## Night School 23: Topics on Industrial Building Design and Design of Non-building Structures

Thank you for joining our live webinar. We will begin shortly. Please standby.

## Session 6 – High and Low Temperature Design for Industrial Structures

July 28, 2020

Smarter.
Stronger.
Steel.

---

## AISC Live Webinars

**Today's live webinar will begin shortly. Please stand by.**

Today's audio will be broadcast through the internet. Please be sure to turn up the volume on your speakers.

Please type any questions or comments in the Q&A window.

# AISC Live Webinars

## AIA Credit

AISC is a Registered Provider with The American Institute of Architects Continuing Education Systems (AIA/CES). Credit(s) earned on completion of this program will be reported to AIA/CES for AIA members. Certificates of Completion for both AIA members and non-AIA members are available upon request.

This program has been submitted for AIA/CES for continuing professional education. As such, it does not include content that may be deemed or construed to be an approval or endorsement by the AIA of any material of construction or any method or manner of handling, using, distributing, or dealing in any material or product.

Questions related to specific materials, methods, and services will be addressed at the conclusion of this presentation.

# AISC Live Webinars

## Copyright Materials

The information presented herein is based on recognized engineering principles and is for general information only. While it is believed to be accurate, this information should not be applied to any specific application without competent professional examination and verification by a licensed professional engineer. Anyone making use of this information assumes all liability arising from such use.

# AISC Live Webinars

## Course Description

**Session 6 – High and Low Temperature Design for Industrial Structures**
**July 28, 2020**

This session will review design considerations in extreme temperature environments. Low temperature applications discussion will address brittle fracture, importance of specification of steels and notch toughness. High service temperature topics include material properties, creep and graphitization, and member stability.

# AISC Live Webinars

## Learning Objectives

- Describe causes of brittle fracture.
- List mitigating measures to address brittle fracture.
- Describe the design objectives for industrial structures subjected to elevated service temperatures.
- List considerations for design for stability for elevated service temperatures.

# Night School 23: Industrial Structures

## Session 6 – High & Low Temperature Design for Industrial Structures

**July 28, 2020**

Robert (Bob) MacCrimmon, P.Eng., Hatch Ltd
Bo Dowswell, P.E., PhD, Arc International LLC

Smarter.
Stronger.
Steel.

---

# Night School 23: Industrial Structures

## Session 6 – High & Low Temperature Design for Industrial Structures

**July 28, 2020**

## Part 1: Brittle Fracture

Robert (Bob) MacCrimmon, P.Eng.
Senior Civil/Structural Specialist
Hatch Ltd

Smarter.
Stronger.
Steel.

## NIGHT SCHOOL SESSIONS

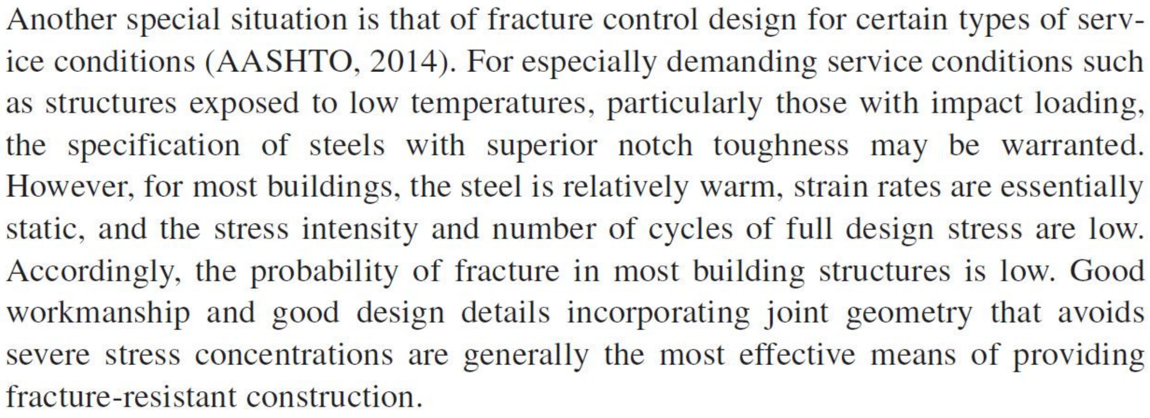
SESSION 1 INTRODUCTION AND CODE PROVISIONS
SESSION 2 INDUSTRIAL BUILDINGS – PART 1
SESSION 3 INDUSTRIAL BUILDINGS – PART 2
SESSION 4 CRANE SUPPORTING STRUCTURES
SESSION 5 FATIGUE DESIGN FOR INDUSTRIAL STRUCTURES
SESSION 6 HIGH & LOW TEMPERATURE DESIGN FOR INDUSTRIAL STRUCTURES
SESSION 7 NON-BUILDING STRUCTURES –PART 1
SESSION 8 NON-BUILDING STRUCTURES –PART 2

## Introduction

- This presentation is meant to be an introduction to the causes of brittle fracture and ideas for how to apply mitigating measures

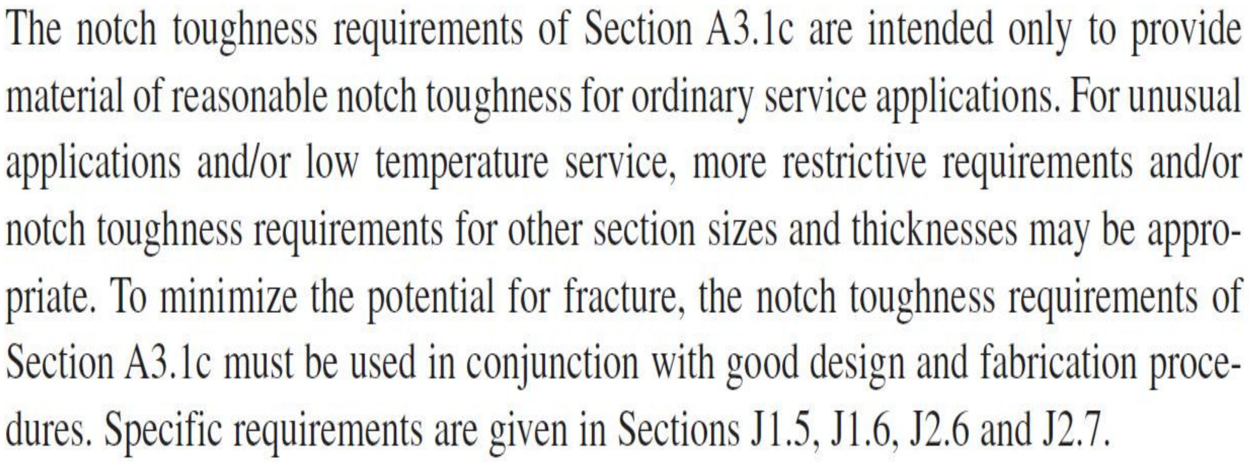
# Codes and Standards

- AISC 360 Commentary for Section A3 refers to fracture control for especially demanding service conditions



Another special situation is that of fracture control design for certain types of service conditions (AASHTO, 2014). For especially demanding service conditions such as structures exposed to low temperatures, particularly those with impact loading, the specification of steels with superior notch toughness may be warranted. However, for most buildings, the steel is relatively warm, strain rates are essentially static, and the stress intensity and number of cycles of full design stress are low. Accordingly, the probability of fracture in most building structures is low. Good workmanship and good design details incorporating joint geometry that avoids severe stress concentrations are generally the most effective means of providing fracture-resistant construction.

# From AISC 360, Cont'd



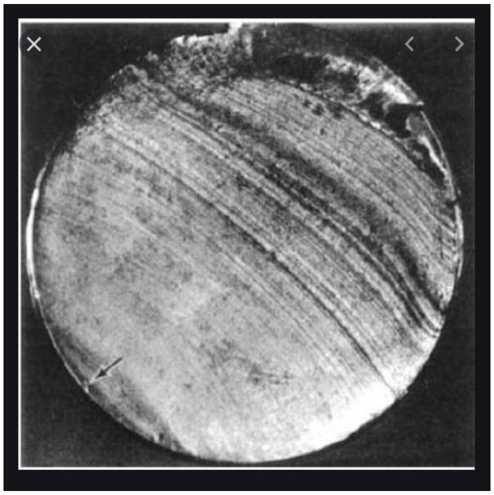
The notch toughness requirements of Section A3.1c are intended only to provide material of reasonable notch toughness for ordinary service applications. For unusual applications and/or low temperature service, more restrictive requirements and/or notch toughness requirements for other section sizes and thicknesses may be appropriate. To minimize the potential for fracture, the notch toughness requirements of Section A3.1c must be used in conjunction with good design and fabrication procedures. Specific requirements are given in Sections J1.5, J1.6, J2.6 and J2.7.

# Introduction

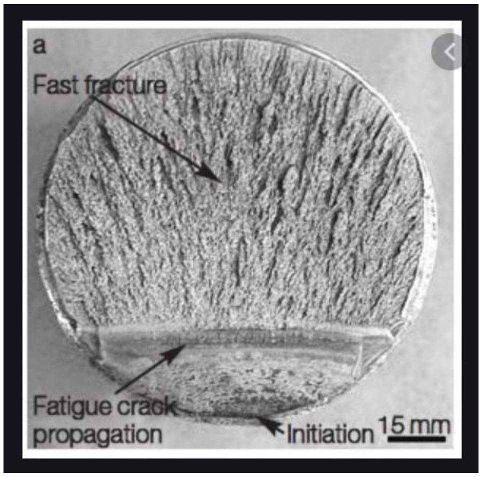
- Beyond the commentaries to AISC 360, there is no definitive AISC Standard or Guide for control of brittle fracture (definitions to follow) at this time. The author has relied to a large extent on AASHTO and Canadian practice
- Important: Brittle fracture is different from fatigue failure in that brittle fracture is sudden and occurs with little warning whereas fatigue failure is gradual and can be controlled
- Although brittle fracture can happen at any temperature, we will focus on low temperatures. The biggest concern for low temperature applications is brittle fracture.

# Fatigue and Brittle Fracture Surfaces

**Fatigue Failure**



**Fatigue + Brittle Fracture**



## Factors Influencing the Potential for Brittle Fracture

- Steel Strength
- Manufacturing Process (higher toughness)
- Post Rolling Heat Treatment (normalizing, q&t, all expensive)
- Material Thickness
- Loading Rate
- Service Temperature
- Material Toughness
- Type of Structural Element
- Members, Connections with Notches or Stress Risers

## Basic References

- Barsom, J.M. and Rolfe, S.T. (1999) “Fracture and Fatigue Control in Structures”, 3rd Edition, American Society for Testing and Materials
- There are several others including AASHTO and the Canadian Standard CSA S16:19, Clause 31, “Control of brittle fracture”
- All based on the same research

## Definitions

- Before we get too far there are some important definitions as shown.
- It is important to understand the difference between brittle fracture and fatigue fracture.

Toughness - ability to absorb energy in a plastic manner before breaking

Brittle Fracture - rapid, catastrophic, crack propagation with no plastic deformation

Lamellar tearing - separation of material due to through-thickness stresses

Fatigue Fracture - cyclic loading to failure of a cracked component, a stable process

Ductile tearing - gradual, slow fracture with extensive deformation and large energy absorption

## Dynamic Loading

For purposes of this presentation, dynamic loads are loads which change with time fairly quickly in comparison to the structure’s natural frequency. Examples include but are not limited to:

- People
- Traffic
- Waves
- Blasts
- Earthquakes

# Impact Loading

- This is a load applied by a moving object (like a blow) applied VERY quickly
- Usually has a greater effect than a lower force applied over a proportionally longer period

# For this Presentation:

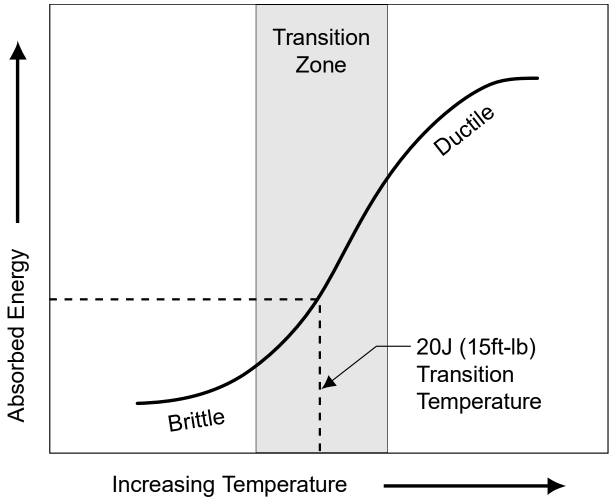
- It is the author’s opinion that we should proceed using D/I (Dynamic/Impact) as the loading of interest

# Fundamental Considerations

- Brittle fracture can be caused by dynamic or impact loads
- Brittle fracture is different from fatigue failure in that brittle fracture is sudden and occurs with little warning whereas fatigue failure is gradual and can be controlled
- But in both cases tensile loading (axial or flexural) must be present
- We do not normally apply fracture mechanics calculations but instead, by identifying critical members, selecting appropriate materials and detailing to minimize the possibility of fracture

# Behavior of Steel

- As temperature decreases the ability to absorb energy also decreases



# Low Temperatures

A decrease in temperature can:

- Increase the strength of steel
- But decrease its notch toughness
- Change in fracture behavior takes place at the “transition temperature”
- To implement measures to resist brittle fracture we must know, among other things, the lowest operating temperature.

## Some key factors increasing possibility of brittle fracture:

- Low temperature (however, low temperature alone is NOT cause for brittle fracture)
- D/I loaded at ANY temperature
- Initiation at a flaw such as a notch, fabrication discontinuity or other stress raisers
- Cyclic loading leading to fatigue cracks (a flaw)
- Stress concentration such as fully welded intersecting thick plates subjected to weld shrinkage
- Brittle steel at service temperature
- High strength steels may be more susceptible to brittle fracture

## Notable Early Brittle Fracture Failures

- Liberty Ships, WW2, hull and deck cracks, some broke in half, material issue

- De Havilland Comet,Three crashed, note square windows, detail issue

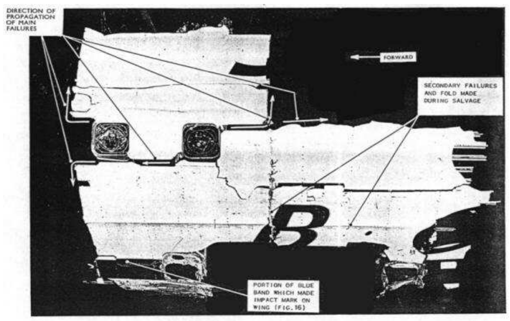
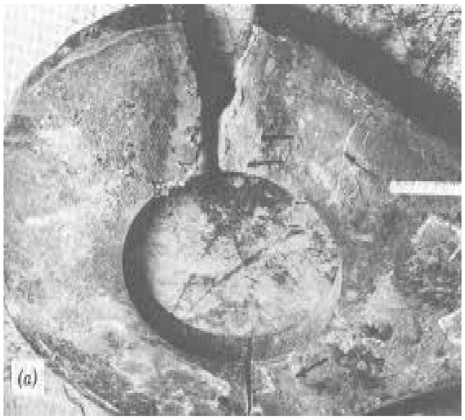
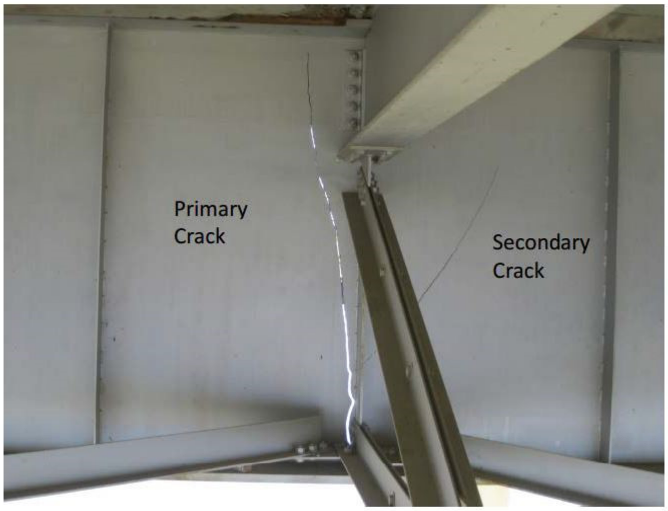


FIG. 12. PHOTOGRAPH OF WRECKAGE AROUND ADF AERIAL WINDOWS—G-ALYP.

## The Silver Bridge Collapse, 1967

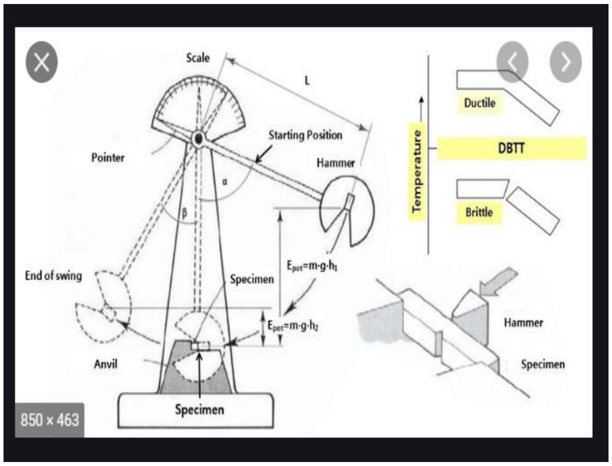


# Bridge Girders



# Toughness Quantified

- The usual way is by the Charpy v-notch tests (CVN) to ASTM A673/A673M
- These are standardized high rate-of-strain tests to determine the amount of energy absorbed during fracture
- Steel and weld metal selection for different service conditions is calibrated to test temperatures and Charpy v-notch impact test values, therefore the test temperature is not the same as the service temperature



## Brittle Fracture-Other Considerations

- Low temperatures in the absence of D/I loading do not necessarily require notch tough steel.
- We can have brittle fracture at high temperatures, another subject
- Therefore statically loaded structures subjected to low temperatures do not normally require the use of notch tough steel
- The usual grades of structural steel produced without CVN tests provide a degree of toughness that may be adequate for the degree of toughness required

## Fracture Critical Elements by AASHTO

- Primary members “a member designed to carry the loads applied to the structure”, a non redundant steel member subjected to tension (truss member?)
- Fracture critical members (FCM) “a steel primary member or portion thereof whose failure would probably lead to a partial or total collapse” (girder?)
- Useful for bridge-like structures

# Examples of highway bridges, beam and truss

# Structures similar to highway bridges

## Critical Elements to Canadian Standard CSA S16:19

- A fracture-critical member is defined as a member or portion thereof including attachments in a non redundant structure that is subject to tensile stress and failure could lead to collapse of the structure (truss member, crane runway beam?)
- A primary tension member or component thereof within a redundant structural system, that is subject to tensile stress
- These members are to be identified on the drawings
- Tables are provided for D/I test temperatures and CVN impact energy requirements for these members under D/I loading

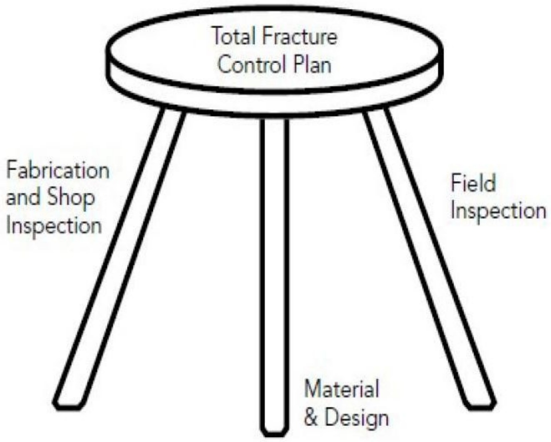
## Industrial Structures Possibly Vulnerable

Consider mitigating measures in colder temperatures and other important circumstances for:

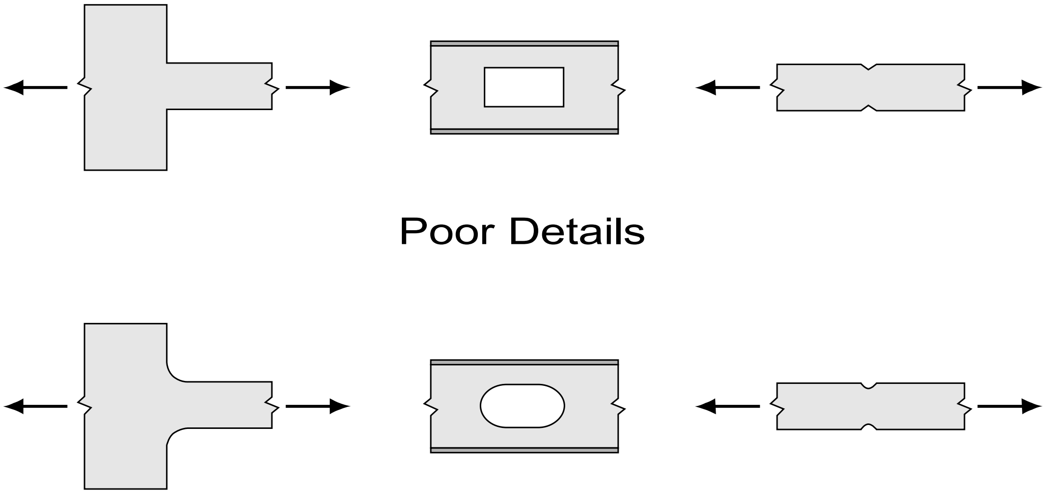
- Equipment supports imposing D/I loadings (mining, hydrocarbon processing industries)
- Bridge-like structures
- Outdoor crane runways
- Hydraulic structures (gates, penstocks)
- Wind turbine supports
- Tanks and silos
- Bins and hoppers
- Lifting gear
- Structures subjected to artificial cooling and D/I loading

## Brittle Fracture-Fundamental Defenses

- Suitably tough steel
- Suitably tough weld metal
- Carefully design and detail
- Good fabrication
- Good erection
- Good inspection



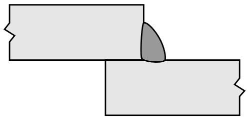
## Design and Details

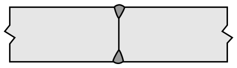


Poor Details

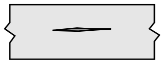
Improved Details

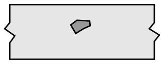
# Concerns that call for improved details

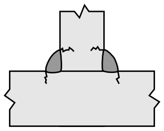

Laps

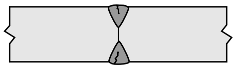

Seams


Cracks, pits

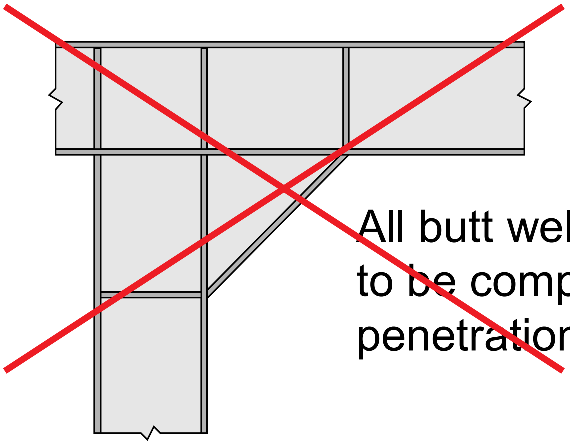

Laminations


Inclusions


Undercut

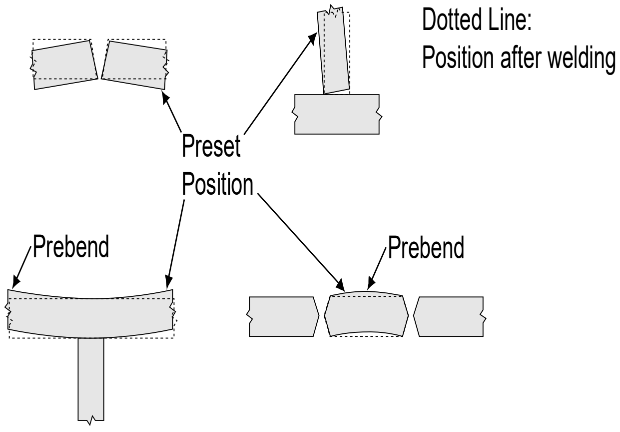

Incomplete fusion,
weld cracks

# Concerns cont'd


All butt welds
to be complete
penetration

## Improved Fabrication Procedures

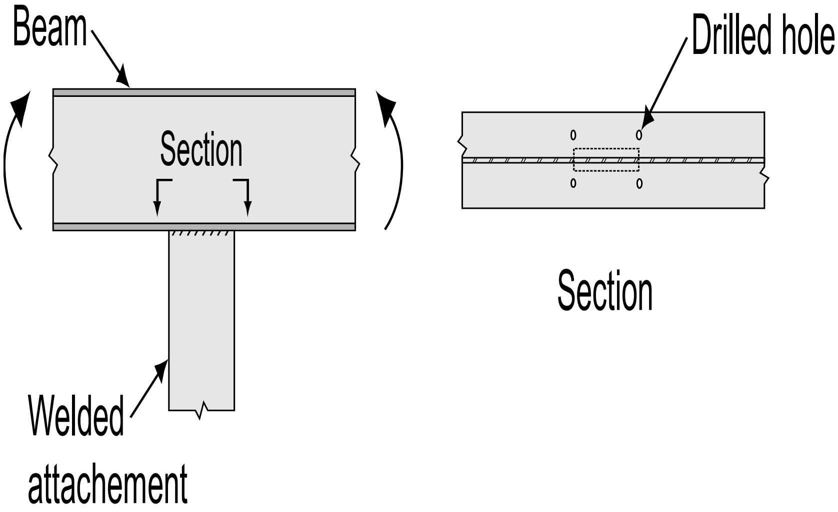
- Illustrations of presetting and pre bending to allow for contraction of weld metal



Example: Good welding procedures,
Pressetting of joint members to allow for
contraction of weld metal

## Improved Details

- Concept of drilling holes to arrest possible cracks



## Brittle Facture Defense Fabrication Considerations

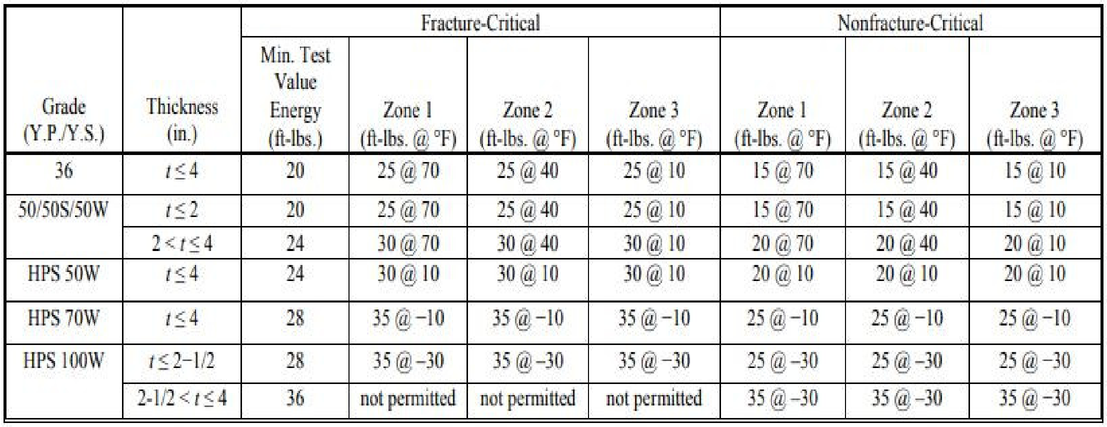
- Notch tough weld metal might be a good investment at little extra cost
- Refer to AWS for D/I loaded structures
- Consider direction of rolling
- Plate shearing and punching can create stress risers, grind and finish
- Minimize discontinuities in flame cut edges, grind and finish
- Avoid cold working and peening
- Avoid heating after cold working (strain aging)

# Fracture Defense cont'd

- Avoid arc strikes
- Small welds on big members can be problematic
- Use good preheating procedures
- Post-heat treatment sometimes
- Adequate inspection

# How to Specify Steel, Referring to AASHTO

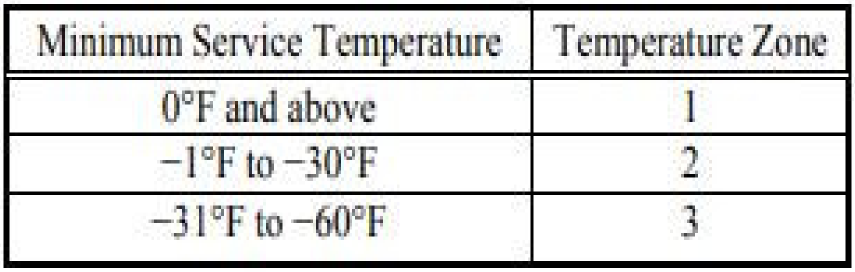
**Table 6.6.2-2—CVN Impact Energy Requirements**



| Grade (Y.P./Y.S.) | Thickness (in.) | Fracture-Critical | | | | Nonfracture-Critical | | |
|---|---|---|---|---|---|---|---|---|
| | | Min. Test Value Energy (ft-lbs.) | Zone 1 (ft-lbs. @ °F) | Zone 2 (ft-lbs. @ °F) | Zone 3 (ft-lbs. @ °F) | Zone 1 (ft-lbs. @ °F) | Zone 2 (ft-lbs. @ °F) | Zone 3 (ft-lbs. @ °F) |
| 36 | $t \leq 4$ | 20 | 25 @ 70 | 25 @ 40 | 25 @ 10 | 15 @ 70 | 15 @ 40 | 15 @ 10 |
| 50/50S/50W | $t \leq 2$ | 20 | 25 @ 70 | 25 @ 40 | 25 @ 10 | 15 @ 70 | 15 @ 40 | 15 @ 10 |
| | $2 < t \leq 4$ | 24 | 30 @ 70 | 30 @ 40 | 30 @ 10 | 20 @ 70 | 20 @ 40 | 20 @ 10 |
| HPS 50W | $t \leq 4$ | 24 | 30 @ 10 | 30 @ 10 | 30 @ 10 | 20 @ 10 | 20 @ 10 | 20 @ 10 |
| HPS 70W | $t \leq 4$ | 28 | 35 @ −10 | 35 @ −10 | 35 @ −10 | 25 @ −10 | 25 @ −10 | 25 @ −10 |
| HPS 100W | $t \leq 2\text{-}1/2$ | 28 | 35 @ −30 | 35 @ −30 | 35 @ −30 | 25 @ −30 | 25 @ −30 | 25 @ −30 |
| | $2\text{-}1/2 < t \leq 4$ | 36 | not permitted | not permitted | not permitted | 35 @ −30 | 35 @ −30 | 35 @ −30 |

# Zones, Referring to AASHTO

**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 |

## Each state’s low temperature record

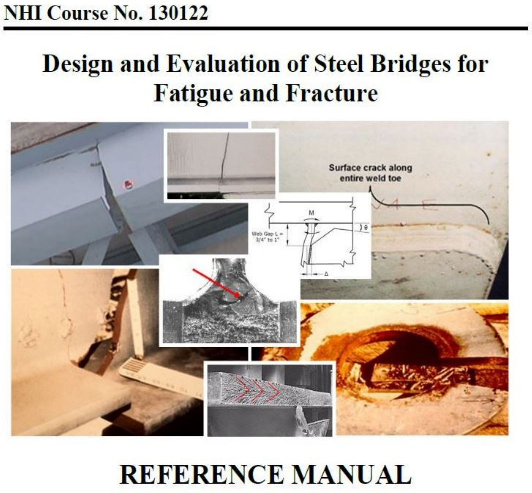
| | | | | |
|---|---|---|---|---|
| New York | -52 | Feb. 18, 1979* | Old Forge | 1,720 |
| North Carolina | -34 | Jan. 21, 1985 | Mt. Mitchell | 6,525 |
| North Dakota | -60 | Feb. 15, 1936 | Parshall | 1,929 |
| Ohio | -39 | Feb. 10, 1899 | Milligan | 800 |
| Oklahoma | -31 | Feb. 9, 2011 | Nowata | 709 |
| Oregon | -54 | Feb. 10, 1933* | Seneca | 4,700 |
| Pennsylvania | -42 | Jan. 5, 1904 | Smethport | est. 1,500 |
| Rhode Island | -25 | Feb. 5, 1996 | Greene | 425 |
| South Carolina | -19 | Jan. 21, 1985 | Caesars Head | 3,100 |
| South Dakota | -58 | Feb. 17, 1936 | McIntosh | 2,277 |
| Tennessee | -32 | Dec. 30, 1917 | Mountain City | 2,471 |
| Texas | -23 | Feb. 8, 1933* | Seminole | 3,275 |
| Utah | -69 | Feb. 1, 1985 | Peter's Sink | 8,092 |
| Vermont | -50 | Dec. 30, 1933 | Bloomfield | 915 |
| Virginia | -30 | Jan. 22, 1985 | Mountain Lake | 3,870 |
| Washington | -48 | Dec. 30, 1968 | Mazama | 2,120 |
| | | | Winthrop | 1,755 |
| West Virginia | -37 | Dec. 30, 1917 | Lewisburg | 2,200 |
| Wisconsin | -55 | Feb.4, 1996 | Couderay | 1,300 |
| Wyoming | -66 | Feb. 9, 1933 | Riverside | 6,650 |

*Also on earlier dates at the same or other places.
*Source: U.S. National Climatic Data Center (Last updated August 2006)*

## AASHTO Summarized

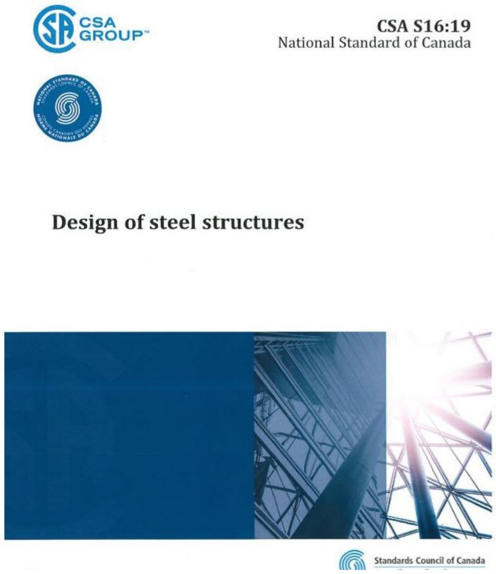
- Decide whether the member is fracture critical or not---see AASHTO
- Identify your steel grade
- Identify your lowest service temperature
- Specify the appropriate CVN toughness

## Useful References for Brittle Fracture


NHI Course No. 130122

**Design and Evaluation of Steel Bridges for Fatigue and Fracture**

REFERENCE MANUAL


CSA GROUP™

CSA S16:19
National Standard of Canada

**Design of steel structures**

Standards Council of Canada

## More references

- See referenced publications
- A good reference including basics of fracture mechanics is a presentation at the 1995Should National Steel Construction by Stan Rolphe of University of Kansas “What The Structural Engineer Should Know About Fracture Mechanics”

# The Last Words

- “Low temperature steel” can be misleading because mild steel will perform well at low temperatures in the absence of D/I loads. “Notch tough steel” may be a preferable nomenclature.
- There are many measures that reduce the possibility of brittle fracture without specifying notch tough steel.
- The usual grades of mild structural steel have an inherent degree of notch toughness
- Before specifying notch tough steel check availability. Plates are more readily available than rolled sections

# END of Part 1

- Thank you for tuning in!

# Night School 23: Industrial Structures

## Session 6 – High & Low Temperature Design for Industrial Structures
July 28, 2020

## Part 2: Elevated Temperature Design

Bo Dowswell, PE, PhD, Arc International LLC

Smarter.
Stronger.
Steel.

---

# Elevated Temperature Design

## Elevated Temperature Design

- Design objectives
- Material properties
- Considerations at temperatures exceeding 700 °F
- Material selection
- Design stresses
- Member stability

## Elevated Temperature Design

## Design Objectives

# Design Objectives

The design objectives for industrial structures subjected to elevated service temperatures are similar to other industrial structures:

- Strength
- Serviceability
- Maintain process functionality for the design life

To meet these objectives, deformations must be limited when subjected to long-term exposure at elevated temperatures.

# Design Objectives

2016 AISC *Specification* Appendix 4 is applicable only to fire conditions

- The primary objective is to avoid collapse
- Large deformations are acceptable
- Short-term exposure to elevated temperatures

# Elevated Temperature Design

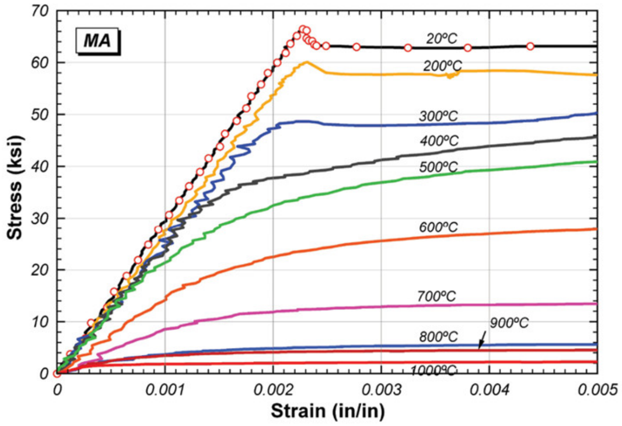
# Material Properties

## Material Properties

- Material properties change with an increase in temperature
  - Coefficient of expansion
  - Modulus of elasticity
  - Yield strength
  - Tensile strength
- The shape of stress-strain curves change, affecting:
  - The yield strength definition
  - The strength of members controlled by stability limit states

# Material Properties

At temperatures greater than ≈ 500 °F (260 °C), the stress-strain curve loses its well-defined yield point and the curve becomes nonlinear at earlier stages of loading.



Stress-Strain Curve for ASTM A992 (Lee et al., 2013)

Lee, J., Morovat, M.A., Hu, G., Engelhardt, M.D. and Taleff, E.M. (2013), “Experimental Investigation of Mechanical Properties of ASTM A992 Steel at Elevated Temperatures,” *Engineering Journal*, AISC, 4th Quarter.

# Material Properties

Material properties for elevated temperatures are available in several publications, including:

- USS (1974), *Steels for Elevated Temperature Service*, United States Steel.
- Khorasani, N.E., Gardoni, P. and Garlock, M. (2015), “Probabilistic Fire Analysis: Material Models and Evaluation of Steel Structural Members,” *Journal of Structural Engineering*, ASCE, Vol. 141, No. 12.

# Material Properties

- Brockenbrough, R.L. (1970), “Theoretical Stresses and Strains from Heat Curving,” *Journal of the Structural Division*, ASCE, Vol. 96, No. ST7.
- ASME: *Boiler & Pressure Vessel Code*
- ASME: *Steel Stacks*, STS-1

---

# Material Properties

The material properties in AISC *Specification* Appendix 4 were developed for fire conditions

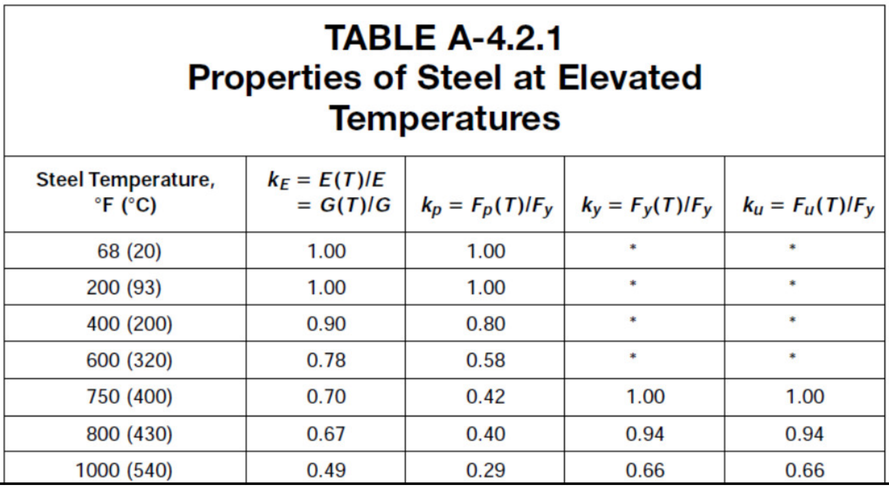
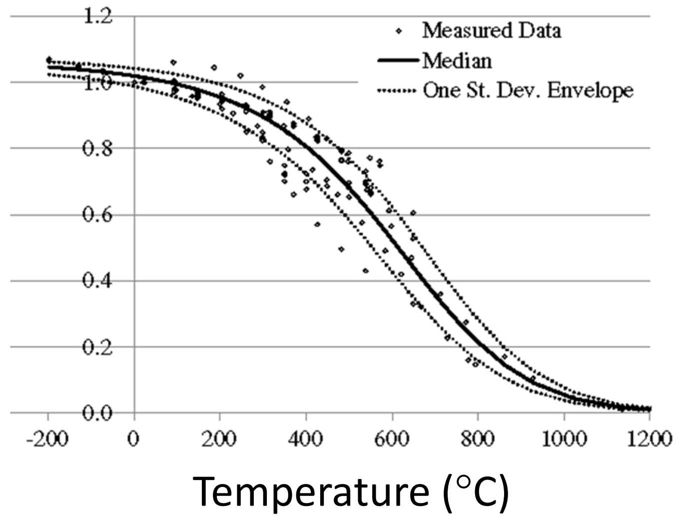


**TABLE A-4.2.1**
**Properties of Steel at Elevated Temperatures**

| Steel Temperature, °F (°C) | $k_E = E(T)/E = G(T)/G$ | $k_p = F_p(T)/F_y$ | $k_y = F_y(T)/F_y$ | $k_u = F_u(T)/F_y$ |
|---|---|---|---|---|
| 68 (20) | 1.00 | 1.00 | * | * |
| 200 (93) | 1.00 | 1.00 | * | * |
| 400 (200) | 0.90 | 0.80 | * | * |
| 600 (320) | 0.78 | 0.58 | * | * |
| 750 (400) | 0.70 | 0.42 | 1.00 | 1.00 |
| 800 (430) | 0.67 | 0.40 | 0.94 | 0.94 |
| 1000 (540) | 0.49 | 0.29 | 0.66 | 0.66 |

# Modulus of Elasticity

$$k_E = \frac{E_t}{E}$$



Khorasani, N.E., Gardoni, P. and Garlock, M. (2015), "Probabilistic Fire Analysis: Material Models and Evaluation of Steel Structural Members," *Journal of Structural Engineering*, ASCE, Vol. 141, No. 12.

---

# Modulus of Elasticity

Values for $k_E$ are listed in AISC *Specification* Appendix 4

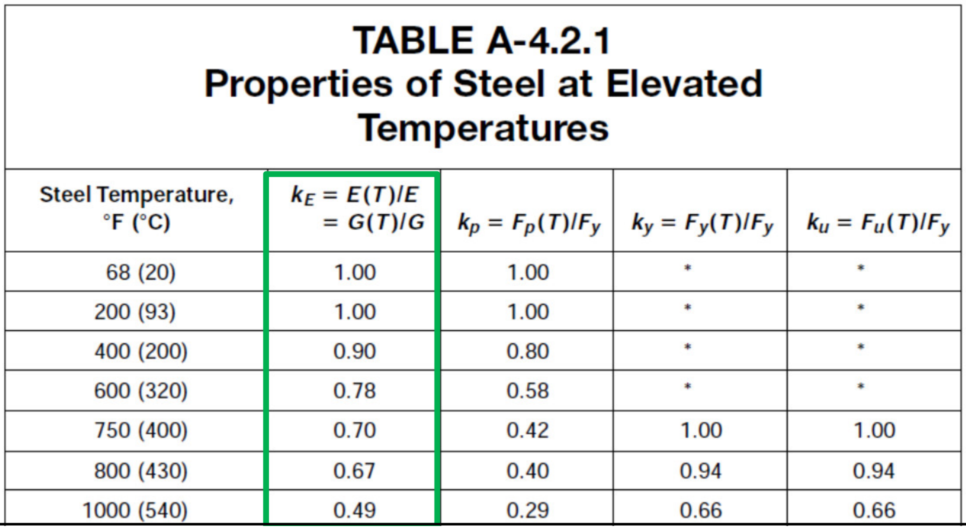


**TABLE A-4.2.1**
**Properties of Steel at Elevated Temperatures**

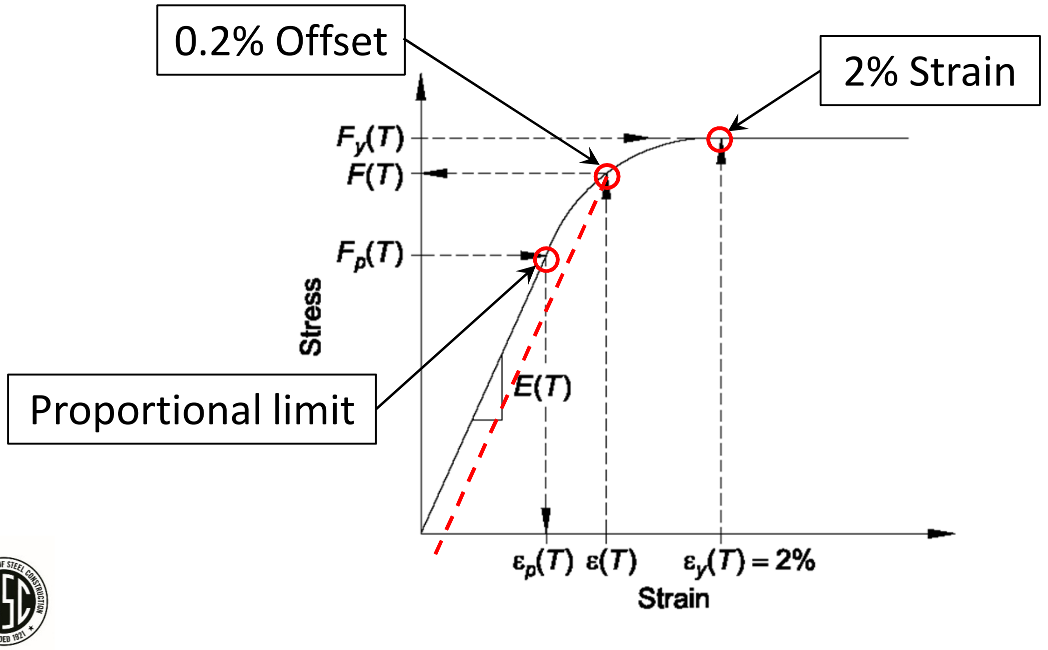
| Steel Temperature, °F (°C) | $k_E = E(T)/E = G(T)/G$ | $k_p = F_p(T)/F_y$ | $k_y = F_y(T)/F_y$ | $k_u = F_u(T)/F_y$ |
|---|---|---|---|---|
| 68 (20) | 1.00 | 1.00 | * | * |
| 200 (93) | 1.00 | 1.00 | * | * |
| 400 (200) | 0.90 | 0.80 | * | * |
| 600 (320) | 0.78 | 0.58 | * | * |
| 750 (400) | 0.70 | 0.42 | 1.00 | 1.00 |
| 800 (430) | 0.67 | 0.40 | 0.94 | 0.94 |
| 1000 (540) | 0.49 | 0.29 | 0.66 | 0.66 |

## Yield Stress

Due to the rounded stress-strain curves, three methods have been used to determine the yield stress:

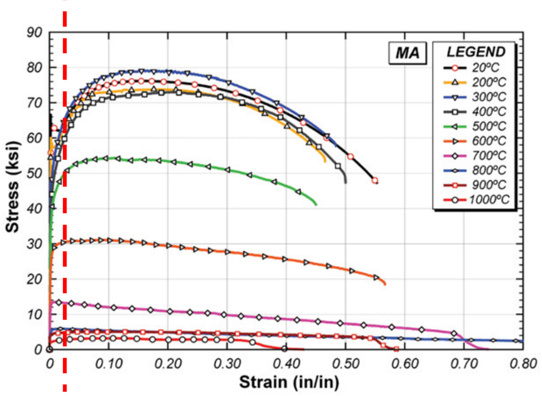
- Proportional limit: $F_{ps} = k_p F_y$
- 0.2% offset method: $F_{ys} = k_s F_y$
- 2% strain: $F_{y2\%} = k_y F_y$

## Yield Stress



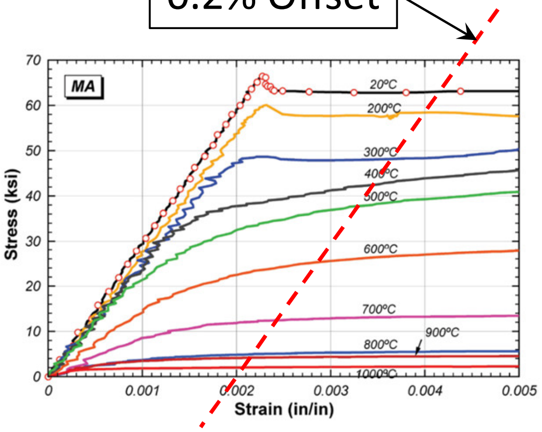
# Yield Stress

2% Strain



Full Range

0.2% Offset



Initial Portion

Lee, J., Morovat, M.A., Hu, G., Engelhardt, M.D. and Taleff, E.M. (2013), “Experimental Investigation of Mechanical Properties of ASTM A992 Steel at Elevated Temperatures,” *Engineering Journal*, AISC, 4th Quarter.

# Yield Stress

Values for $k_p$ and $k_y$ are listed in AISC *Specification* Appendix 4

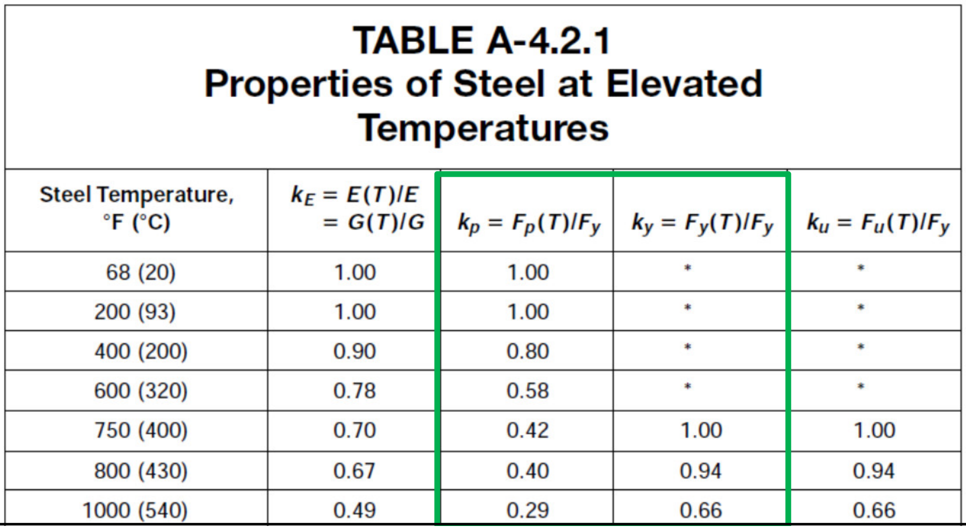
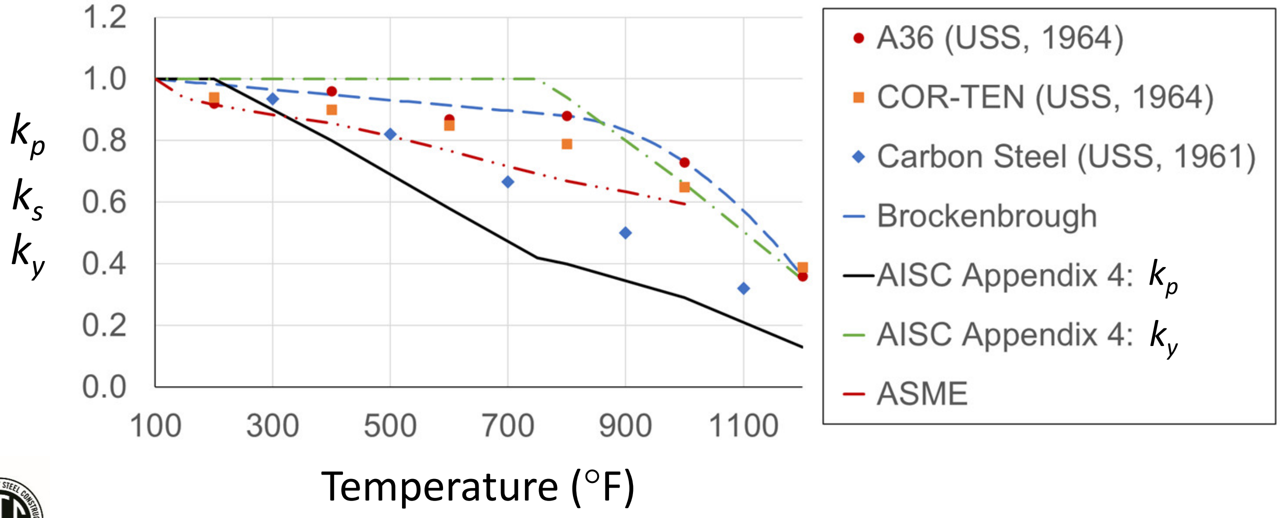


**TABLE A-4.2.1**
**Properties of Steel at Elevated Temperatures**

| Steel Temperature, °F (°C) | $k_E = E(T)/E = G(T)/G$ | $k_p = F_p(T)/F_y$ | $k_y = F_y(T)/F_y$ | $k_u = F_u(T)/F_y$ |
|---|---|---|---|---|
| 68 (20) | 1.00 | 1.00 | * | * |
| 200 (93) | 1.00 | 1.00 | * | * |
| 400 (200) | 0.90 | 0.80 | * | * |
| 600 (320) | 0.78 | 0.58 | * | * |
| 750 (400) | 0.70 | 0.42 | 1.00 | 1.00 |
| 800 (430) | 0.67 | 0.40 | 0.94 | 0.94 |
| 1000 (540) | 0.49 | 0.29 | 0.66 | 0.66 |

# Yield Stress



# Yield Stress

- $k_y$ is defined at 2% strain, which is applicable only where large inelastic deformations are acceptable
- Generally, 2% strain is not acceptable for designing at elevated service temperatures

# Yield Stress

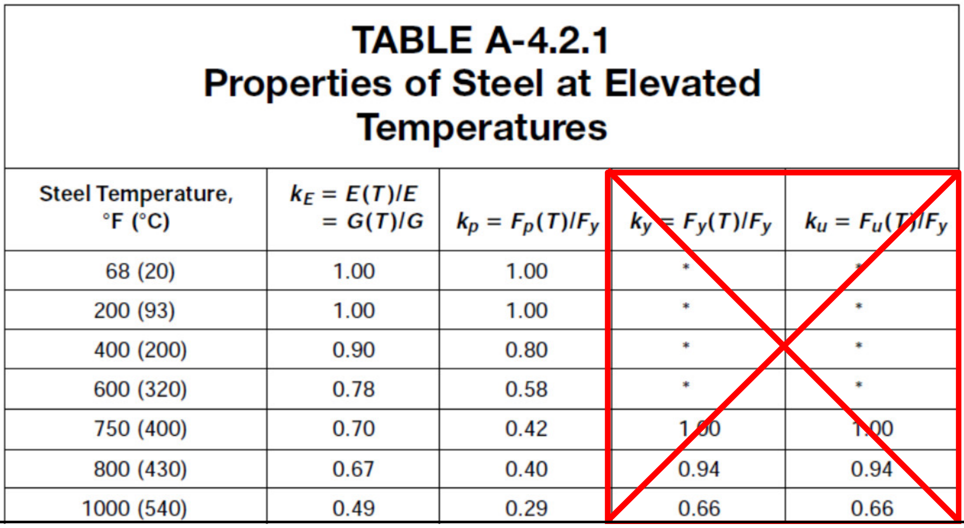
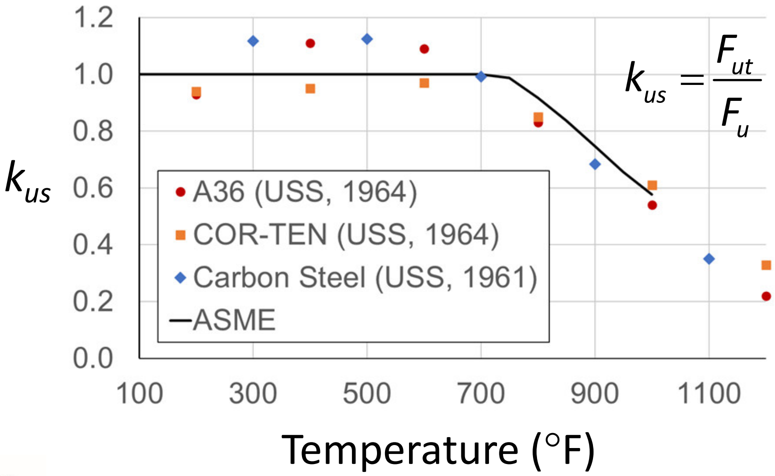


**TABLE A-4.2.1**
**Properties of Steel at Elevated Temperatures**

| Steel Temperature, °F (°C) | $k_E = E(T)/E = G(T)/G$ | $k_p = F_p(T)/F_y$ | $k_y = F_y(T)/F_y$ | $k_u = F_u(T)/F_y$ |
|---|---|---|---|---|
| 68 (20) | 1.00 | 1.00 | * | * |
| 200 (93) | 1.00 | 1.00 | * | * |
| 400 (200) | 0.90 | 0.80 | * | * |
| 600 (320) | 0.78 | 0.58 | * | * |
| 750 (400) | 0.70 | 0.42 | 1.00 | 1.00 |
| 800 (430) | 0.67 | 0.40 | 0.94 | 0.94 |
| 1000 (540) | 0.49 | 0.29 | 0.66 | 0.66 |

# Tensile Stress



$$k_{us} = \frac{F_{ut}}{F_u}$$

**Reduction Factor for Tensile Strength at Elevated Temperatures**

| Temperature °F | $k_{us}$ |
|---|---|
| 100 | 1.0 |
| 200 | 1.0 |
| 300 | 1.0 |
| 400 | 1.0 |
| 500 | 1.0 |
| 600 | 1.0 |
| 700 | 1.0 |
| 800 | 0.92 |
| 900 | 0.75 |
| 1,000 | 0.58 |

ASME (2011), *Boiler & Pressure Vessel Code*, The American Society of Mechanical Engineers.

ASME (2011), *Steel Stacks*, STS-1-2011, The American Society of Mechanical Engineers.

# Elevated Temperature Design

## Considerations at Temperatures Exceeding 700 °F

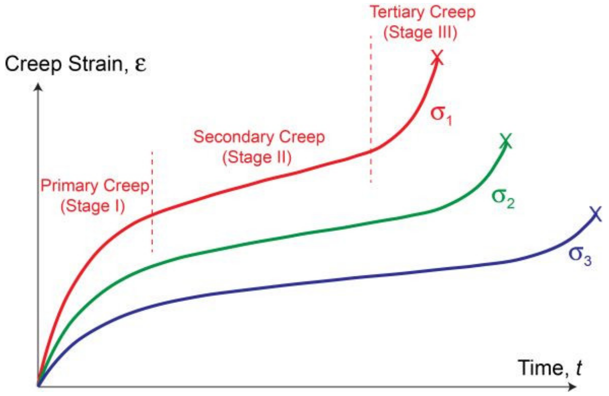
## Temperatures Exceeding 700 °F

Other effects that, generally, are a consideration only for service temperatures exceeding 700 °F are:

- Creep
- Metallurgical effects
- Oxidation/scaling

## Creep

Creep is the time-dependent permanent deformation that occurs when a material is subjected to sustained loading at temperatures in the creep range.



Creep Deformation of Metals. University of Cambridge web page: https://www.doitpoms.ac.uk/tlplib/creep/printall.php

---

## Creep

**Performance is Dependent on Several Factors**

- Stress magnitude
- Service temperature
- Time
- Chemical composition of the steel

# Creep

**Limit States**

- Excessive deformation
- Creep rupture
- Creep buckling

---

# Creep

General guidelines for maximum temperatures without considering creep:

- Carbon and low-alloy steels: 700 to 800 °F
- Alloy steels: 850 °F
- Chromium-nickel austenitic stainless steels: 1050 °F
- Stainless steels: 1150 to 2000 °F

# Metallurgical Changes

Metallurgical changes can reduce the ductility, potentially resulting in brittle behavior when steels are exposed to high temperatures.

- Graphitization: typically a consideration for temperatures exceeding 800 °F (Meier et al., 2014)
- Temper embrittlement: typically a consideration for temperatures between 700 to 1,100 °F (ASCE, 1995)

ASCE (1995), *The Structural Design of Air and Gas Ducts for Power Stations and Industrial Boiler Applications*, ASCE.

Meier, A.A., Hammerschmidt, D.M. and Skibbe, E.R. (2014), "Graphitization Effects on High Temperature Ductwork," Proceedings of the Structures Congress, ASCE.

# Metallurgical Changes

- Strain aging: heavily cold-worked members such as rectangular cold-formed HSS shapes and bent plates may be susceptible to cracking at ambient temperatures upon cooldown (Pense, 2004)

Pense, A. (2004), *HPS Corrugated Web Girder Fabrication Innovations, Part 4: Literature and Experimental Study of Strain Aging in HPS and Other Bridge Steels*, Lehigh University.

# Elevated Temperature Design

## Material Selection

## Material Selection

**Material Selection Considerations**

- Weldability
- Resistance to oxidation/corrosion/scaling
- Reduced material properties at elevated temperature
- Creep performance
- Metallurgical effects

# Material Selection

- For service temperatures equal to or less than 700 °F, commonly-available structural steel shapes and plates are usually the most economical materials
- For service temperatures greater than 700 °F, material selection is a compromise between cost and performance

# Material Selection

- Alloying elements such as chromium and molybdenum increase the resistance to creep, graphitization and temper embrittlement
- Usually graphitization can be eliminated by selecting a steel with at least 0.5% chromium

# Shapes and Plates

**Recommended Maximum Temperatures:**

- ASTM A36, A572, A992, A53 Grade B, A501: 750 to 800 °F
- ASTM A242 Type 1, A618 Grade 1: 900 to 1000 °F
- ASTM A588 Grade A: 800 to 1000 °F
- ASTM A588 Grade B: 900 to 1000 °F
- ASTM A335: 1,100 °F
- ASTM A387: 1,100 °F

# Bolts

**Recommended Maximum Temperatures:**

- ASTM A325 Type 1 bolts can be used for a maximum sustained temperature of 400 to 600 °F, with short excursions up to 850 °F
- ASTM A193 Grade B7 bolts can be used for a maximum sustained temperature of 900 °F

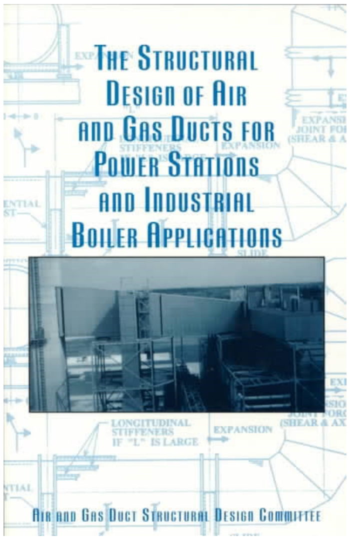
## Weld Filler Metal

- The weld filler metal should be selected to match the base material
- Welding electrodes with a minimum tensile strength of 70 ksi are commonly specified for carbon steel applications in ductwork construction
- For service temperatures exceeding 750 °F, alloy steels such as ASTM A335 and ASTM A387 are usually welded with E8018-B2L electrodes

## Material Selection

**Further Information:**

ASCE (1995), *The Structural Design of Air and Gas Ducts for Power Stations and Industrial Boiler Applications*, ASCE.



# Elevated Temperature Design

## Design Stresses

# Shapes and Plates

**Common Design Practice**

- For designing with the AISC *Specification* for service temperatures equal to or less than 700 °F, the material properties at elevated temperature can be used with the AISC safety factors (ASD) and reduction factors (LRFD)
- For sustained loads at service temperatures greater than 700 °F, creep performance should also be considered when determining the available stresses

# Bolts

Values for the bolt strength reduction factor, $k_b$, for ASTM A325 and A490 bolts are listed in AISC *Specification* Appendix 4

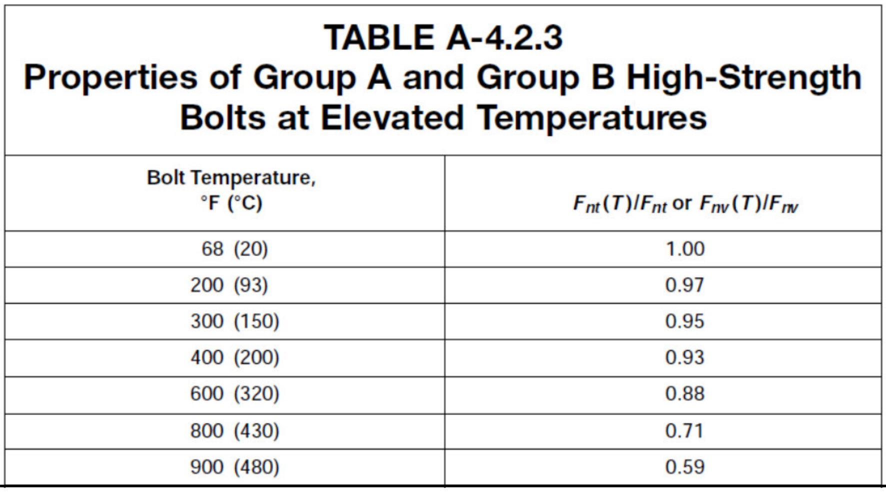
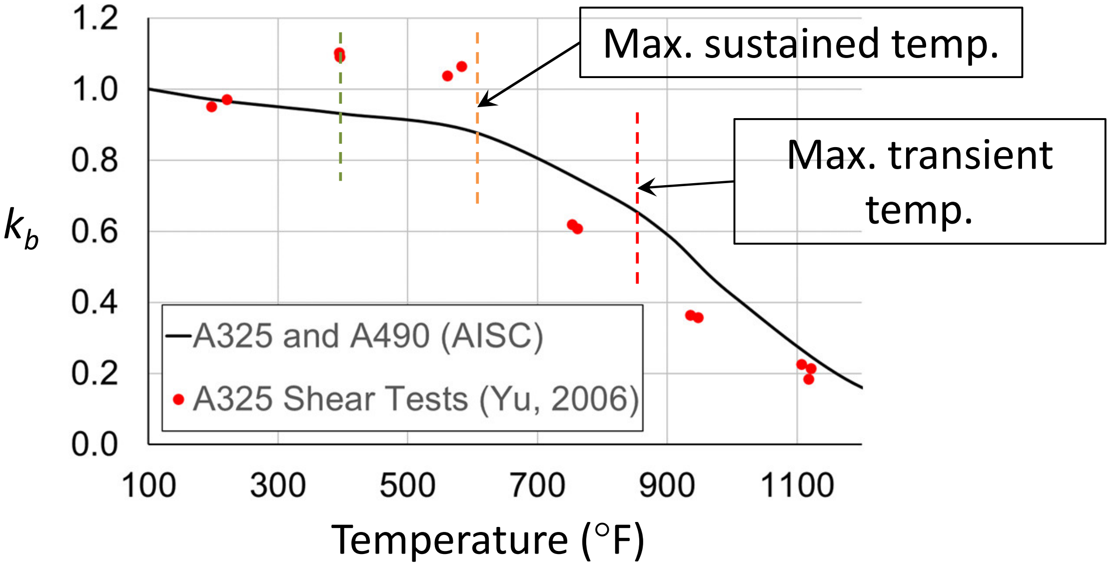


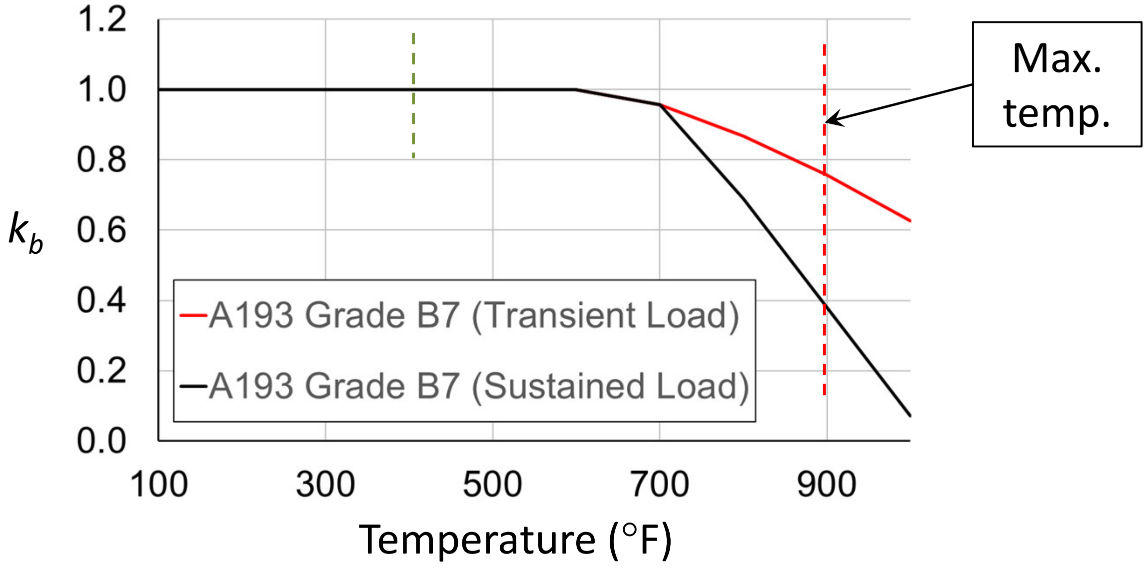
**TABLE A-4.2.3**
**Properties of Group A and Group B High-Strength Bolts at Elevated Temperatures**

| Bolt Temperature, °F (°C) | $F_{nt}(T)/F_{nt}$ or $F_{nv}(T)/F_{nv}$ |
|---|---|
| 68 (20) | 1.00 |
| 200 (93) | 0.97 |
| 300 (150) | 0.95 |
| 400 (200) | 0.93 |
| 600 (320) | 0.88 |
| 800 (430) | 0.71 |
| 900 (480) | 0.59 |

# Bolts



## Bolts



## Bolts

| Reduction Factor for Bolts at Elevated Temperatures | | | |
|---|---|---|---|
| Temperature °F | A325 Type 1 | A193 Grade B7 | |
| | | Sustained Load | Transient Load |
| 100 | 1.0 | 1.0 | 1.0 |
| 200 | 0.97 | 1.0 | 1.0 |
| 300 | 0.95 | 1.0 | 1.0 |
| 400 | 0.93 | 1.0 | 1.0 |
| 500 | 0.91 | 1.0 | 1.0 |
| 600 | 0.88 | 1.0 | 1.0 |
| 700 | | 0.96 | 0.96 |
| 800 | | 0.69 | 0.87 |
| 900 | | 0.38 | 0.76 |
| 1,000 | | 0.072 | 0.63 |

# Welds

If the weld filler metal is selected to match the base metal, the strength reduction factor for the weld can be assumed to be the same as that for the base metal (ASCE, 1995).

ASCE (1995), *The Structural Design of Air and Gas Ducts for Power Stations and Industrial Boiler Applications*, ASCE.

# Design Stresses

**Further Information:**

- The American Society of Mechanical Engineers (ASME)
  - *Boiler & Pressure Vessel Code*
  - *Steel Stacks*, STS-1
- ASCE (1995), *The Structural Design of Air and Gas Ducts for Power Stations and Industrial Boiler Applications*, ASCE.

# Elevated Temperature Design

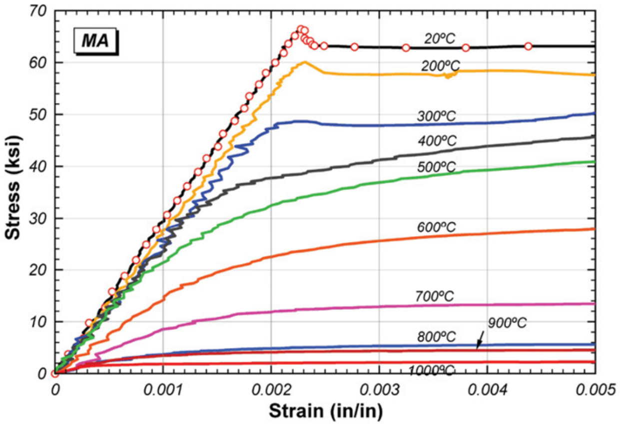
## Member Stability

---

## Member Stability

Rounded stress-strain curves have a negative effect on member stability.

The effect is greater than that caused by the degraded yield strength and modulus of elasticity.



Stress-Strain Curve for ASTM A992 (Lee et al., 2013)

Lee, J., Morovat, M.A., Hu, G., Engelhardt, M.D. and Taleff, E.M. (2013), "Experimental Investigation of Mechanical Properties of ASTM A992 Steel at Elevated Temperatures," *Engineering Journal*, AISC, 4th Quarter.

# Member Stability

## AISC *Specification* Appendix 4

- Design equations developed by Takagi and Deierlein (2007)
  - Flexural buckling of columns
  - Lateral-torsional buckling of beams
- Valid at temperatures greater than 400 °F
- Based on the yield stress at 2% strain
- Long-term creep is not considered
- Not applicable for elevated service temperatures

Takagi, J. and Deierlein, G.G. (2007), “Strength Design Criteria for Steel Members at Elevated Temperatures,” *Journal of Constructional Steel Research*, Vol. 63, pp. 1036-1050.

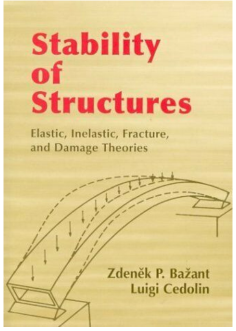
# Member Stability

## Design for Elevated Service Temperatures ($T$ > 700 °F)

At temperatures greater than 700 °F the effects of both creep buckling and reduced material properties must be considered.

# Member Stability

## Further Information on Creep Buckling



Stability of Structures

Elastic, Inelastic, Fracture, and Damage Theories

Zdeněk P. Bažant
Luigi Cedolin

- Bazant, Z.P. and Cedolin, L. (1991), *Stability of Structures, Elastic, Inelastic, Fracture, and Damage Theories*, Oxford University Press.
- Shanley, F.R. (1952), *Weight-Strength Analysis of Aircraft Structures*, McGraw Hill.

# Member Stability

## Design for Elevated Service Temperatures ($T \leq 700$ °F)

At temperatures equal to or less than 700°F, the effects of reduced material properties must be considered. It is common design practice to use the provisions in AISC *Specification* Chapters B, E and F with the reduced properties substituted for $F_y$ and $E$.

## Member Stability

- Design practice varies for the reduced yield stress
- Substitute either $F_{ys}$ (0.2% offset method) or $F_{ps}$ (proportional limit) for $F_y$
- For temperatures greater than ≈ 500 °F, where the stress-strain curve loses its well-defined yield point, it may be appropriate to substitute $F_{ps}$ (proportional limit) for $F_y$
- For temperatures less than ≈ 500 °F, it may be appropriate to substitute $F_{ys}$ (0.2% offset method) for $F_y$

## Member Stability

- The most conservative method is to use the temperature reduction factors ($k_p$ and $k_E$) in Table A-4.2.1 of AISC *Specification* Appendix 4
  - $F_{ps} = k_pF_y$ is substituted for $F_y$
  - $E_s = k_EE$ is substituted for $E$

# Member Stability

## AISC *Specification* Appendix 4

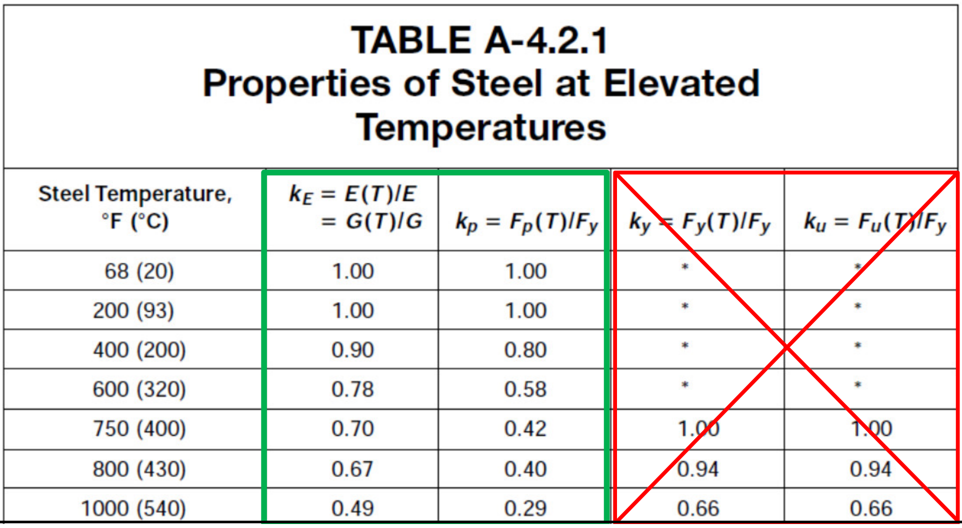
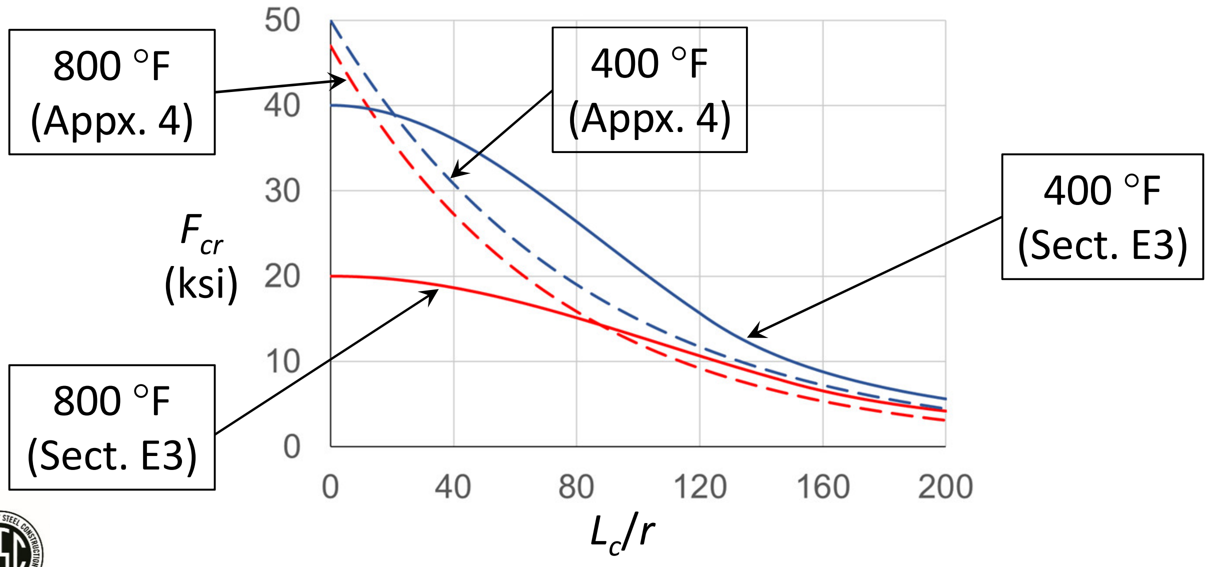


**TABLE A-4.2.1**
**Properties of Steel at Elevated Temperatures**

| Steel Temperature, °F (°C) | $k_E = E(T)/E = G(T)/G$ | $k_p = F_p(T)/F_y$ | $k_y = F_y(T)/F_y$ | $k_u = F_u(T)/F_y$ |
|---|---|---|---|---|
| 68 (20) | 1.00 | 1.00 | * | * |
| 200 (93) | 1.00 | 1.00 | * | * |
| 400 (200) | 0.90 | 0.80 | * | * |
| 600 (320) | 0.78 | 0.58 | * | * |
| 750 (400) | 0.70 | 0.42 | 1.00 | 1.00 |
| 800 (430) | 0.67 | 0.40 | 0.94 | 0.94 |
| 1000 (540) | 0.49 | 0.29 | 0.66 | 0.66 |

# Flexural Buckling



# Session 6
# the End

---

# Thank you!

**AISC** | Questions?

Smarter.
Stronger.
Steel.

# Individual Session Registrants

## PDH Certificates

- You will receive an email on how to report attendance from: registration@aisc.org.
- Be on the lookout: Check your spam filter! Check your junk folder!
- Completely fill out online form. Don’t forget to check the boxes next to each attendee’s name!

---

# Individual Session Registrants

## PDH Certificates

- Reporting site (URL will be provided in the forthcoming email).
- Username: Same as AISC website username.
- Password: Same as AISC website password.

# Individual Session Registrants

## PDH Certificates

- Accommodations for Work-From-Home situations:
- AISC will provide the list of attendees from your company to report attendance. These are the only individuals that you should report for attending this session.
- The lists will be send out within 3 business days.

# 8-Session Registrants

## PDH Certificates

One certificate will be issued at the conclusion of all 8 sessions.

# 8-Session Registrants

## Access to the quiz

Information for accessing the quiz will be emailed to you by Thursday. It will contain a link to access the quiz. EMAIL COMES FROM NIGHTSCHOOL@AISC.ORG.

## Quiz and attendance records

Posted Thursday mornings. www.aisc.org/nightschool -- Click on Current Course Details.

## Reasons for quiz

- EEU – You must take all quizzes and the final exam to receive EEU.
- PDHs – If you watch a recorded session, you must pass quiz for PDHs.
- REINFORCEMENT – Reinforce what you learn tonight. Get more out of the course.

*Note: If you attend the live presentation, you do not have to take the quizzes to receive PDHs*

# 8-Session Registrants

## Access to the recording

Information for accessing the recording will be emailed to you by Thursday. The recording will be available for four weeks. (For 8-session registrants only.) EMAIL COMES FROM NIGHTSCHOOL@AISC.ORG.

## PDHs via recording

If you watch a recorded session, you must take *and pass* the quiz for PDHs.

# 8-Session Registrants

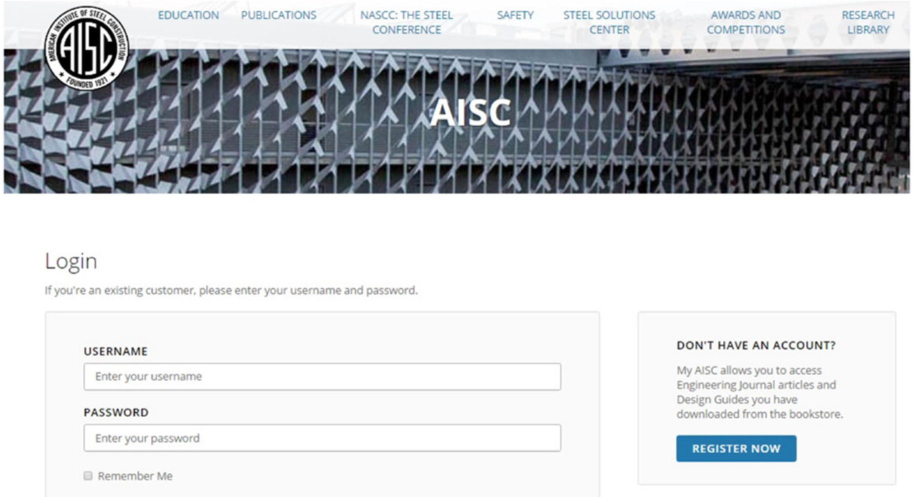
## Night School Resources

Find all your handouts, quizzes and quiz scores, recording access, and attendance information all in one place!

# 8-Session Registrants

## Night School Resources

Go to www.aisc.org and sign in.



Login

If you're an existing customer, please enter your username and password.

USERNAME
Enter your username

PASSWORD
Enter your password

☐ Remember Me

DON'T HAVE AN ACCOUNT?

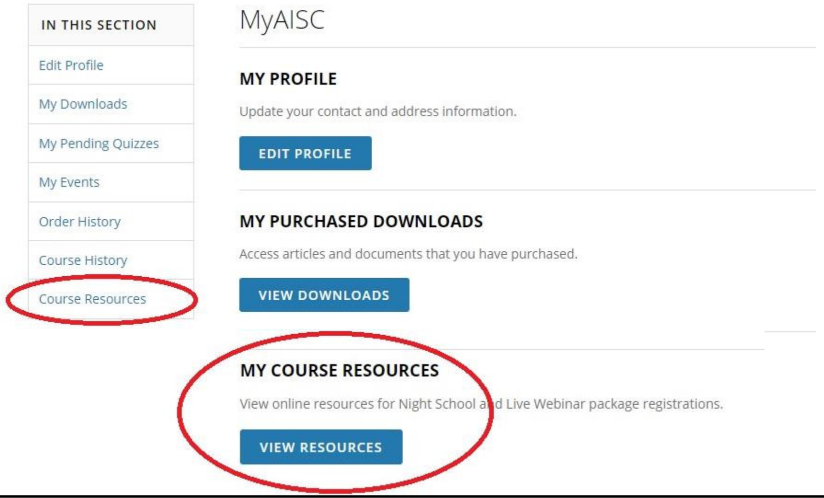
My AISC allows you to access Engineering Journal articles and Design Guides you have downloaded from the bookstore.

REGISTER NOW

# 8-Session Registrants

## Night School Resources

Go to [www.aisc.org](http://www.aisc.org) and sign in.



MyAISC

**MY PROFILE**

Update your contact and address information.

**MY PURCHASED DOWNLOADS**

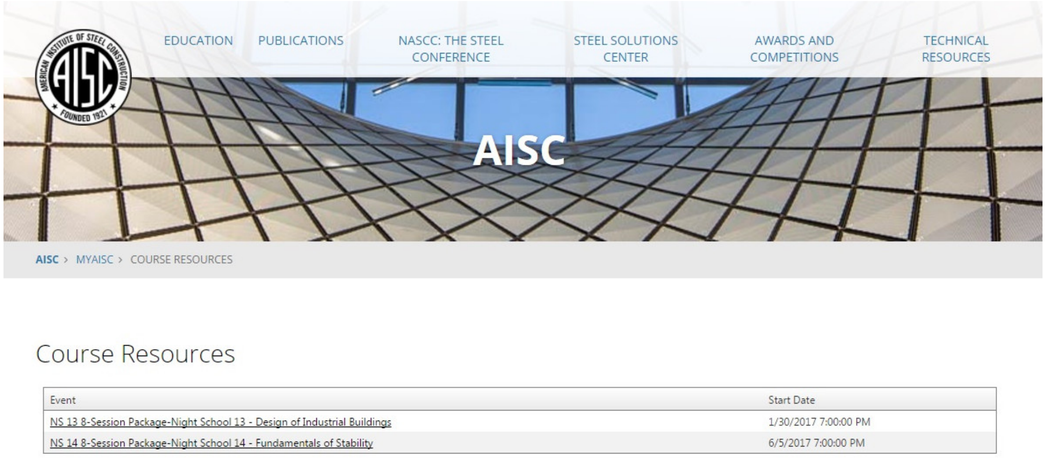
Access articles and documents that you have purchased.

**MY COURSE RESOURCES**

View online resources for Night School and Live Webinar package registrations.

# 8-Session Registrants

## Night School Resources

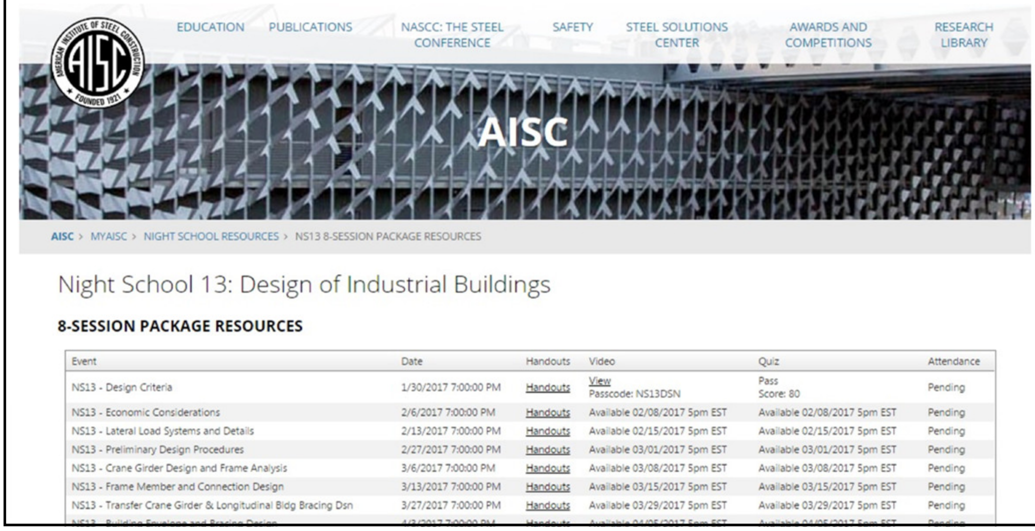


Course Resources

| Event | Start Date |
|---|---|
| NS 13 8-Session Package-Night School 13 - Design of Industrial Buildings | 1/30/2017 7:00:00 PM |
| NS 14 8-Session Package-Night School 14 - Fundamentals of Stability | 6/5/2017 7:00:00 PM |

# 8-Session Registrants

## Night School Resources



AISC > MYAISC > NIGHT SCHOOL RESOURCES > NS13 8-SESSION PACKAGE RESOURCES

Night School 13: Design of Industrial Buildings

**8-SESSION PACKAGE RESOURCES**

| Event | Date | Handouts | Video | Quiz | Attendance |
|---|---|---|---|---|---|
| NS13 - Design Criteria | 1/30/2017 7:00:00 PM | Handouts | View<br>Passcode: NS13DSN | Pass<br>Score: 80 | Pending |
| NS13 - Economic Considerations | 2/6/2017 7:00:00 PM | Handouts | Available 02/08/2017 5pm EST | Available 02/08/2017 5pm EST | Pending |
| NS13 - Lateral Load Systems and Details | 2/13/2017 7:00:00 PM | Handouts | Available 02/15/2017 5pm EST | Available 02/15/2017 5pm EST | Pending |
| NS13 - Preliminary Design Procedures | 2/27/2017 7:00:00 PM | Handouts | Available 03/01/2017 5pm EST | Available 03/01/2017 5pm EST | Pending |
| NS13 - Crane Girder Design and Frame Analysis | 3/6/2017 7:00:00 PM | Handouts | Available 03/08/2017 5pm EST | Available 03/08/2017 5pm EST | Pending |
| NS13 - Frame Member and Connection Design | 3/13/2017 7:00:00 PM | Handouts | Available 03/15/2017 5pm EST | Available 03/15/2017 5pm EST | Pending |
| NS13 - Transfer Crane Girder & Longitudinal Bldg Bracing Dsn | 3/27/2017 7:00:00 PM | Handouts | Available 03/29/2017 5pm EST | Available 03/29/2017 5pm EST | Pending |

# 8-Session Registrants

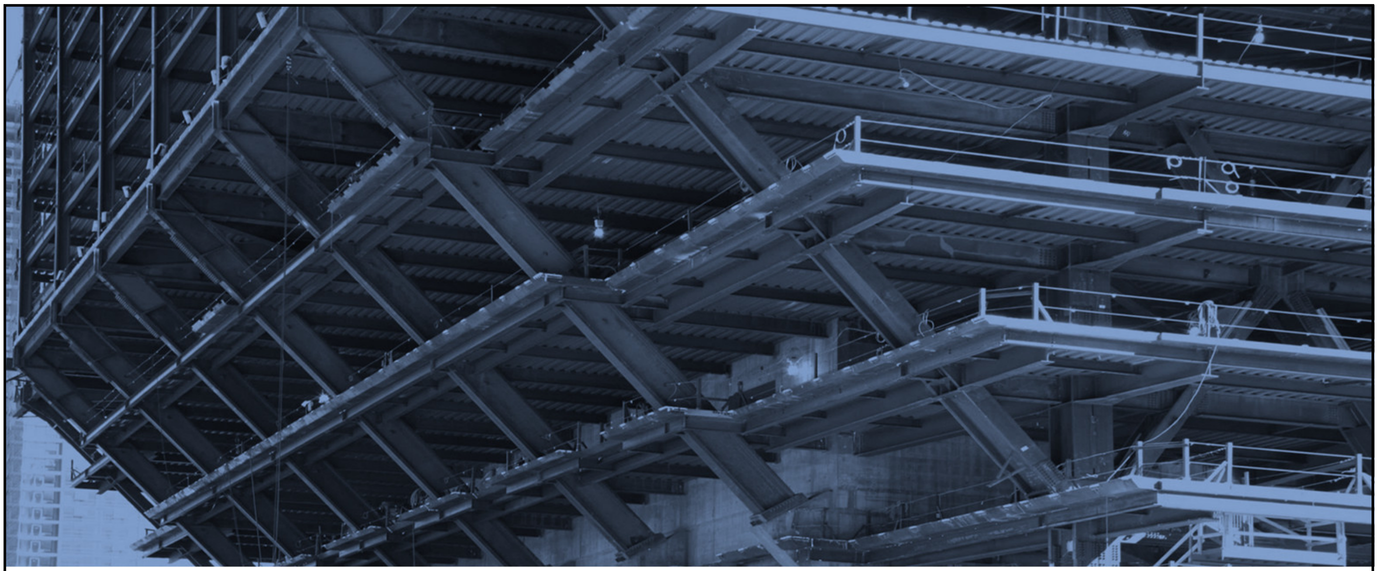
## Night School Resources

- Weekly “quiz and recording” email.
- Weekly updates of the master quiz and attendance record, found at www.aisc.org/nightschool23. Scroll down to Quiz and Attendance records.
    - Updated on Thursday mornings.

# 8-Session Registrants

## Night School Resources

- Webinar connection information
    - Reminder email sent out Tuesday mornings
- Links to handouts also found here



**AISC** | Thank you

Smarter.
Stronger.
Steel.