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Course Description

Session 3: Steel Material Properties

June 20, 2016

This session will provide an introduction to steel production and metallurgy followed by an explanation of the special requirements in A709, the material specification for bridge steel. The basis for fracture toughness specifications and special requirements for steel for use in fracture critical member are presented. The attributes of high performance steels (HPS), weathering steels and stainless steel are introduced. The new bolt specification for high strength bolts, F3125, is presented along with the basis for the rotational capacity provisions required for bolts in bridges. The recommended specification for anchor rods and bolts are presented including potential problems associated with very high strength rods in highway applications.

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Learning Objectives

- Gain an understanding of the steel production process and be introduced to steel metallurgy.
- Become familiar with the special requirements for A709, the material specification for bridge steel.
- Become familiar with special requirements for high performance steels, weathering steels and stainless steel.
- Gain an understanding of the new bolt specification for high strength bolts, F3125, and the rotational capacity provisions required for bolts in bridges.

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Introduction to Steel Bridge Design

Session 3: Steel Material Properties

Presented by
Karl H. Frank
Hirschfeld Industries
Austin, Texas

structural STEEL

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Night School Course B1

Introduction to Steel Bridge Design

- June 6 - Session 1: Introduction to Bridge Engineering
- June 13 - Session 2: Introduction and History of AASHTO LRFD Bridge Design Specifications
- **June 20 - Session 3: Steel Material Properties**
- June 27 - Session 4: Loads and Analysis
- July 11 - Session 5: Steel Bridge Fabrication
- July 18 - Session 6: Plate Girder Design and Stability
- July 25 - Session 7: Effects of Curvature and Skew
- August 1 - Session 8: Fatigue and Fracture Design

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Outline

- A Little Metallurgy
- Hot Rolled Steel
  - Unique Bridge Requirements
  - Range of Strengths
  - High Performance Steel (HPS)
- Bolting Material
  - New A3125 Specification
  - Anchor Rods

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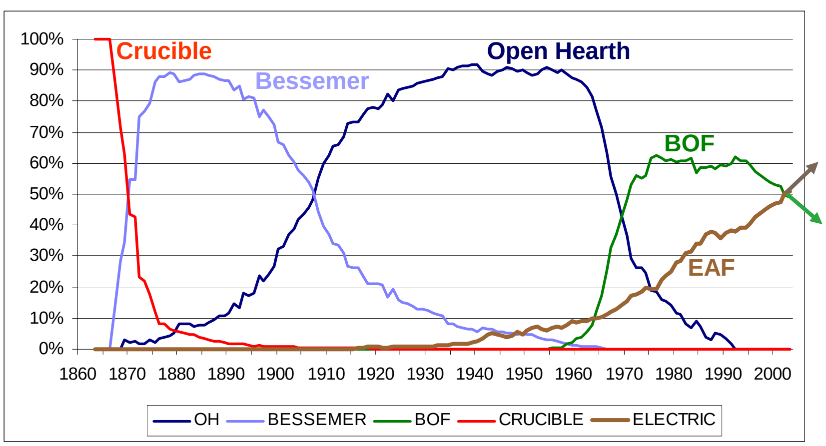
Making Steel
and
Some Metallurgy

Steelmaking History 1860 – 2003+
Process Share of Total Production



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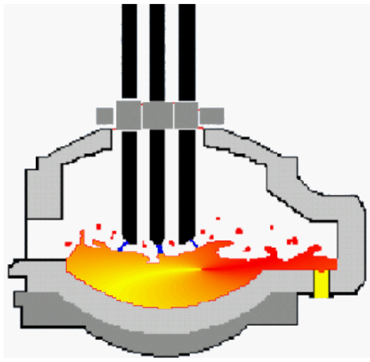
Electric Arc Furnace (EAF)

Tap-To-Tap Time: ~ 35 Minutes



Electric Arc Furnace

Blended Scrap

- Cost
- Density
- Melting Efficiency
- Chemistry

EAF Heat Size: ~ 120 Tons

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EAF Steelmaking

Electric Arc Furnace
(EAF)

Ladle Metallurgy Furnace
(LMF)

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Ladle Metallurgy Furnace (LMF)

<u>Metallurgy</u>

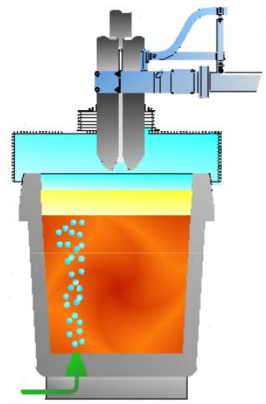
Desulfurization

Build Chemistry

Inclusion Control

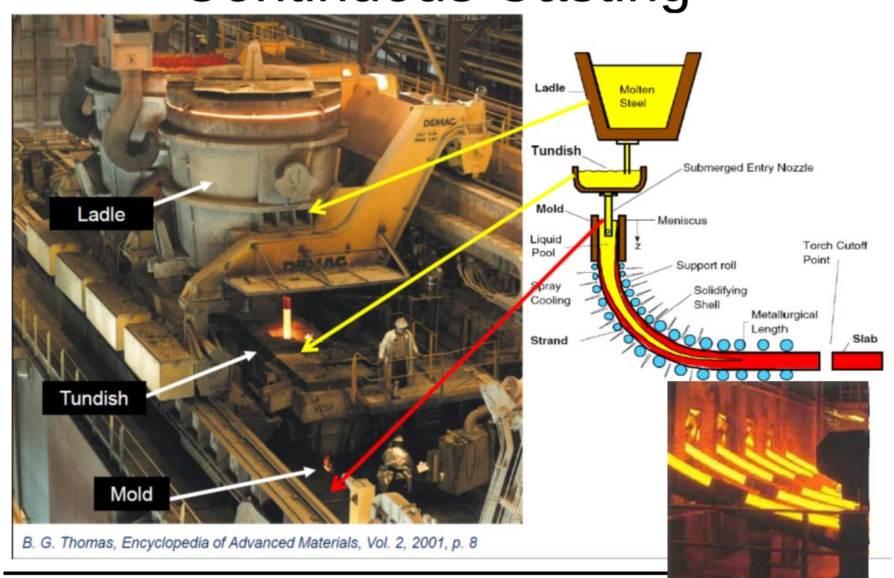
Temperature

Homogeneity



LMF Heat Size: ~ 120 Tons

Continuous Casting



B. G. Thomas, Encyclopedia of Advanced Materials, Vol. 2, 2001, p. 8

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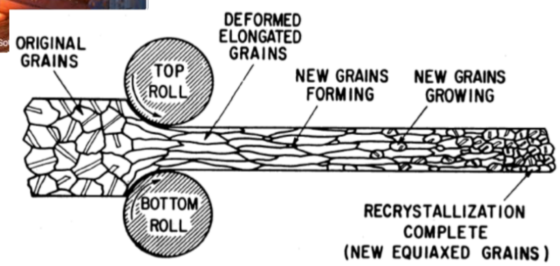
Slab Rolled to Final Plate Thickness

Rolling Temperature 2100 to 2300 ^{o} F

Austenite Phase- Soft and Ductile



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Hot Rolling Stands

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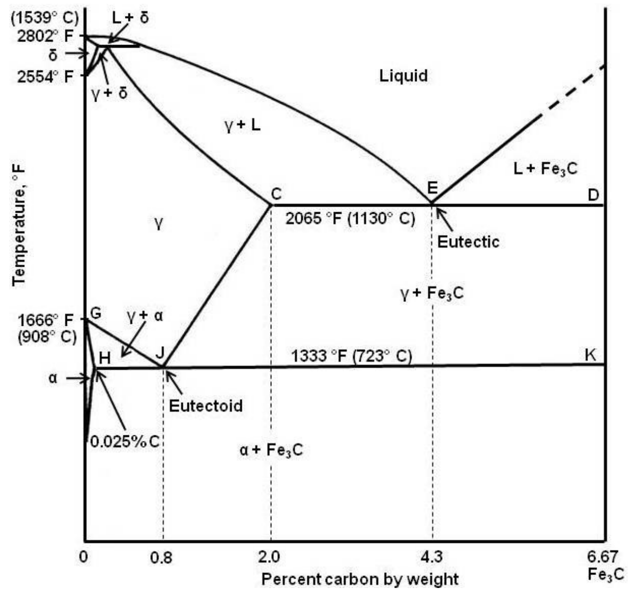
Iron Carbon Phase Diagram



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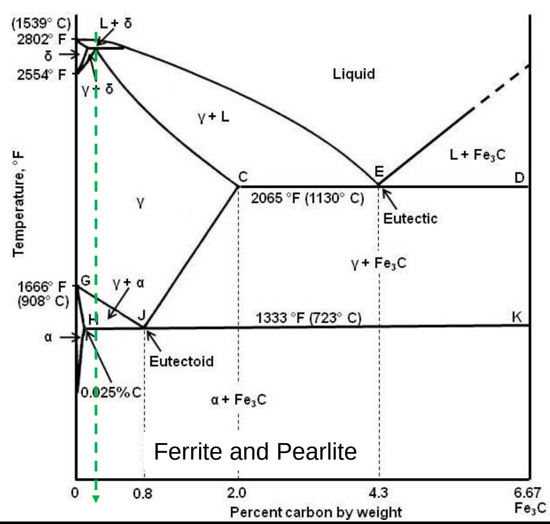
Phase Transformation During Cooling of Liquid Steel

γ- **Austenite** (face centered cubic structure) High Solubility for Carbon *Soft*

α- **Ferrite** (body centered cubic structure) Low Solubility for Carbon *Ductile*

Carbide- Fe_3C High Solubility for Carbon *Hard*

Pearlite- a micro structure of Ferrite and Carbide



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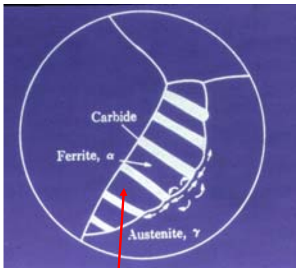
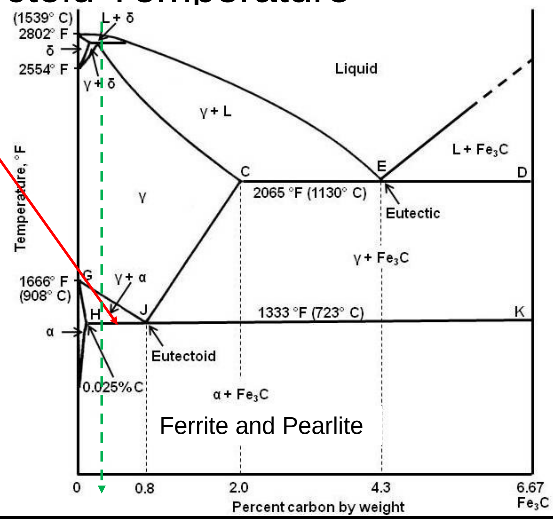
Diffusion of Carbon from Austenite to Carbide at Eutectoid Temperature



Pearlite-Lamellar structure of alternating bands of Ferrite and Carbide



Methods of Increasing Strength of Steel

- More Alloy Content
  - Expensive
  - Weldability
- Quench and Tempered Steel
  - Lower Alloy Requirements
  - A325 & A490 Bolts, HPS 70W and HPS 100W
- TMCP-Thermal Mechanical Control Process
  - In line process

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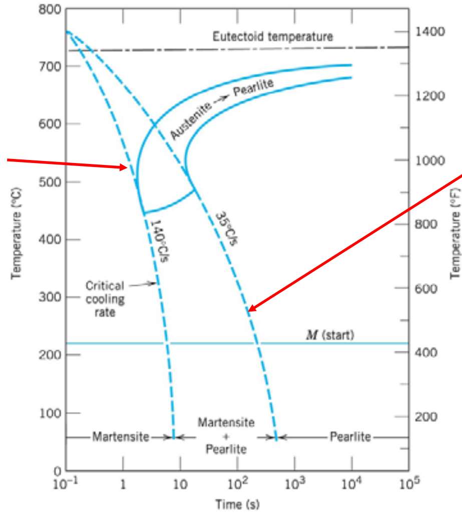
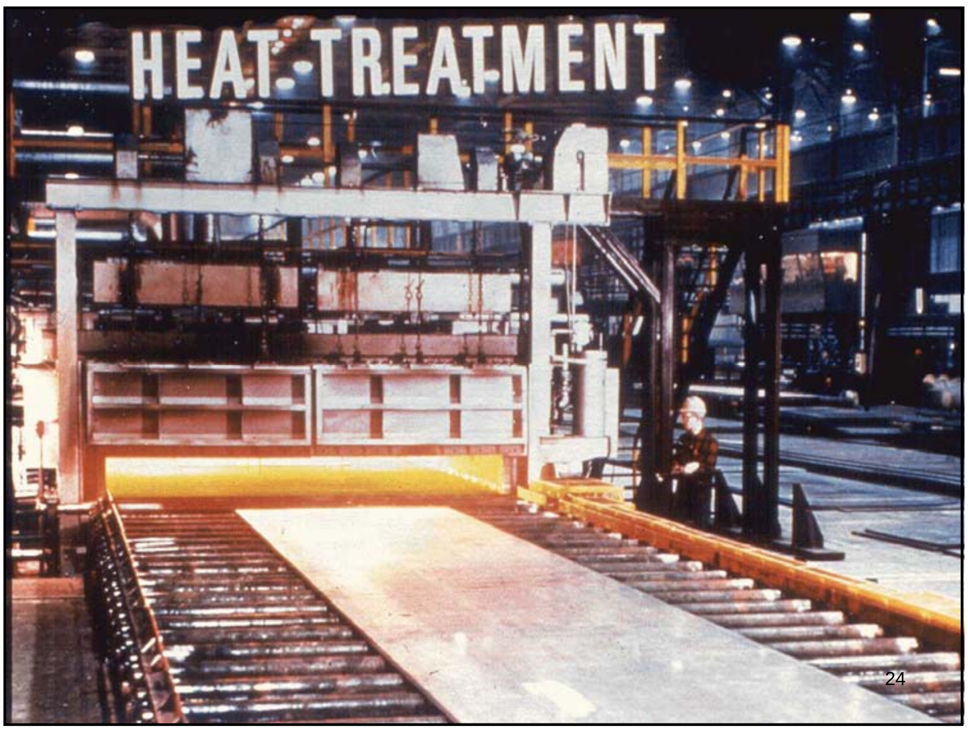
Effect of Cooling Rate Upon Microstructure

Quick cooling rate - Martensite formed. Diffusion of carbon from Austenite to Carbide does not occur.
Hard Brittle Microstructure



Cooling rate slow enough to allow formation of Pearlite structure.



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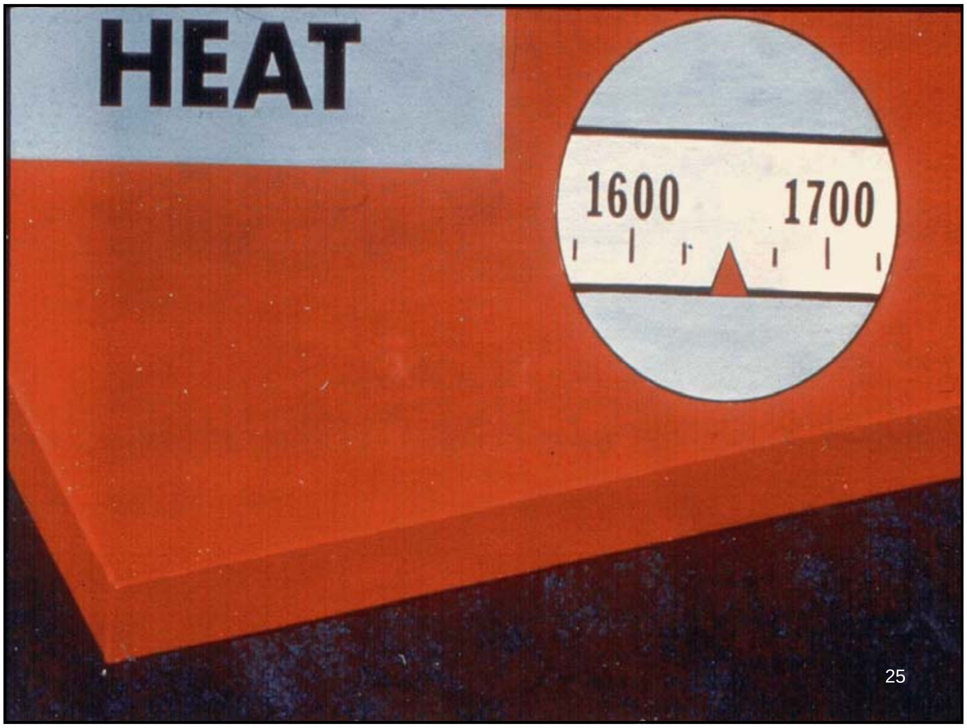

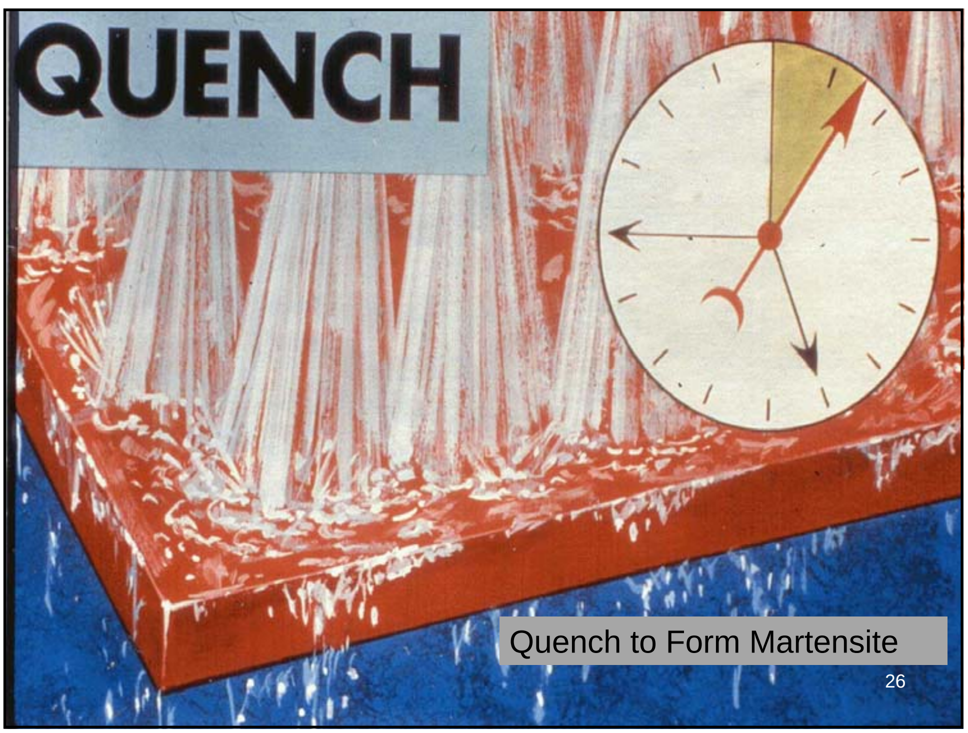

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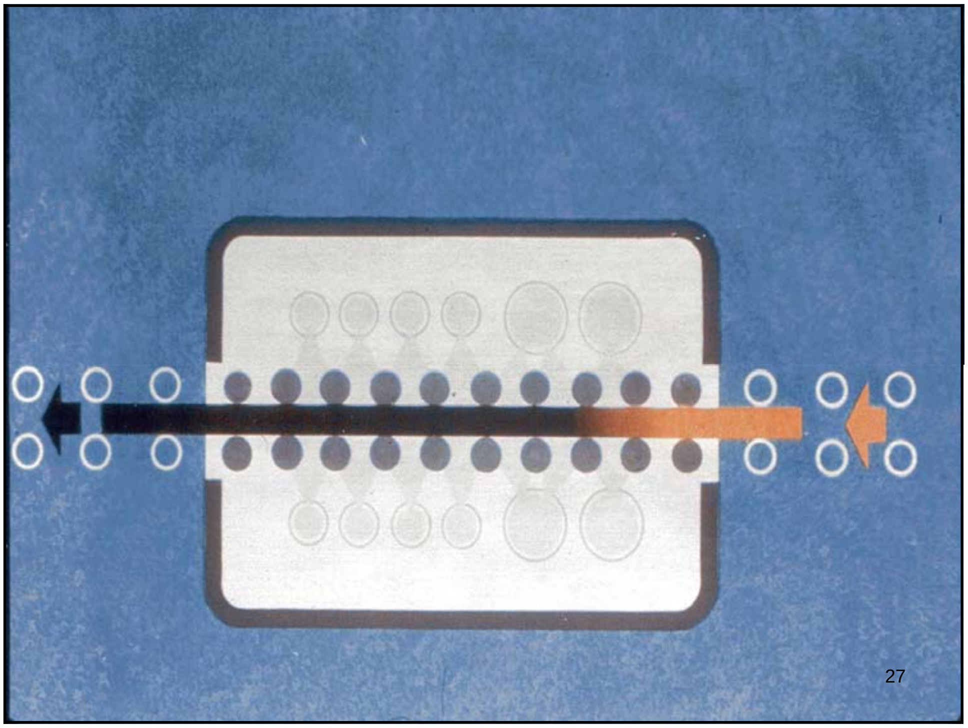

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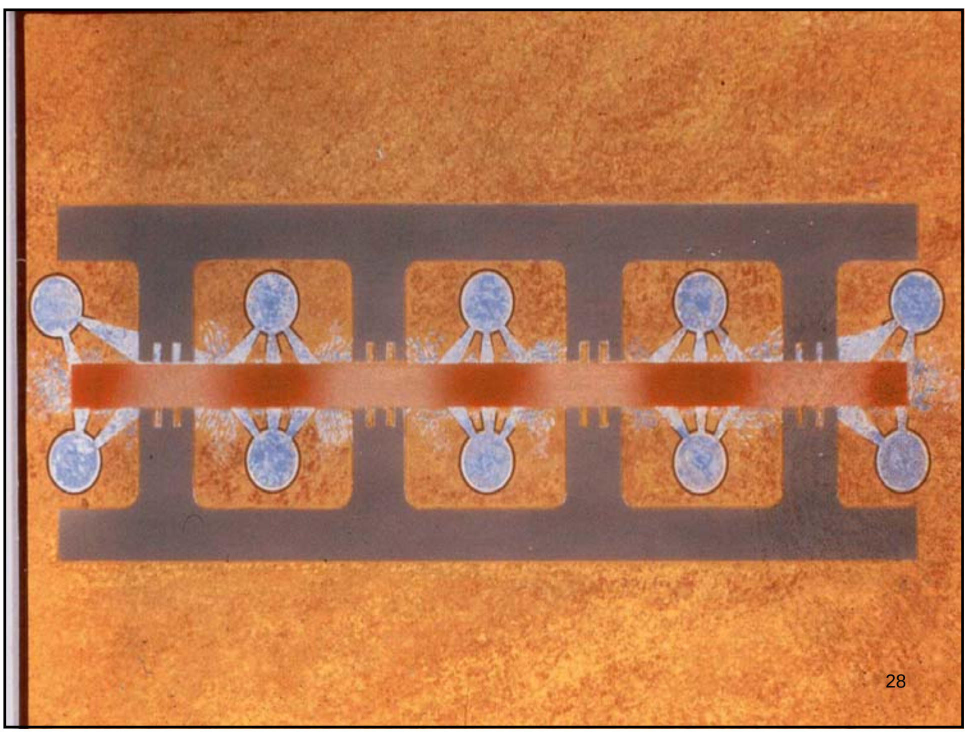

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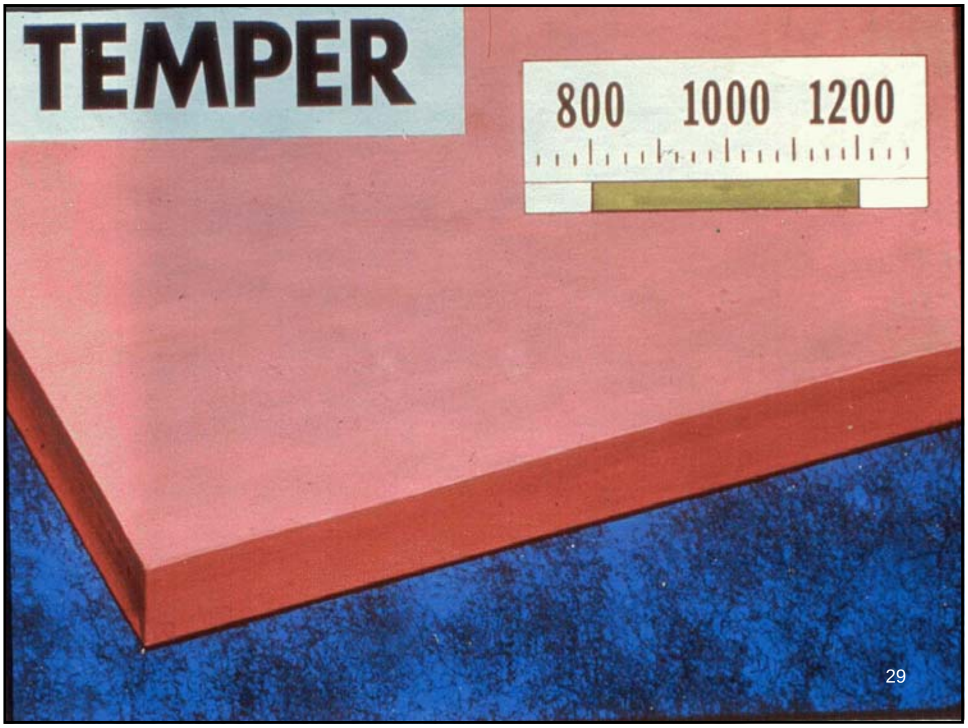

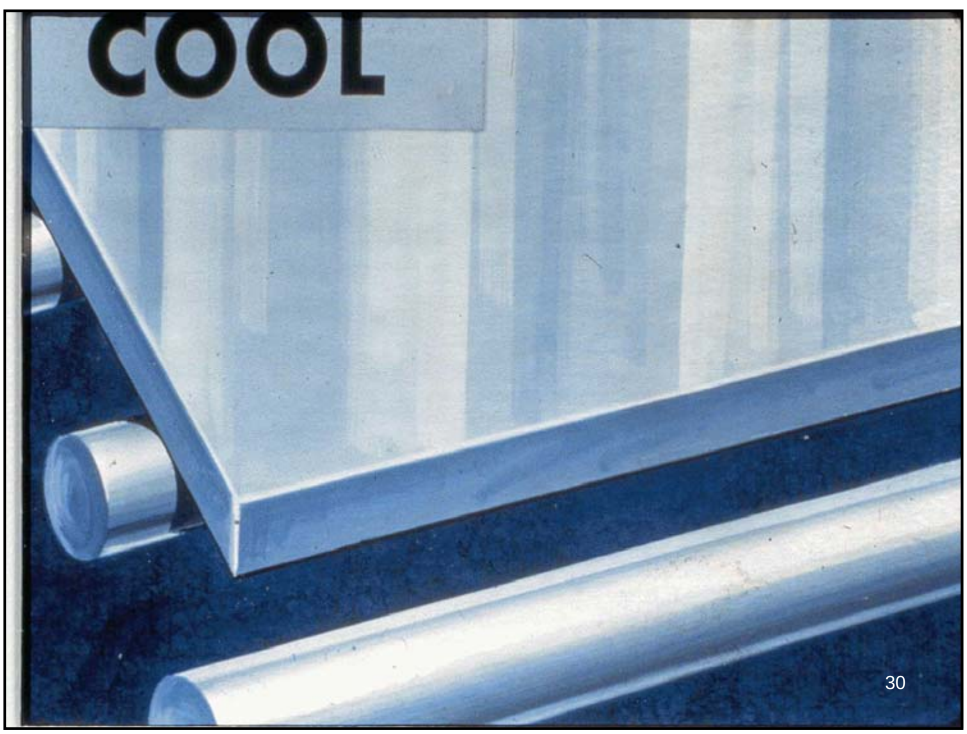

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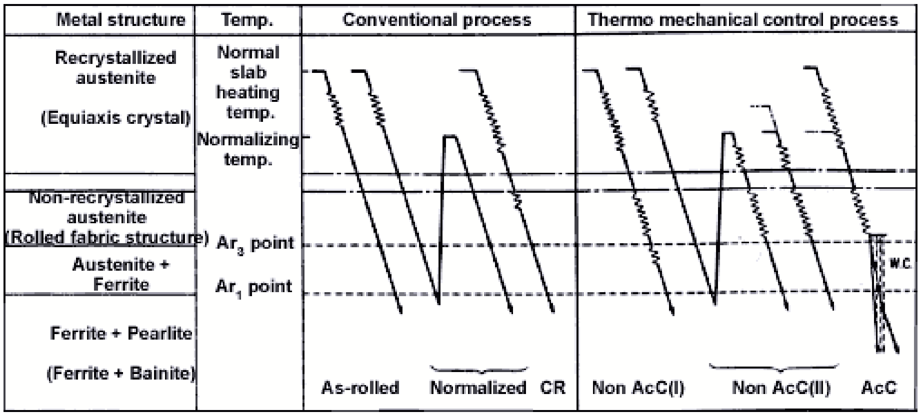
TMCP

TWI-Global.com



Produces Fine Ferrite Grain Size- Higher Strength with Less Alloy, Higher Toughness

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Welding-
Role of Steel Chemistry and Cooling

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Submerged Arc Welding
SAW

Butt Splice

Web to Flange Weld

Fusion Welding: Melting of Base Metal and Welding Wire/Electrode

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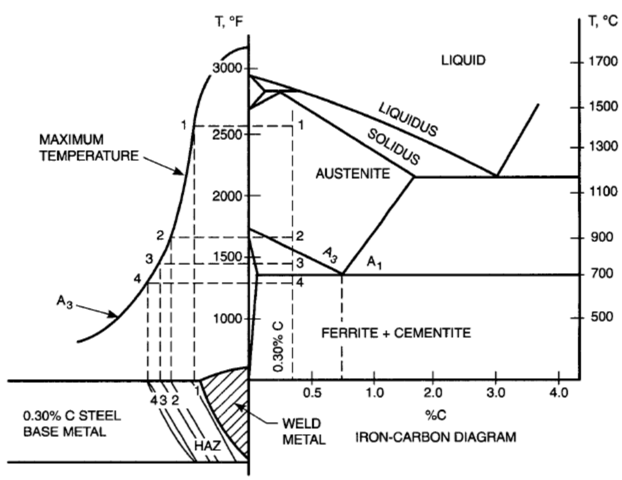
What Happens to Base Metal During Welding



Weldcor

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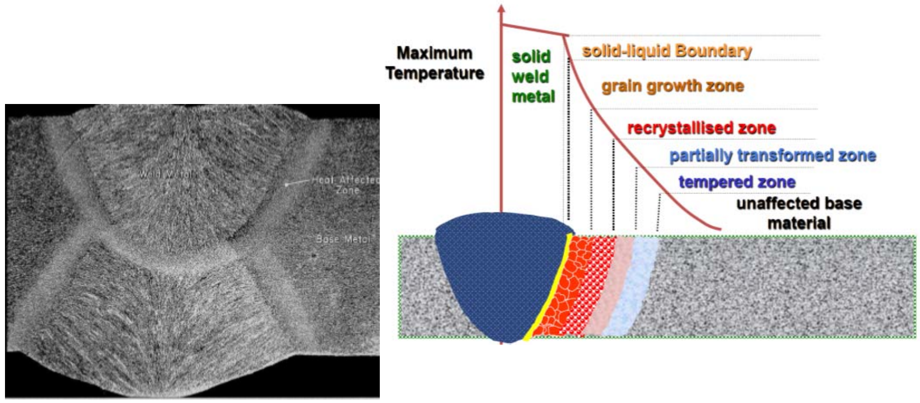
HAZ
Heat Affected Zone



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Cooling Rates

- Quenched and Tempered Steel
  - Alloyed to improve hardenability(curves move to the right) to allow the center which cools slower to form Martensite
  - Fast cooling, quenched, to form Martensite
    - Hard and brittle
  - Temper (reheat)
    - Softer tougher tempered martensite
- Welding
  - Slow cooling to prevent formation of martensite
  - Preheat to slow cooling rate-Thick Plates Larger Heat Sink
  - Alloyed Steel and High Carbon Steel require slower cooling therefore Higher Preheat

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Bridge Steels

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ASTM Steel Specifications for Bridges

	Specification	Availability	Strength
•	ASTM A7	1952 to 1967	33 ksi min. YS
•	ASTM A36	1960 to today	36 ksi min. YS
•	ASTM A514	1964 to 2009	100 ksi min.YS
•	ASTM A572	1966 to today	50 ksi min. YS
•	ASTM A588	1968 to today *	50 ksi min. YS
•	ASTM A709	1974 to today	**

* Weathering steel
** Collection of all grades including HPS

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Bridge Steel

- ASTM A709- 7 Grades
  - Plate Material
    - A36-Grade 36
    - A572-Grade 50
    - A588-Grade 50W
    - HPS: Grade HPS 50W, Grade HPS 70W, HPS 100W
    - Maximum Thickness- 4 in. single producer, 3 in. most producers
  - Rolled Sections- A992-Grade 50S

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A709 ?

Why a separate Specification?

- Contains Unique Requirements for Bridge Steels
  - Charpy V Notch Testing Requirements
  - Special requirements for material in fracture critical members
  - Test specimen sampling and limitations on weld repair

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What does W stand for?

- Weathering Steel

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Weathering Steel

- Specially alloyed steel which provides a stable rust like patina
  - Requires no painting (washing off salts recommended)
  - Not for underwater or costal regions
- Steel costs about 10% more than non-weathering steel but offset by painting costs

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Weathering Steel Details

- Drip bars on bottom flange to prevent pier staining:

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High Performance Steel

- HPS 50W- no structural advantage, limited plate length if heat treated
- HPS 100W- Limited availability and limited use.
- HPS 70W- Up to 4 in., over 2 in. generally quenched and tempered- 1 producer

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High Performance Steel

- HPS 70W- Primary use as flange material in hybrid pier sections and tension flange in span region of long span girders
  - High strength, excellent toughness, and good weldability (%C<=0.11%)
  - Enhanced weathering capability
  - as-rolled, control-rolled, thermo-mechanical control processed (TMCP) with or without accelerated cooling, or quenched and tempered.

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HPS 70W Availability

Producer	Maximum Thickness (in)	Maximum Width (in)	Maximum Length (ft)
Arcelor-Mittal (Q&T)	4	162	50
Arcelor-Mittal (TMCP)	1-3/8	120	125
Nucor Steel (Q&T)	2	124	48.3
SSAB (TMCP)	2	103	95

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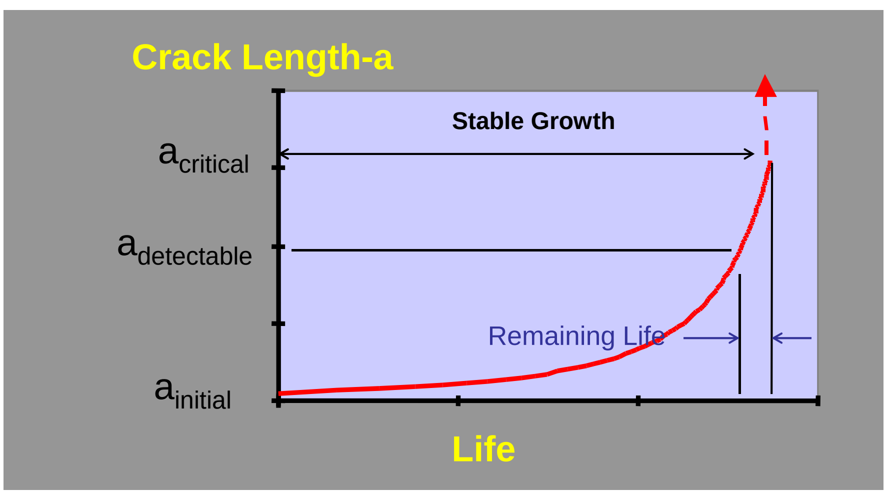
Charpy Test Requirements

(not required for members or part of members in compression)

- Provide Fracture Toughness to Tolerate Fatigue Cracks Large Enough to be Found During In-service Inspection
- Increased Sampling and Higher Energy Requirements for Steels in Fracture Critical Members
- Designate Tension Members
  - Non-fracture critical: T suffix plus temp. zone 1,2,3
  - Fracture Critical: F suffix plus temp. zone 1,2,3

Role of Toughness

Provide Critical Crack Size>Detectable



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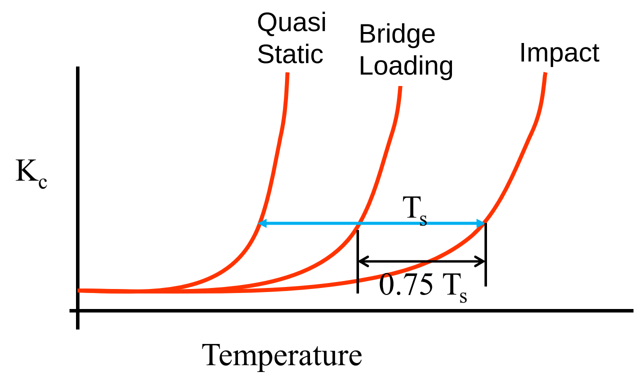
Loading Rate And Temperature

$$T_s = 215 - 1.5\ F_y$$

Bridge Loading to Impact =0.75 T_s



Conversion of K_c to CVN

$$K_{ID} = (10 - 15)\sqrt{CVN} \approx 12.5\sqrt{CVN}$$

Dynamic Toughness Proportional to
Dynamic Charpy Vee Notch Energy

Units:

K_c: ksi-in$^{1/2}$ CVN: ft-lb

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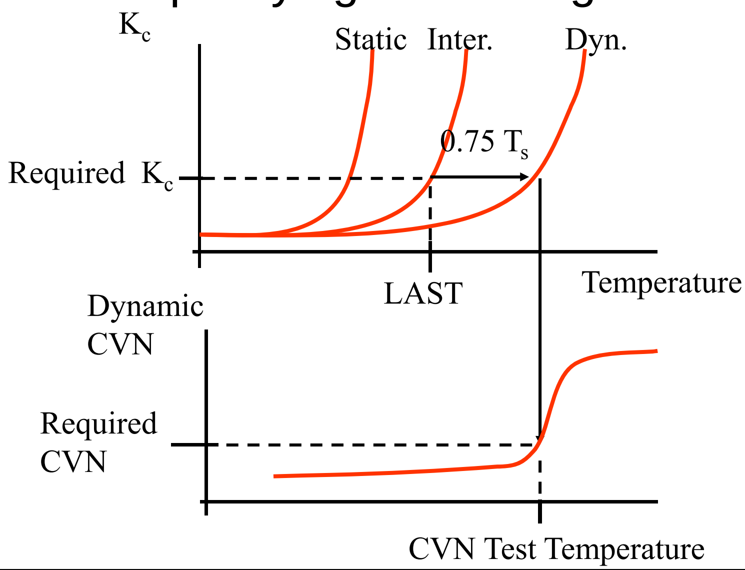
Specifying CVN Toughness



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Grade 50 Steel Example

F_y=50 ksi LAST=0 °F

CVN Test Temperature Determination:

Intermediate Service Loading Rate

Intermediate to Dynamic=0.75 (215-1.5 x 50)
= 105 °F
CVN Test Temperature = LAST+0.75 T_s
= 0+105
=105 use room temperature 70°F

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Required Toughness:

Tolerate 1 inch Long Crack At Yield Strength Level Applied Stress

$$K_{required} = 50\sqrt{\pi\, 0.5} = 62.7\,\text{ksi-in}^{1/2}$$

$$CVN = \left(\frac{K_{ID}}{12.5}\right)^2$$

$$CVN = \left(\frac{62.7}{12.5}\right)^2 = 25.1\,\text{ft-lbs}$$

Material Requirement: Average of 3 Specimens Tested at 70 ^{o}F Must Exceed 25 ft-lbs

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A709 Non Fracture Critical

max. thickness 4 in.

Grade	Required Toughness ft-lbs	Test Temp. Zone 1 ^{o} F	Test Temp. Zone 2 ^{o} F	Test Temp. Zone 3 ^{o} F
36T	15	70	40	10
50T, 50ST,50WT	15 (t<=2) 20 (t>2)	70	40	10
HPS 50WT	20	10	10	10
HPS 70WT	20	-10	-10	-10
HPS 100WT	25 (t<=2.5) 35 (t>2.5)	-30	-30	-30

Grade 50 plate reduce test temperature by 15 ^{o} F if yield point exceeds 65 ksi
Grade 70 plate reduce test temperature by 15 ^{o} F if yield point exceeds 85 ksi

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Point Pleasant Bridge Collapse

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

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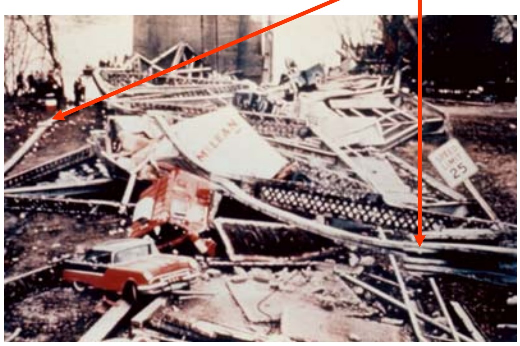
Total Bridge Collapse

Eye Bar 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

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Eyebars

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

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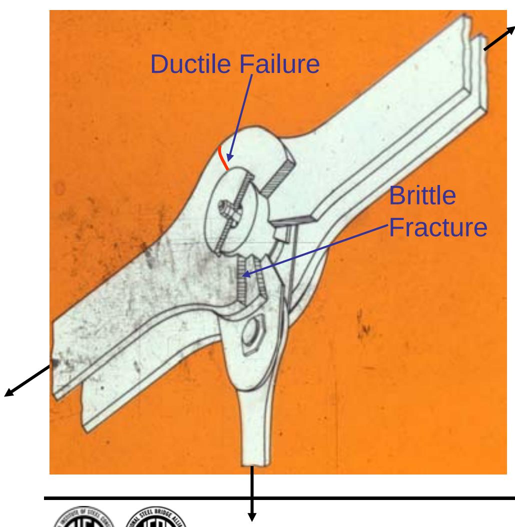
Failure Events



1. Brittle Facture 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

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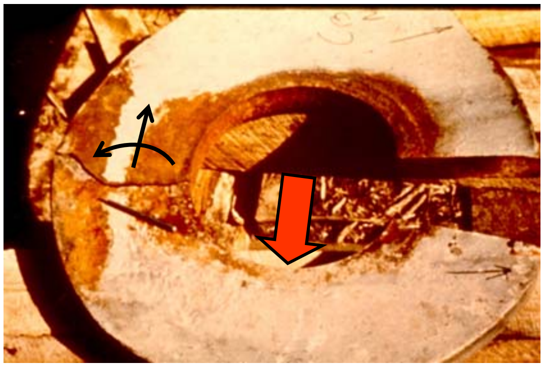
Fractured Eye Bar



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

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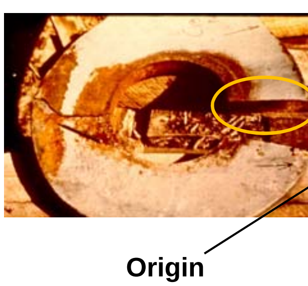
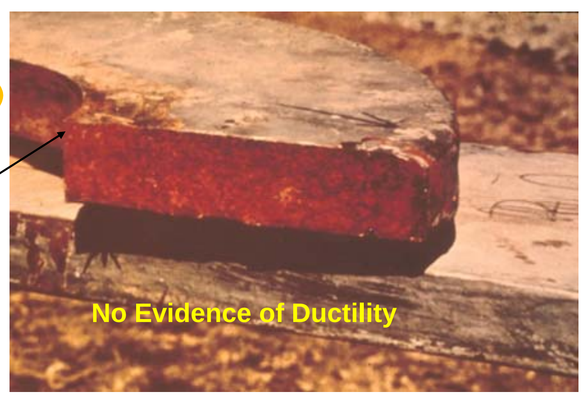
Fracture Surface





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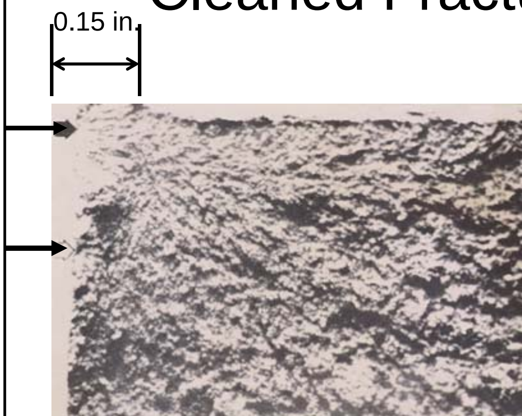
Cleaned Fracture Surface



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

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Need Crack Tolerant Steel

- Higher Toughness for Critical Members
  - 2 eyebars not enough reserve strength if one fractured
  - These members require higher toughness and closer inspection

Labeled Fracture Critical- Collapse Would Occur if they Fractured

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A709 Fracture Critical

max. thickness 4 in.

Grade	Required Toughness ft-lbs	Test Temp. Zone 1 °F	Test Temp. Zone 2 °F	Test Temp. Zone 3 °F
36T	25	70	40	10
50F, 50SF,50WF	25 (t<=2) 30 (t>2)	70	40	10
HPS 50WF	30	10	10	10
HPS 70WF	35	-10	-10	-10
HPS 100WF	35 (t<=2.5)	-30	-30	-30

Grade 50 plate reduce test temperature by 15 °F if yield point exceeds 65 ksi
Grade 70 plate reduce test temperature by 15 °F if yield point exceeds 85 ksi

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Temperature Zones

Table 6.6.2-1—Temperature Zone Designations for Charpy V-Notch Requirements

Minimum Service Temperature	Temperature Zone
0°F and above	1
−1°F to −30°F	2
−31°F to −60°F	3

AASHTO LRFD Bridge Design Specifications

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Sampling Requirements

- Tension Non Fracture Critical (T)
  - Heat Frequency (H) Testing For Grade 50 steels and Grade 36
  - HPS 70WT and 100WT Plate Frequency (P)
- Fracture Critical (F)
  - Plate Frequency (P) for All Grades
    - Test Both Ends except normalized plate

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The Fracture Control Plan

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Newest Steel-A1010

Higher-Strength Martensitic Stainless Steel Plate, Sheet, and Strip

- Corrosion loss 5 times less than 50W but 6-7 times the cost
- Tempered Martensite
- 10.5-12.5% Chrome, 1.5% Nickel
- Grade 50 Used for Bridges
- Maximum Thickness of 2 in.
- High Toughness
- Special Fabrications Requirements

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A1010 Bridge in Oregon

Fought and Company, INC

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Hollow Structural Sections

- ASTM A1085
  - CVN impact value of 25 ft-lbs at 40°F, exceeds AASHTO Temperature Zone 2 requirements
  - Carbon equivalent maximum
  - Maximum yield strength of 70 ksi, 50 ksi minimum
  - Wall thickness >= 95% of specified (A500-90%)
  - Minimum corner radius

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Bolts

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High Strength Bolts

- New Specification Combines 4 Specifications into 1 for both buildings and bridges-F3125
  - A325 Standard Hex Bolt
  - F1852 (A325 Tension Control)
  - A490 Standard Hex Bolt
  - F2280 (A490 Tension Control)
  - + Metric
- These old names become Grades

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Significant Changes

- Grade A325- F_u = 120 ksi for all diameters (results in an increase in shear capacity for bolts >= 1 in.)
- Annex A1- Table gives permitted coatings and over tapping required for nuts
  - No hot dip or mechanical galvanizing of Grade A490 bolts
  - F1136 and F2833 Zinc/Aluminum Allowed on **all** Grades A325 and A490
- Rotational Capacity Test in Appendix A2

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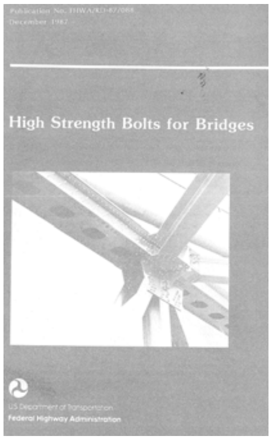
Rotational Capacity Testing

Based on 1987 Research



State of The Practice In 1980's

- Problems Were Occurring with Galvanized Fasteners
- Bolts Broke During Installation
- ASTM Required a Rotation Test but No Matching of Nuts to Bolts (Separate Specifications)
- No Specific Lubrication Requirements
- Stripping Problems:
  - Over tapping Limits too Large
  - Soft Nuts Allowed for A325 black bolts

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All bolts Pretensioned Required minimum installation tension

0.7 X tensile strength

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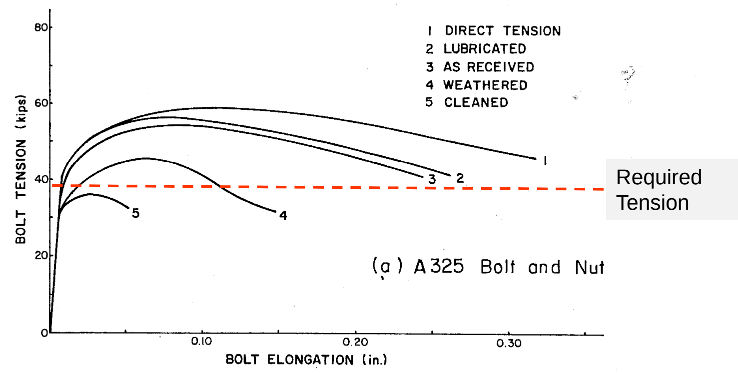
Influence of Lubrication Upon Tightening Performance



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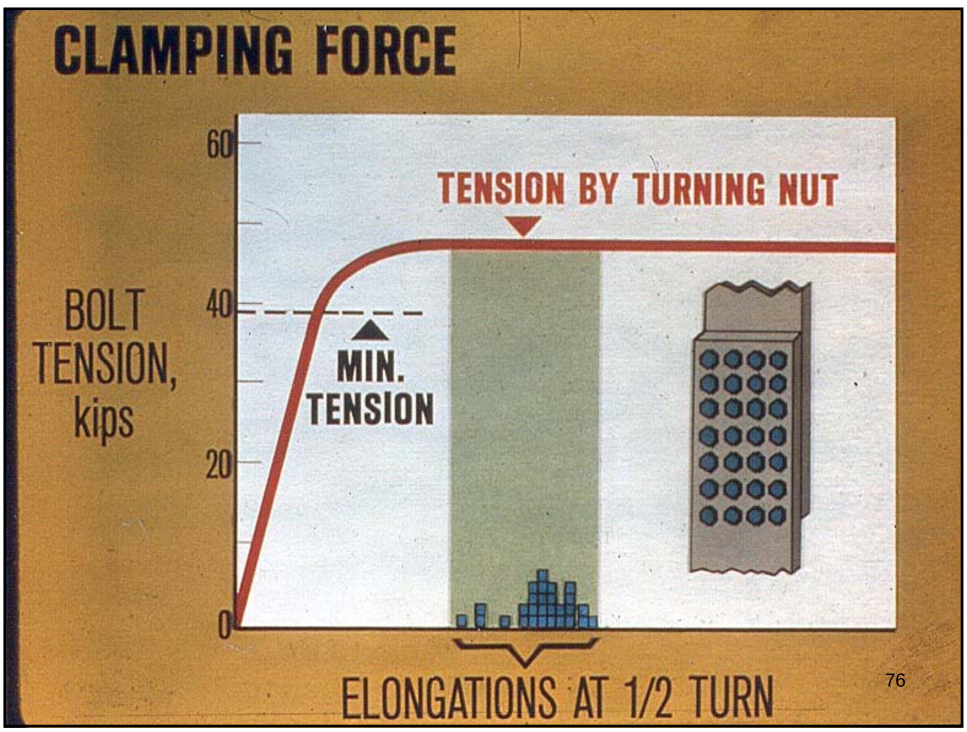

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Rotational Capacity Elements

- Test Bolt and Nut as an Assembly
- Use Torque at Measured Tension to Determine Lubrication Efficiency
- Require Tightening to 2x Installation for A325, Slightly less for A490 to Insure Ductile Behavior
- Maximum Tension Must Exceed 1.15x Required
- No Evidence of Stripping.

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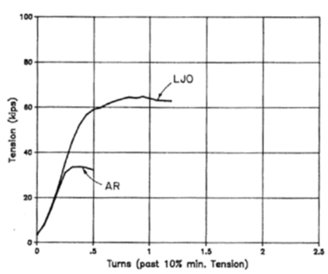
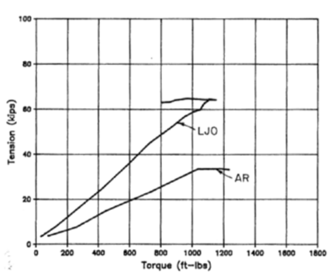
Lubrication/Torque Requirement





- Torque<=0.25 x Tension x Bolt Diameter
- 0.25 is the Nut Factor, Measure of Lubrication
  - High Torque Reduces Installed Tension and Ductility
- Minimum Tension is 1.15 x Required

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Snugging is the most important part of bolt installation

- Purpose- eliminate reduction in tension as plates are brought into contact from tightening adjacent fasteners.
  - Start all tightening methods with snugging bolts to bring plates in firm contact at the fastener
  - If using turn of the nut- match mark end of bolt and nut after snugging to provide visual evidence of proper tightening
  - This is the stage to check for proper bolt installation
- Checking bolt tension with a torque wrench is unreliable and unnecessary

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Footnote on Bolting

- New Hole Size
  - 1 inch and greater: Standard hole = diameter of fastener +1/8 in.
- Miss drilled holes- fill with fully tensioned high strength bolt (Category B fatigue strength)
- New electric wrenches can be programmed for required turn of the nut

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Anchor Rod/Bolts

- ASTM F1554
  - Grades 36,55,&105
  - Diameters:
    - ½ to 4 in. Grades 36 and 55
    - ½ to 3 in. Grade 105
  - All grades can be galvanized
  - Supplemental Provisions
    - Grade 55 available with weldable chemistry
    - CVN Grade 55: 15 ft-lbs at +40 º F
    - CVN Grade 105: 15 ft-lbs at +40 º F or -20 º F

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Anchor Rods

- Do Not Use A354 Grade BD
  - Tempting since available in large diameter<=4 in.
  - High Hardness R_c=39 >38 A490
  - "*When bolts of Grade BD of this specification are considered for pretensioned applications in excess of 50 % of the bolt tensile strength, the additional requirements of head size, maximum tensile strength, nut size and strength, washer hardness, tests, and inspections contained in Specification A490 should be* ***carefully*** *considered.*"
  - Never Galvanize- Stress Corrosion Sensitive

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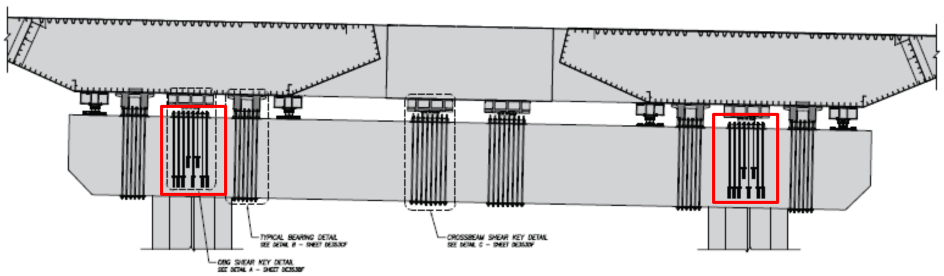
New S.F. to Oakland Bay Bridge Connection Detail East Pier with 3 inch A354 Grade BD Rods



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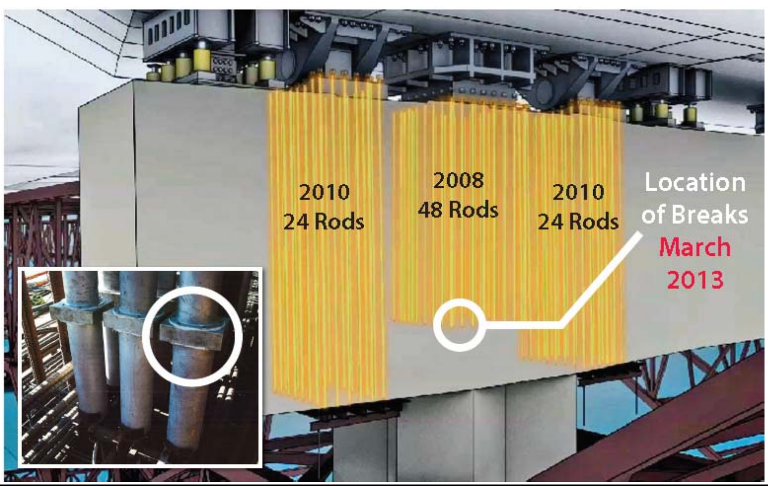
Location of Rods at East Pier All Rods Pretensioned to 0.7 x F_u



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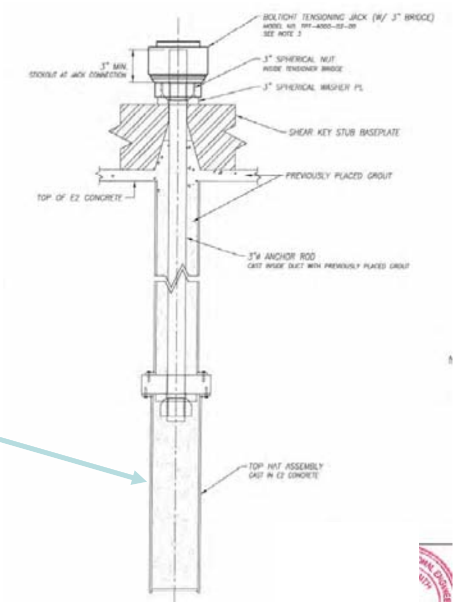
Short Bolt Details



So Called Top Hat at Bottom to Hold Rod Before It is Lifted in Place

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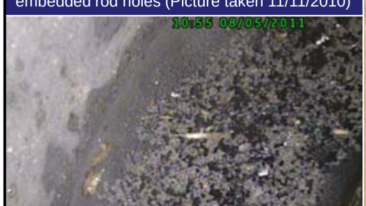
Rods Left In Structure Approximately 4 years Before Stressing

Construction workers removing water from the embedded rod holes (Picture taken 11/11/2010)



Boroscope photo (Picture taken 08/05/2011)

20 rods seen entirely submerged in water (Picture taken 1/12/2011)

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Shear Key Bolts Post Fracture

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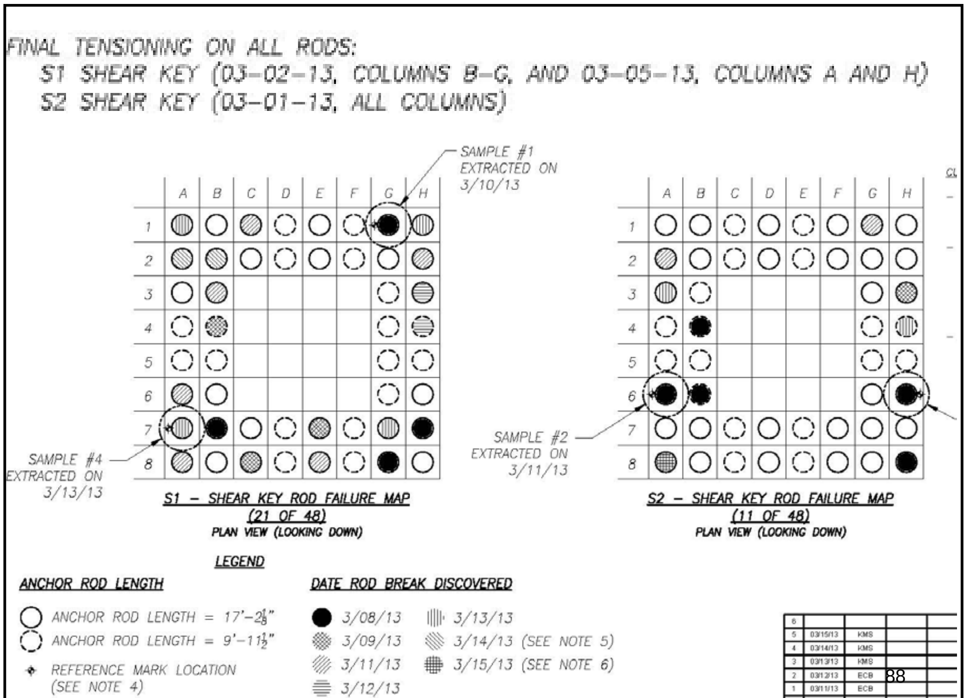

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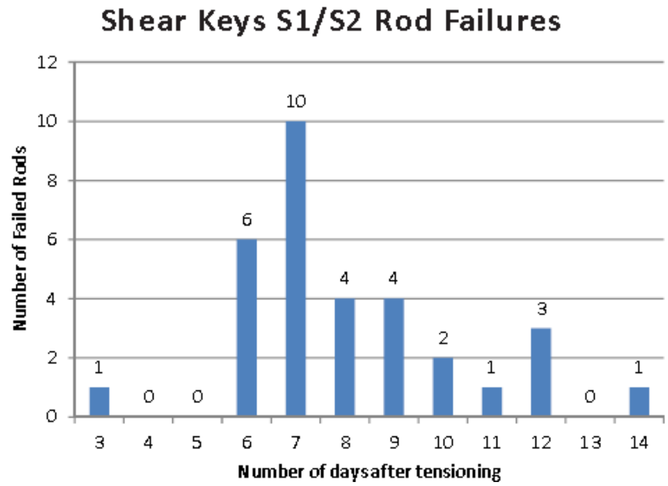
Number of Days to Fracture
32 Bolts



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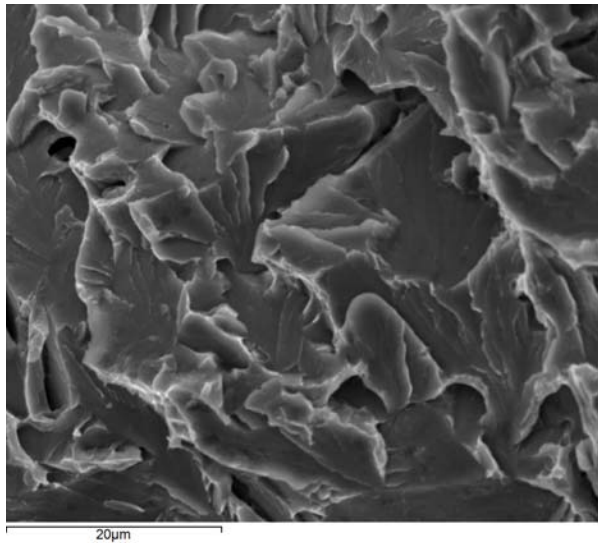
Cleavage Cracking at Center



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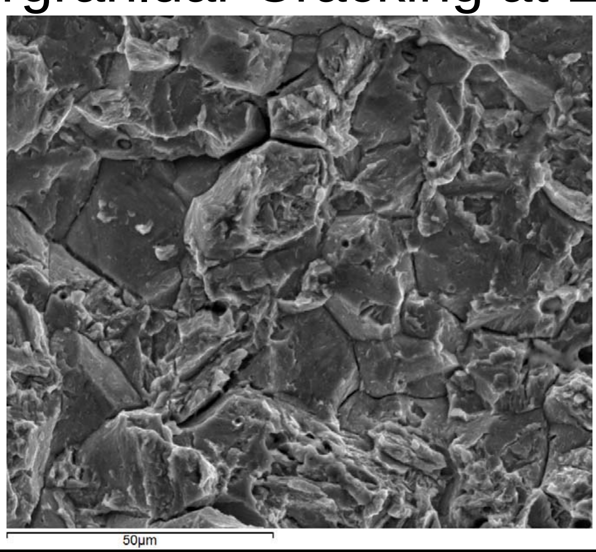
Intergranluar Cracking at Edge



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The Lessons Learned

- EHE-Evironmentally Induced Hydrogen Embrittlement
- Hydrogen Formed From the Galvanic Reaction Between the Steel and Zinc
- Tests Showed that a Threshold Stress Exists Below Which No Cracking Will Occur
- High Strength/Hardness + High Stress + Galvanizing + Water = **Cracking**

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Summary

- Steel strength a function of chemistry, heat treatment, and inline processing
- Steels with high alloy or high carbon content need to be cooled slower to prevent formation of martensite in HAZ
- A709 Specification- All the special requirements of bridge steels
- A3125- New specification for high strength bolts.

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Summary

- CVN toughness provides for crack tolerance needed for inspection reliability
- Rotational Capacity Test insures that the nut and bolt combination will provide reliable bolt pretension
- New Steels:
  - A1010 Stainless Steel- enhanced corrosion resistance
  - A1085 Hollow Section Steel- CVN requirements, tighter thickness control and corner radius.

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8-Session Package Registrants

Course Resources

1. Log on to your AISC account and go to Course Resources. https://www.aisc.org/myaisc/course-resources/
2. Locate your course.
3. Access handouts, videos, quizzes, quiz scores and attendance records.

AISC > MYAISC > COURSE RESOURCES > STEEL BRIDGE DESIGN

Steel Bridge Design

8-SESSION PACKAGE RESOURCES

Event	Date	Handouts	Video	Quiz	Attendance
R1: Introduction To Bridge Engineering	N/A	Handouts	View Passcode: RZNS141	Pass Score: 80	N/A
R2: Introduction and History of AASHTO Bridge Design	N/A	Handouts	Available 9/11/2017 5:00 PM EDT	Available 9/11/2017 5:00 PM EDT	N/A
R3: Steel Material Properties	N/A	Handouts	Available 9/11/2017 5:00 PM EDT	Available 9/11/2017 5:00 PM EDT	N/A
R4: Loads and Analysis	N/A	Handouts	Available 9/11/2017 5:00 PM EDT	Available 9/11/2017 5:00 PM EDT	N/A
L1: Steel Bridge Fabrication	Oct 12 2017 1:30PM EDT	Handouts	Available 10/14/2017 5:00PM EDT	Available 10/14/2017 5:00PM EDT	Pending
L2: Plate Girder Design and Stability	Oct 19 2017 1:30PM EDT	Handouts	Available 10/21/2017 5:00PM EDT	Available 10/21/2017 5:00PM EDT	Pending
L3: Effects of Curvature and Skew	Oct 26 2017 1:30PM EDT	Handouts	Available 10/28/2017 5:00PM EDT	Available 10/28/2017 5:00PM EDT	Pending
L4: Fatigue and Fracture	Nov 2 2017 1:30PM EDT	Handouts	Available 11/04/2017 5:00PM EDT	Available 11/04/2017 5:00PM EDT	Pending
Intro To Steel Bridge Design - Final Exam	Nov 23 2017 8:00AM EST			Available 11/25/2017 5:00PM EST	

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8-Session Package Registrants

Videos and Quizzes

Videos

- For Sessions R1 – R4, find access to recordings starting September 11. Recording access expires on November 23.
- For Sessions L1 – L4, find access to recordings within two days after the live air date. Recording access expires three weeks after the live session.

Quizzes

- For Sessions R1 – R4, find access to quizzes starting September 11. Quizzes are due on November 23.
- For Sessions L1 – L4, find access to quizzes within two days after the live air date. Quizzes are due three weeks after the live session.
- A final exam will also be given.
- Quiz scores are displayed in the Course Resources table.

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8-Session Package Registrants

Course Credit

Attendance and PDH Certificates

- For Sessions R1 – R4, you must pass the quiz to receive credit for the session.
- For Sessions L1 – L4, you have two options to receive credit for the session.
  - Option 1: Watch the session live. Credit for live attendance will be displayed in the Course Resources table within two days of the session.
  - Option 2: Watch the recording and pass the quiz.

EEU Certificates – Certificate of Completion

- In addition to PDH certificates earned for each individual session, an EEU (Equivalent Education Unit) certificate of completion will be issued for participants who complete the full course. Participants must pass at least 7 of 8 quizzes and the final exam to earn the EEU.

Distribution of Certificates

- All certificates (PDH and EEU) will be issued after the final session. Only the registrant will receive certificates for the course.

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