Ultimate Strength (ksi)	Failure Location
3/4x3/4	26.5	
	115	
1x1	48.5	
	48	
	83	

Fatigue Performance of Wrought Iron Eyebars

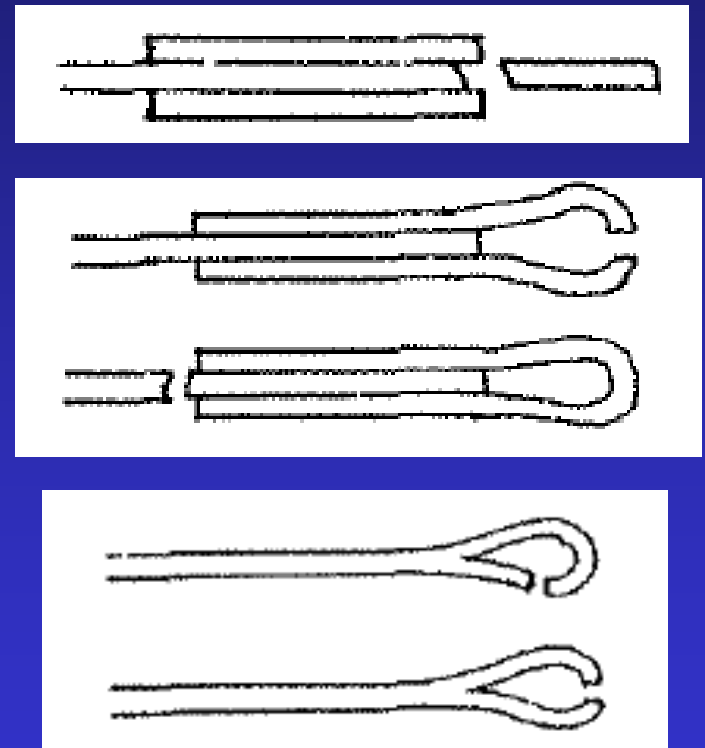


Typical Fatigue Failure Locations

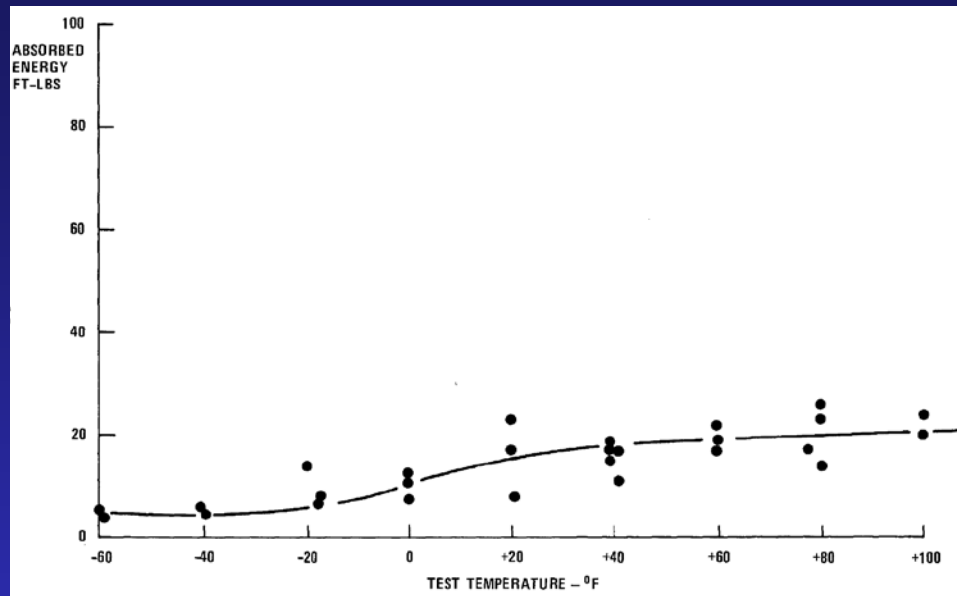
Undamaged Eyebars



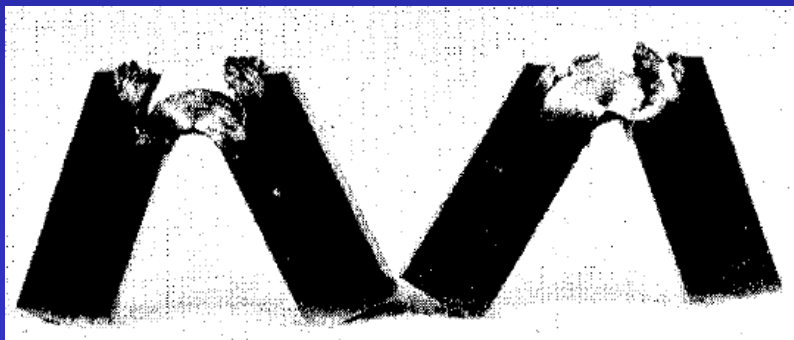
Damaged Eyebars



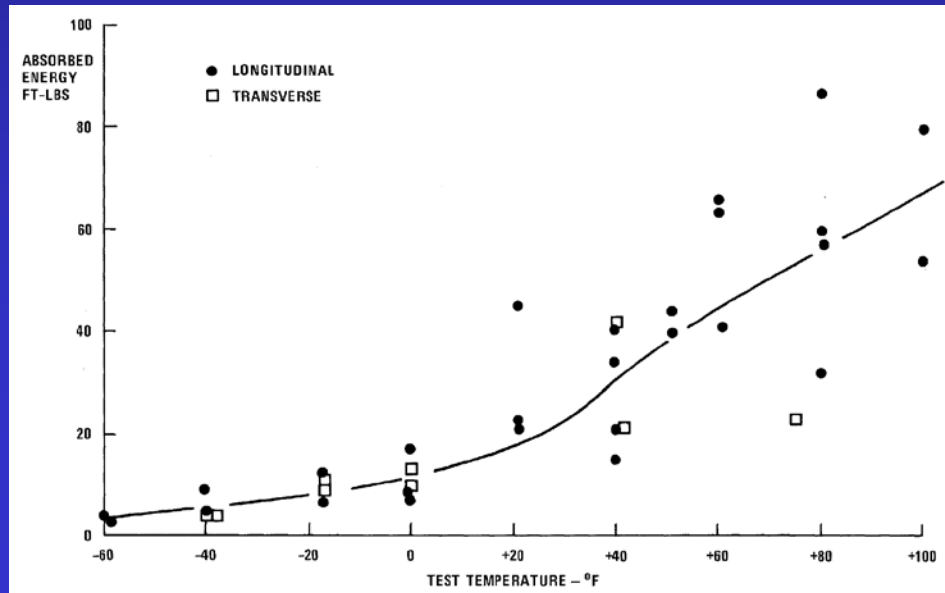
Toughness of Wrought Iron



High Temperature Toughness
a Function of Inclusion Size
and Orientation Relative to
Crack Propagation Path



Blunting of Crack at Inclusion



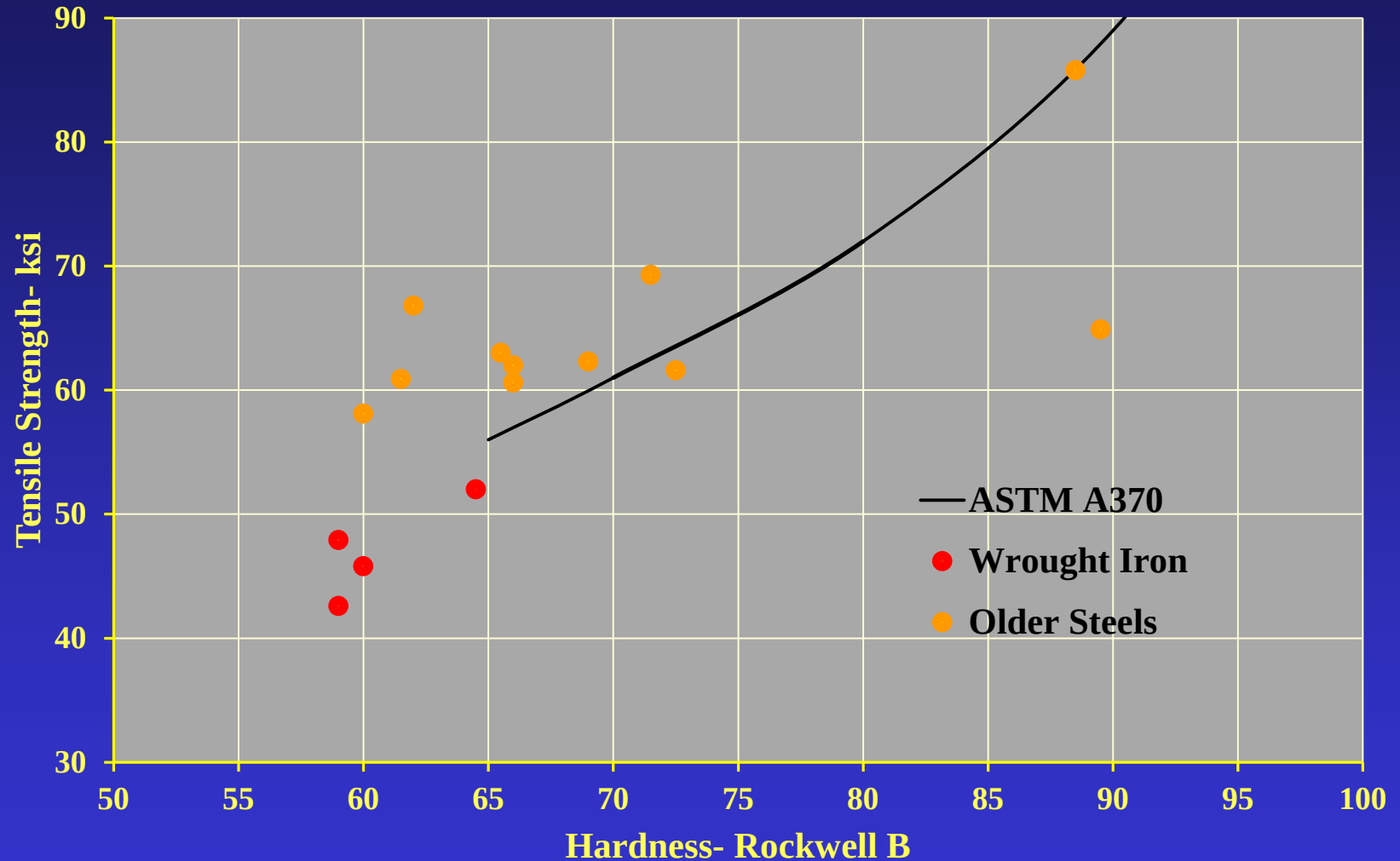
Older Steels

Element	FHWA-A7	Steel-Hubby Bridge	FHWA-A373 (A2,3)	FHWA-A373 (A4)	A709 Grade 36
Carbon	0.19	0.19	0.19-0.22	0.11	<0.25
Manganese	0.67	0.40	0.57-0.64	0.49	0.80-1.20
Phosphorus	0.017	0.12	0.009-0.010	0.029	<0.04
Sulfur	0.030	0.029	0.019-0.26	0.052	<0.05
Silicon	0.07	<0.05	na	0.15	<0.40

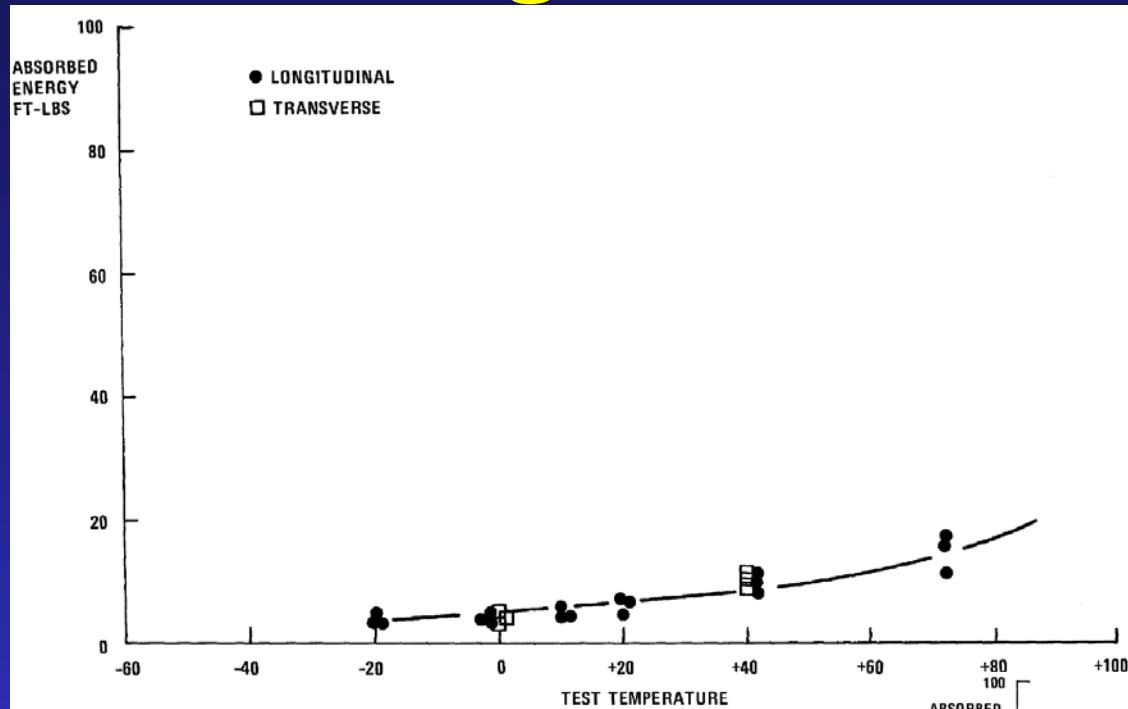
Older Steel Strengths

Bridge/Material	Yield Strength (ksi)	Ultimate Strength (ksi)	Modulus (ksi)
Hubby/Steel	42.0	58.7	30,900
A7	50.3	69.3	na
A373	36.5-37.5	58.1-66.8	na

Tensile Strength-Hardness Correlation

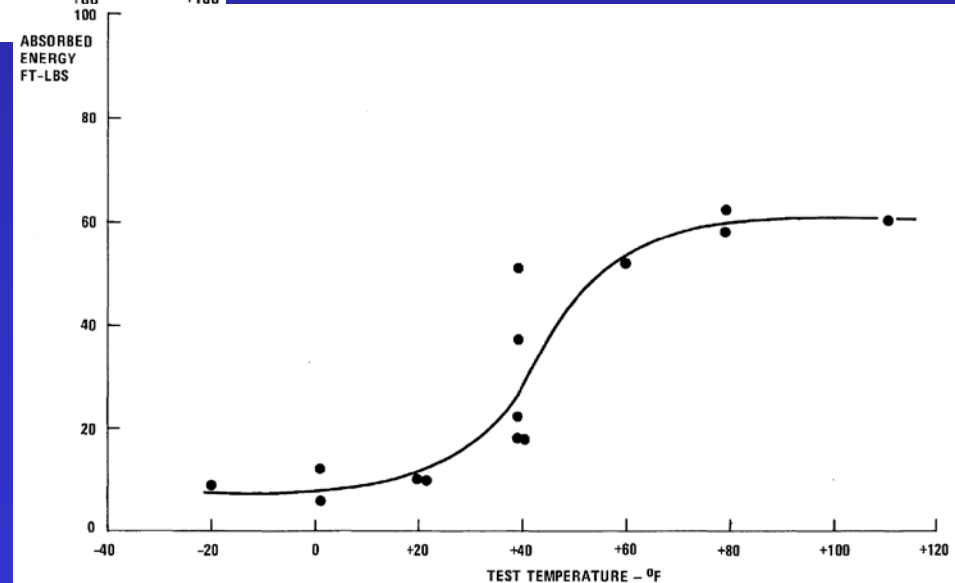


Toughness of Older Steels



No Toughness

Good Toughness



Critical Crack Size Indicator

$K \propto F_y \sqrt{\pi a}$ - Required Toughness

$K_c = 12.5 \sqrt{CVN}$ - Material Toughness

Setting the two equal to each other to determine the critical crack size

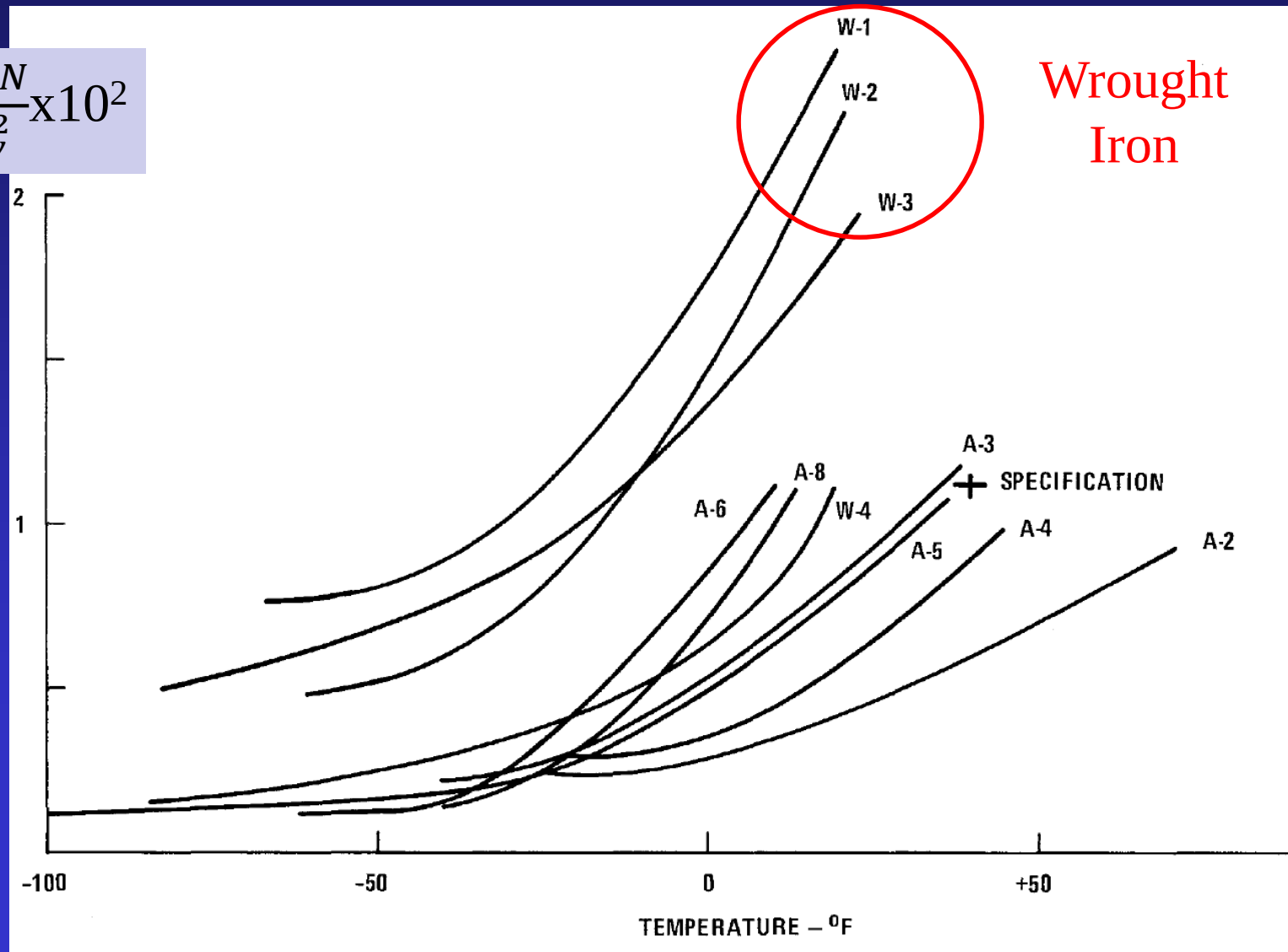
$$12.5 \sqrt{CVN} = F_y \sqrt{\pi a}$$

Solving for the crack size:

$$a \propto \frac{CVN}{F_y^2}$$

Relative Toughness of the Material

$$\frac{CVN}{F_y^2} \times 10^2$$

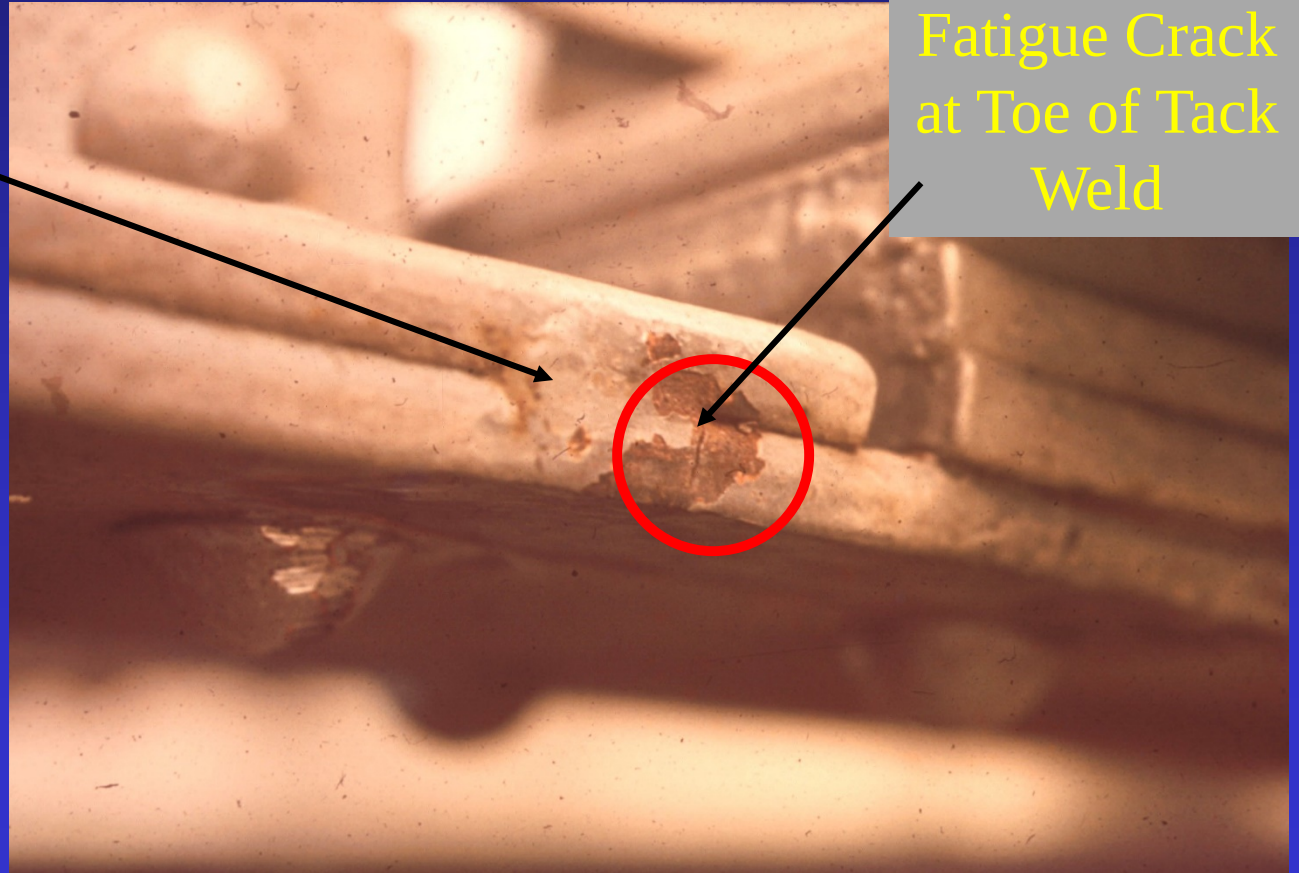


Old Eye Bars

- Typically Wrought Iron
 - Toughness Adequate Due to Low Strength
 - Fatigue Strength- Category E'
 - Welded Repairs
 - Restored Strength
 - Did not Reduce Fatigue Strength
- Inspect Eyes and at Turnbuckles for Fatigue Cracks

Tack Welds Can Be Trouble

Tack Weld
Used to Hold
Plates in
Position for
Riveting

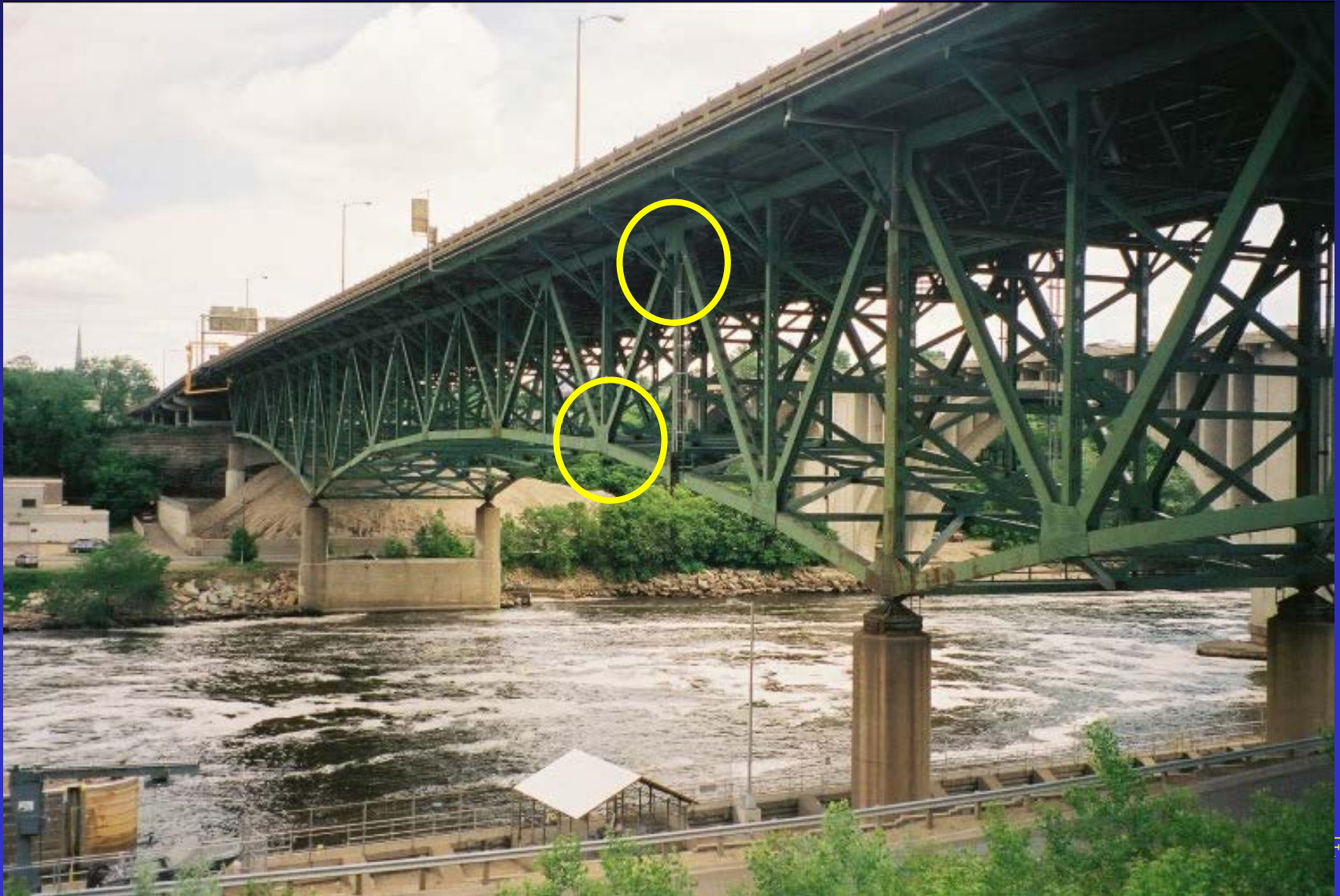


Fatigue Crack
at Toe of Tack
Weld

I35 Bridge Collapse



Critical Connections



Snooper truck inspection
of I-35W bridge

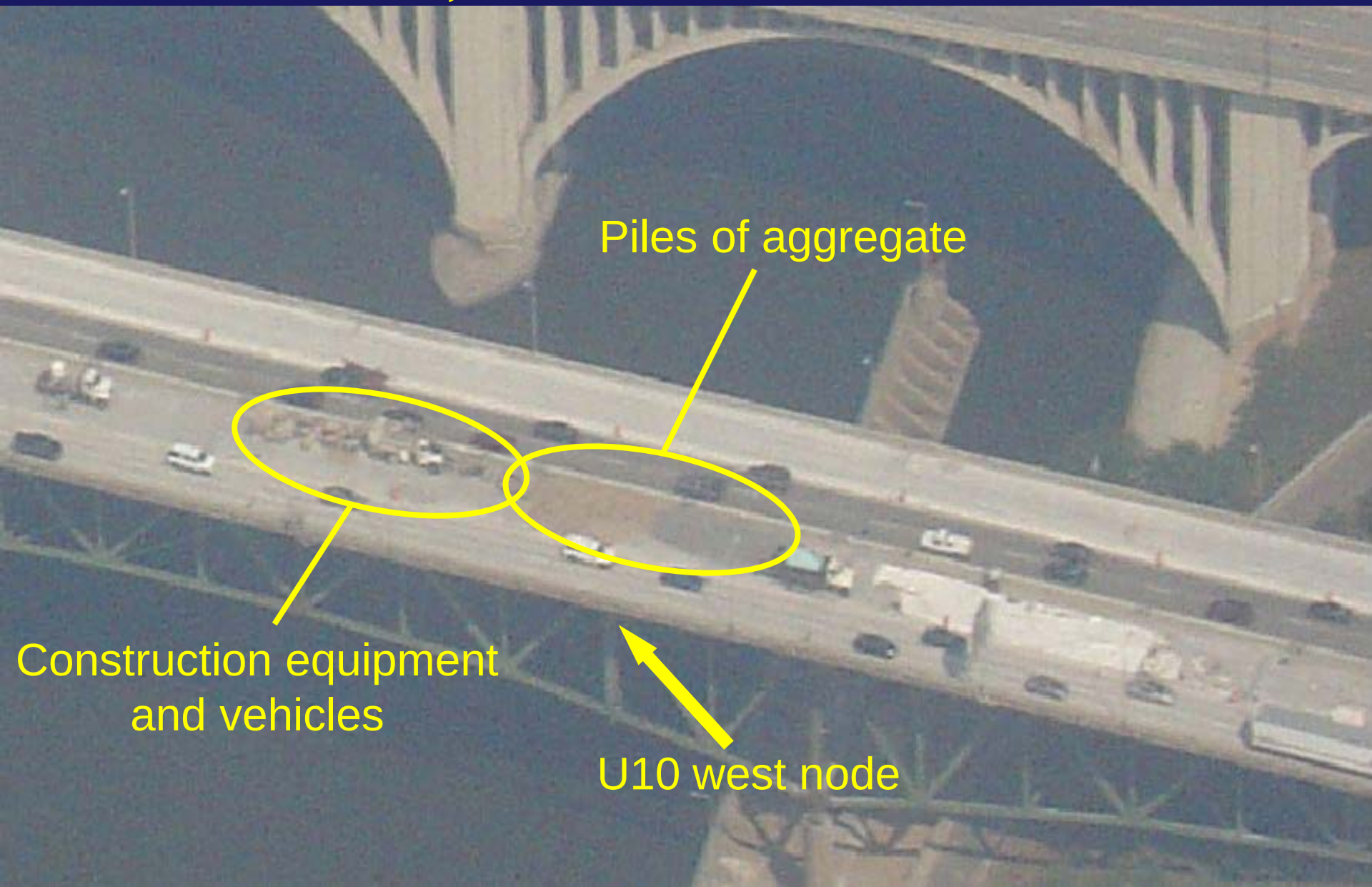


Major Concern Was Fatigue Cracking From Tack Welds of Fit-up Plates Inside of Box Members



Construction Work – Day of Accident

578,500 lbs added dead load

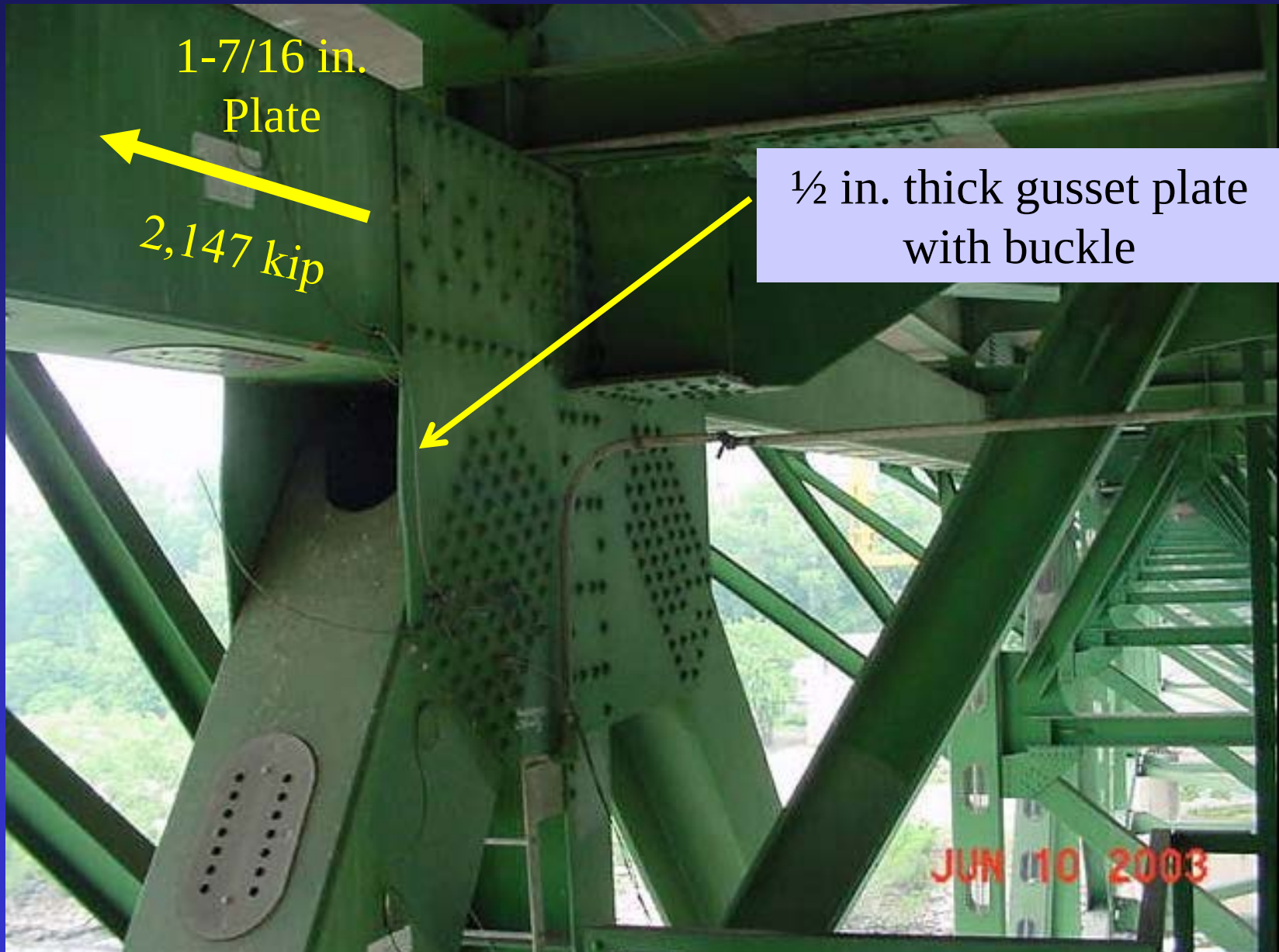


Piles of aggregate

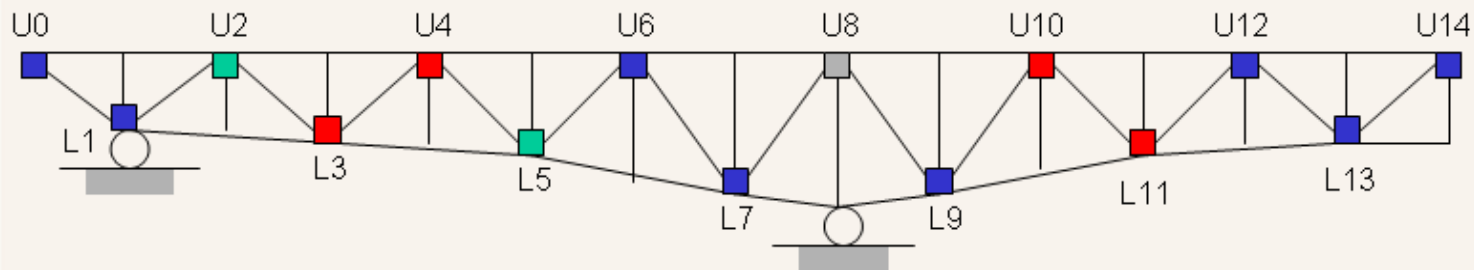
Construction equipment
and vehicles

U10 west node

The Critical Connection



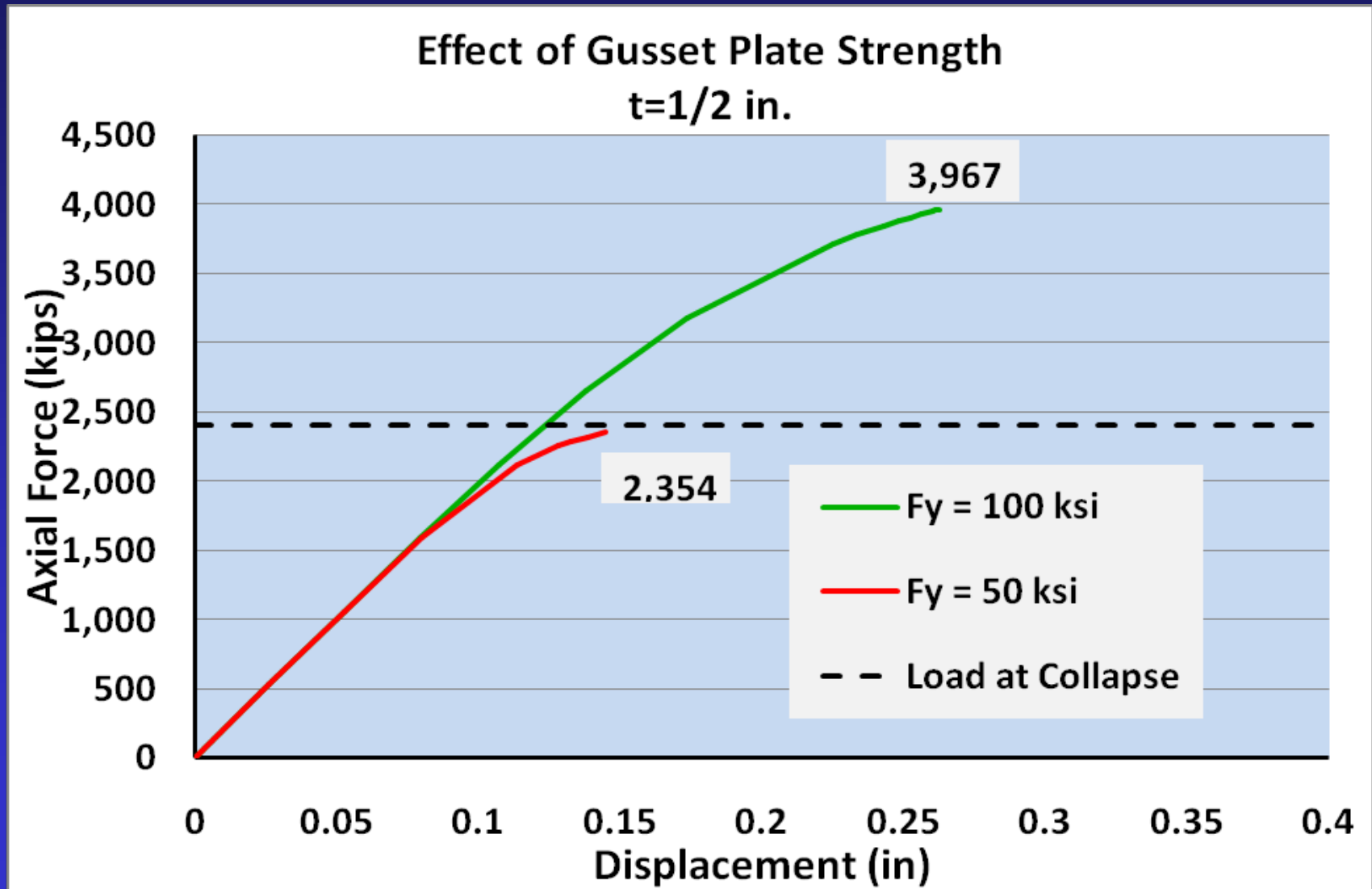
Gusset Plate Thickness Comparison



Legend:

- 1 3/8" thick gusset plate (100 ksi)
- 1" thick gusset plate (50 ksi)
- 5/8" thick gusset plate (50 ksi)
- 1/2" thick gusset plate (50 ksi)

Strength of Gusset Plate Connection



Lessons from I35W

- I35W Collapse was Due to an Error in Specifying the Correct Gusset Plate Strength
 - Designed using Grade 100
 - Specified Grade 50
- Inspection and Concern Focused on Internal Tack Welds
 - Buckled Gusset Plate Noted-Checked Drawings
 - No Analysis Check of Gusset Plate Strength
 - Simple Shear Check Would Have Caught Problem

Conclusions

- Fracture Control Plan Developed for Welded Structures
- Fatigue Cracking in Low Strength Steel and Wrought Iron Members Not Likely Due to Low Live Load Stress Range
 - Check eyebars with Category E'
- Gusset Plate Strength Normally Not of Concern if Proper Material Provided
- Don't Overlook the Obvious