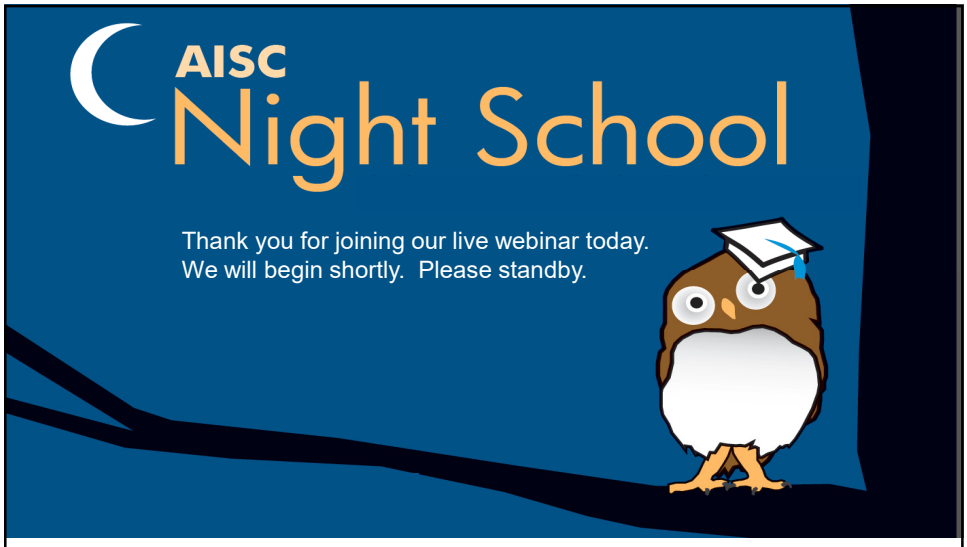


**Fundamentals of earthquake engineering for building structures**

Session 3: Building Dynamics and Response

March 1, 2021 | Rafael Sabelli

Smarter. Stronger. Steel.

AISC Night School

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## Course Description

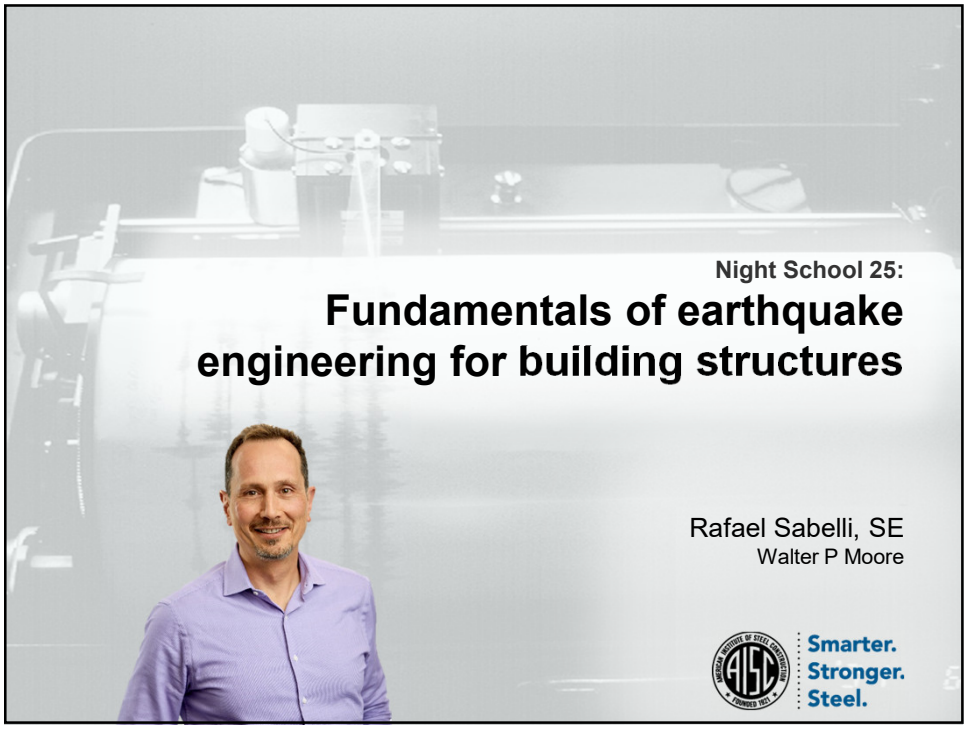
**Session 4: Steel Behavior**

**March 8, 2021**

This lecture presents the basic mechanics of steel behavior, including yield, elongation, strain-hardening, and rupture. Multi-axial stress and its effects will be discussed. Steel behavior issues related to welded joints as well as the important concept of steel toughness will be presented.

## Learning Objectives

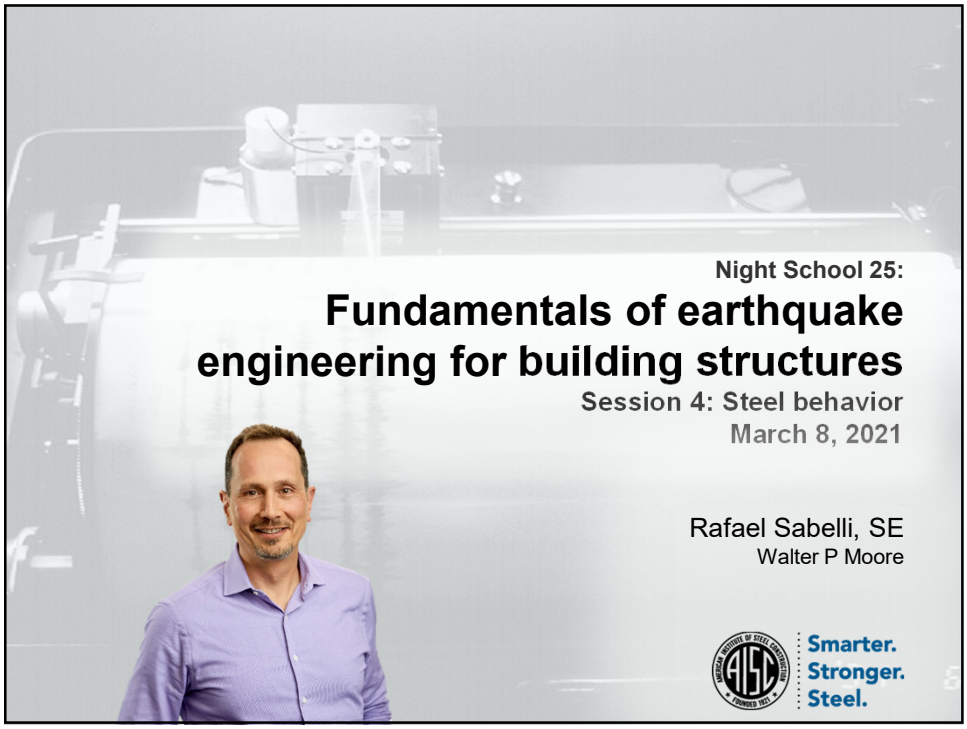
- Understand the material properties of steel.
- Explain the reasons for toughness requirements for structural steel.
- Describe the production process for structural steel and its effects on the properties.
- Explain the importance of detailing welded connections, particularly as it pertains to seismic design.



## Course outline

1. Seismology and earthquake effects
2. Dynamics and response
3. Building dynamics and response
4. **Steel behavior**
5. System ductility and seismic design
6. Steel systems
7. Building configuration
8. Building codes

9



## Session topics

- Yield
- Toughness
- Production
- Welding

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## Steel

- System ductility is necessary for controlled seismic response
- System ductility can be provided, in part, through the use of ductile material
- Steel can provide high levels of ductility
- Proper detailing is required to allow steel to exhibit this ductility

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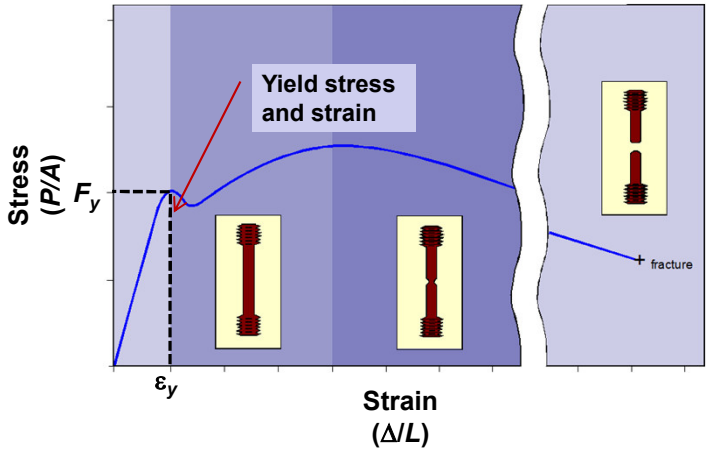
## Yield

- What is yield?
- Steel stress-strain relationships
- Cyclic behavior
- Dynamic behavior
- Fatigue
- Multi-axial stress
- Variability and predictability

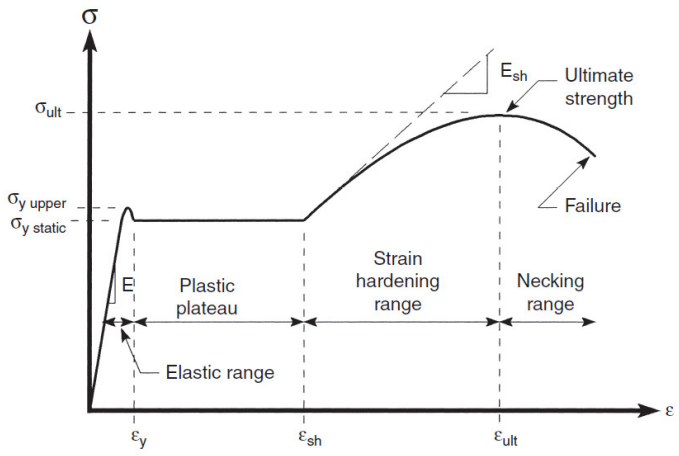
14

# What is yield?




15

# What is yield?

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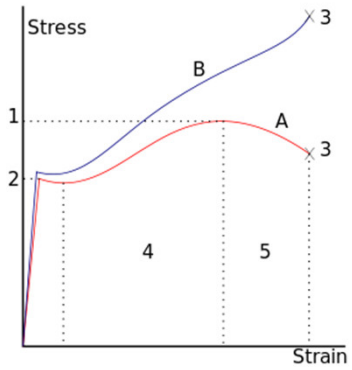
# What is yield?

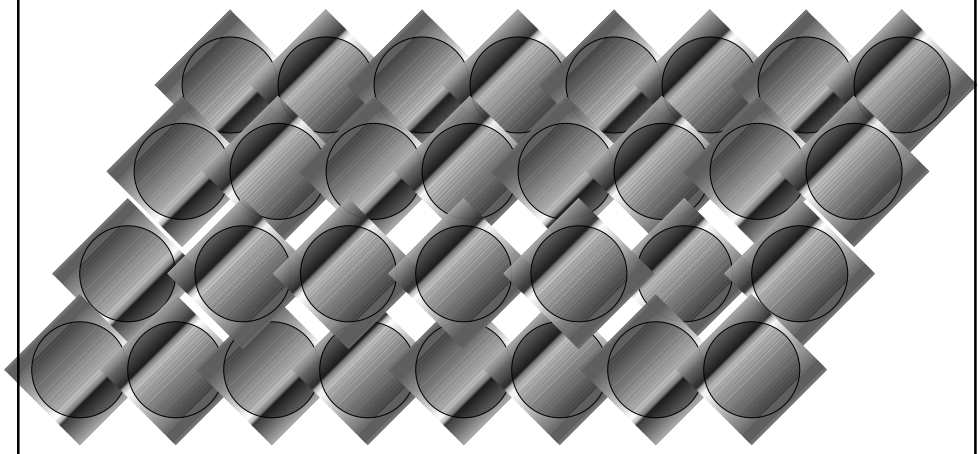



True stress:
*P/A'*
(reduced area due to Poisson's effect)

Engineering stress:
*P/A*

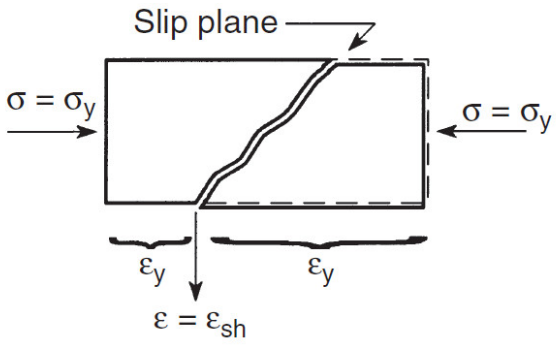
17

# What is yield?



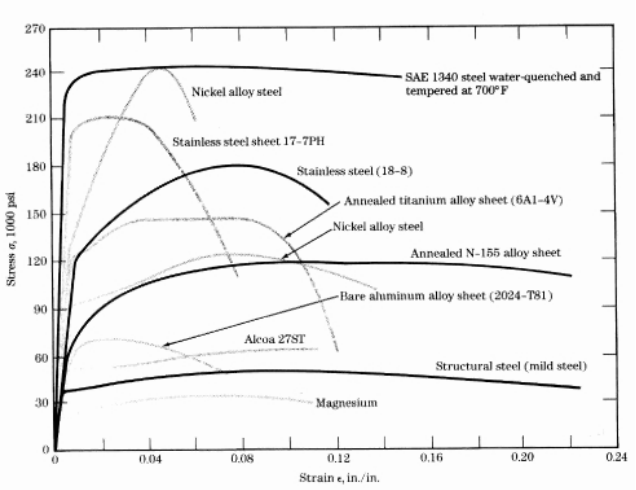
18

# What is yield?



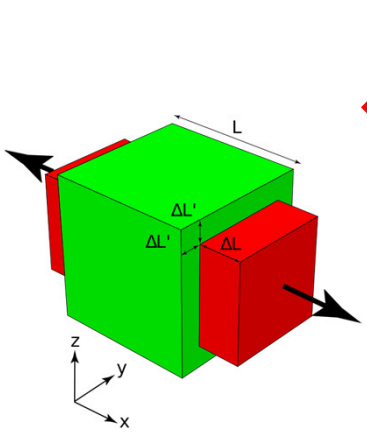

19

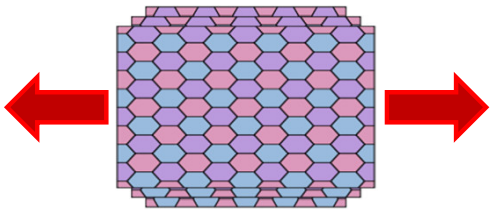
# Stress-strain relationships




20

# Poisson's effect

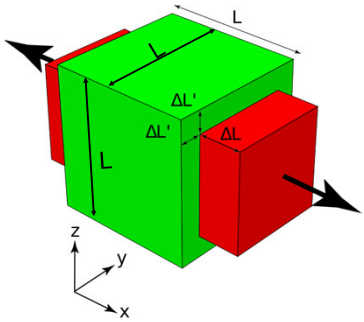


Resistance to volume change creates shear distortion in steel matrix

21

# Poisson's effect




$\varepsilon_{long} = \Delta L/L$

$\varepsilon_{trans} = \Delta L'/L$

$\upsilon = \varepsilon_{trans}/\varepsilon_{long}$

$= \frac{E}{2G} - 1$

$\upsilon$ = 0.3 for steel

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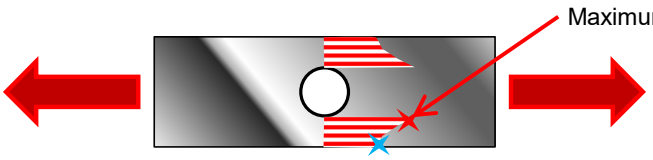
# Yield and strength




**Elastic stress distributions are non-uniform**


**Non-ductile materials cannot be fully utilized**

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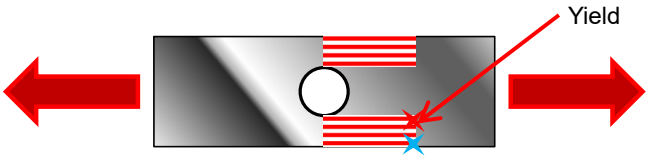
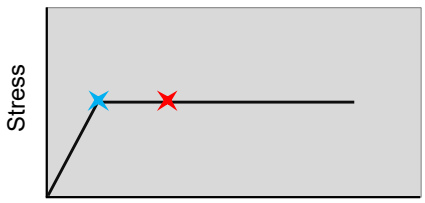
# Yield and strength




**Elongation permits development of full strength**




**Ductile materials can be fully utilized**

Steel design strength equations typically incorporate local ductility

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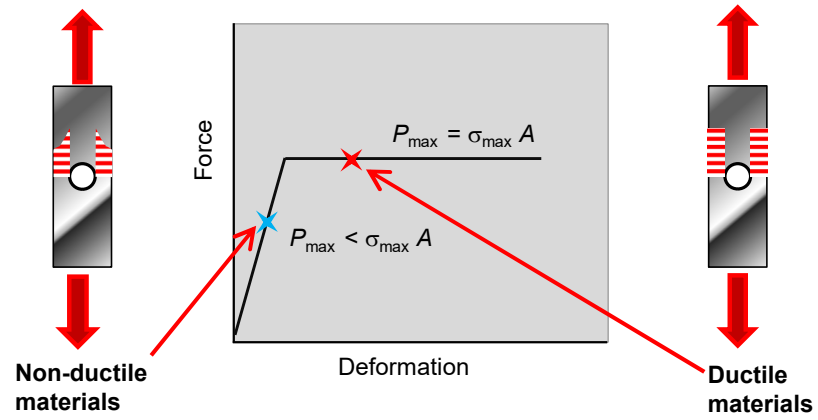
# Yield and strength

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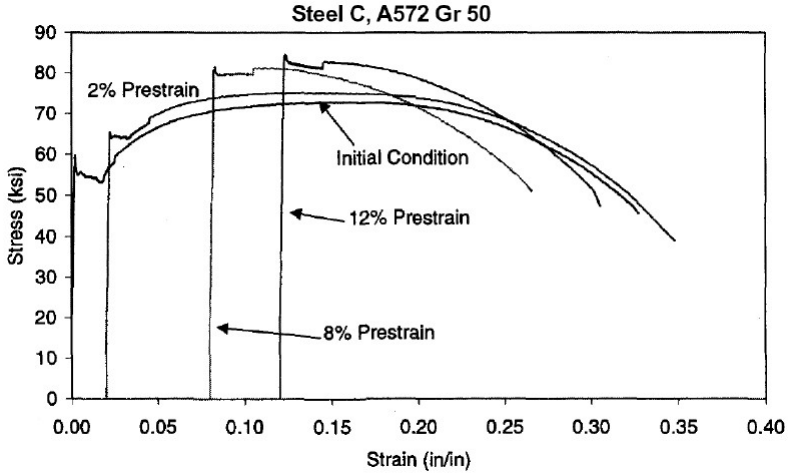
# Strain hardening

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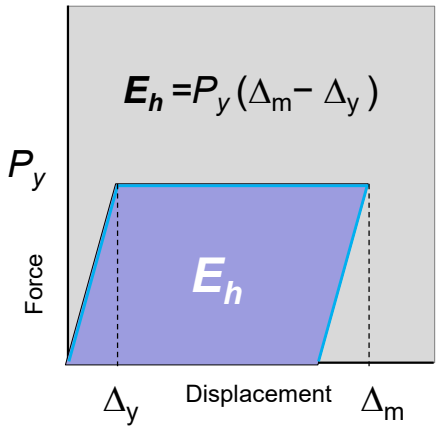
# Dissipated energy

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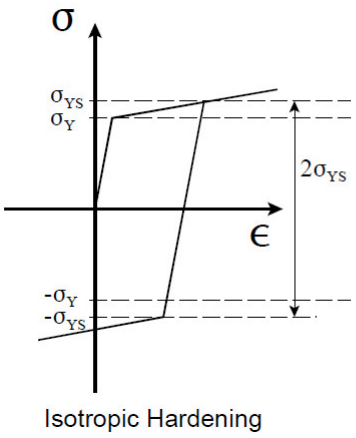
# Cyclic behavior




Isotropic Hardening

Strain hardening affects member forces in seismic response

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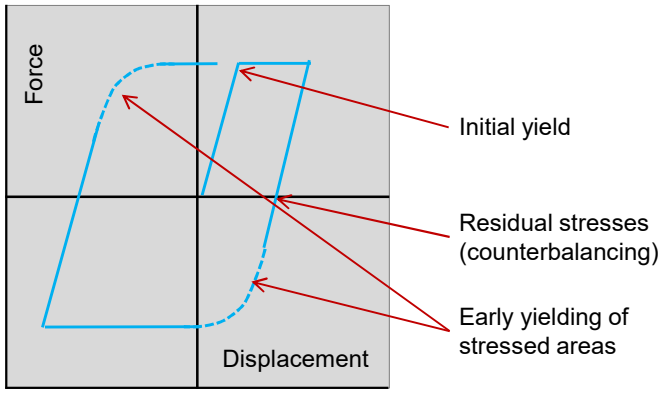
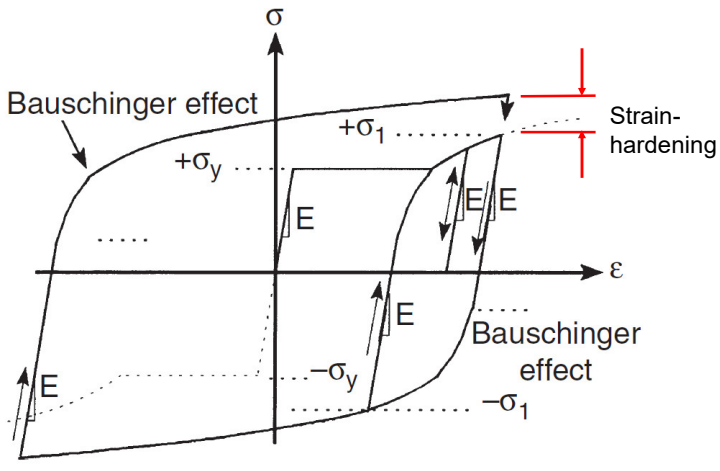
# Bauschinger effects




29

# Cyclic behavior

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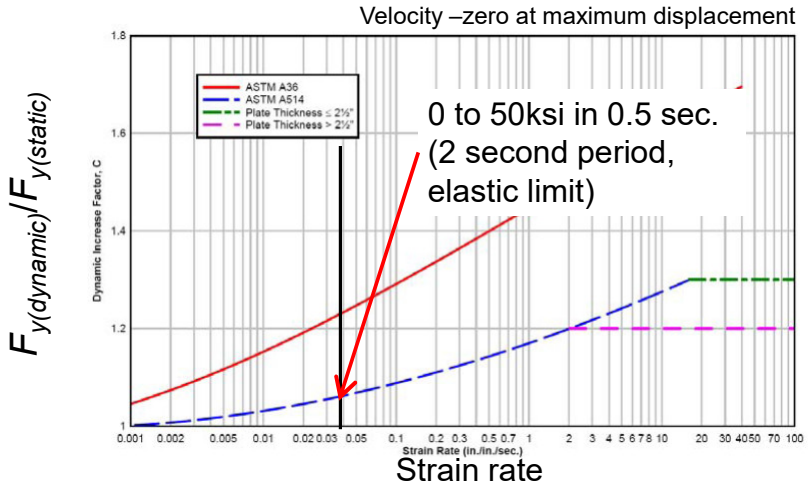
# Dynamic behavior

Velocity –zero at maximum displacement




Rate-of-loading is implicitly addressed in seismic design

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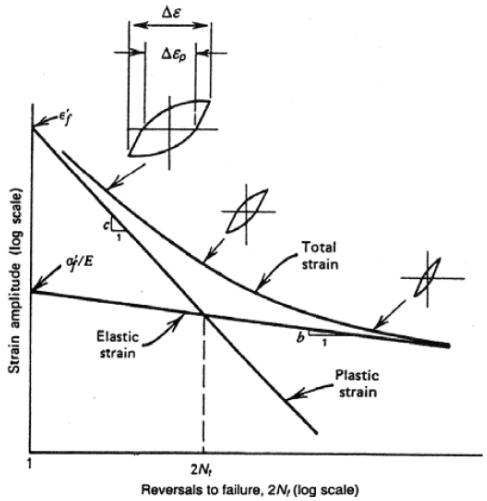
# Fatigue

Low-cycle fatigue:
Few cycles of high (inelastic) amplitude

Example:
Seismic yielding




High-cycle fatigue:
Many cycles of low (elastic) amplitude

Example:
Highway traffic

Seismic design methods implicitly address low-cycle fatigue

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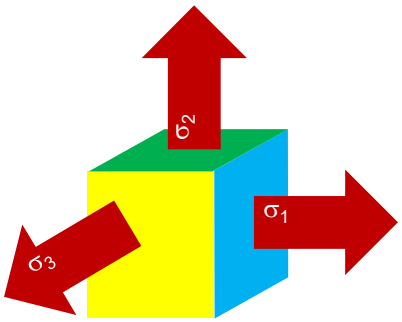
# Multi-axial stress

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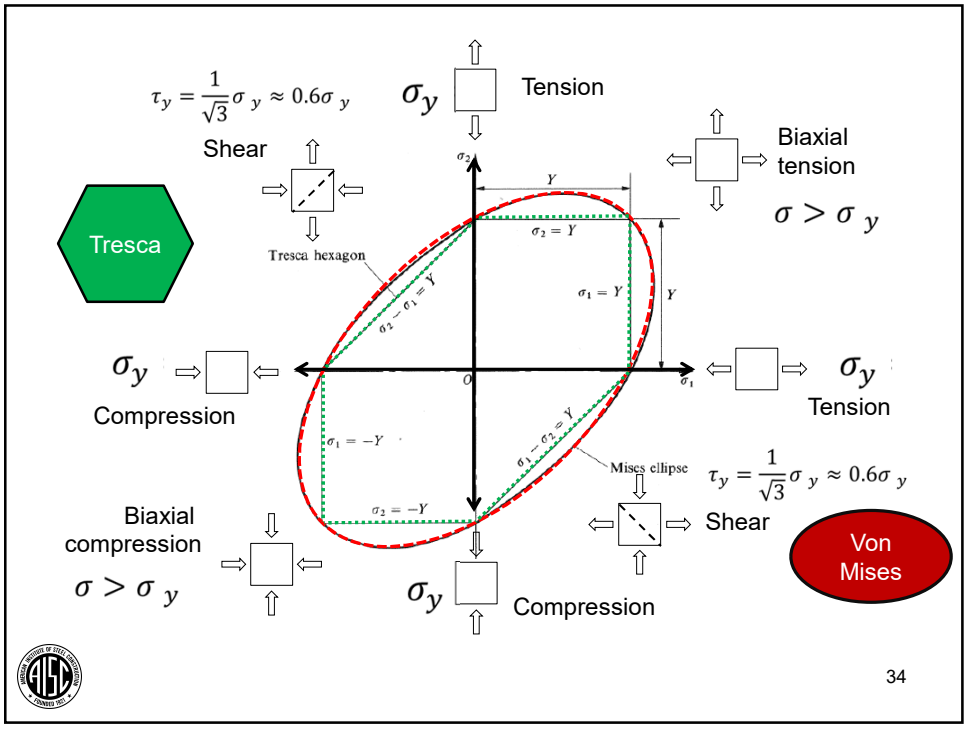


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# Von Mises interaction

$$\sigma_y = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}$$

$\sigma_3 = 0$

$$\sigma_y = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2}$$

Sometimes we can assume $\sigma_3 = 0$

- Plates
- Webs

$$\sigma_y^2 = 3\tau^2$$

$$\tau_y = \frac{1}{\sqrt{3}}\sigma_y \approx 0.6\sigma_y$$

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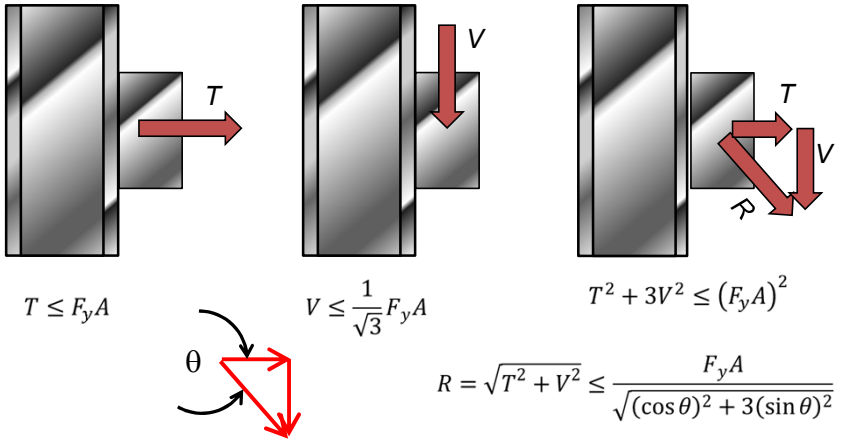
# Shear and tension




$T \le F_y A$

$V \le \frac{1}{\sqrt{3}} F_y A$

$T^2 + 3V^2 \le (F_y A)^2$

$$R = \sqrt{T^2 + V^2} \le \frac{F_y A}{\sqrt{(\cos\theta)^2 + 3(\sin\theta)^2}}$$

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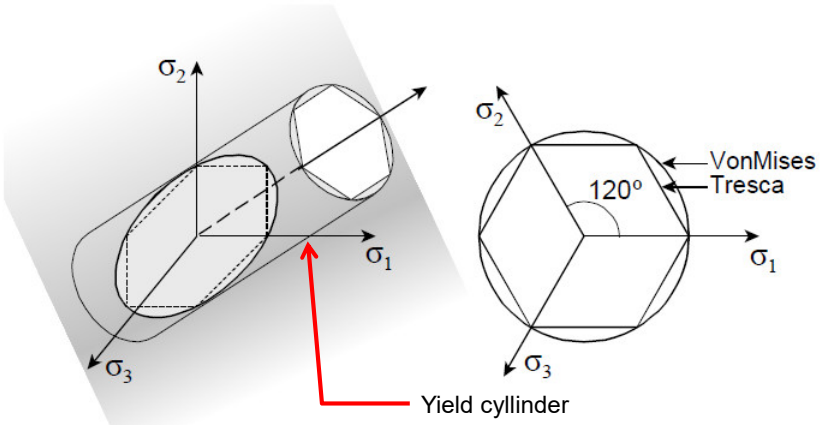
# Multi-axial stress

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# Rupture

- Separation of material under stress
- Non-ductile limit
- Multi-axis interactions do not apply

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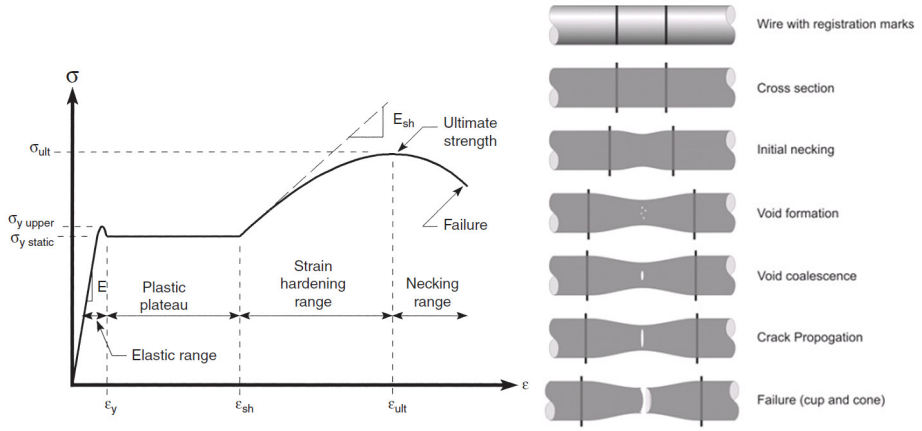
# Rupture

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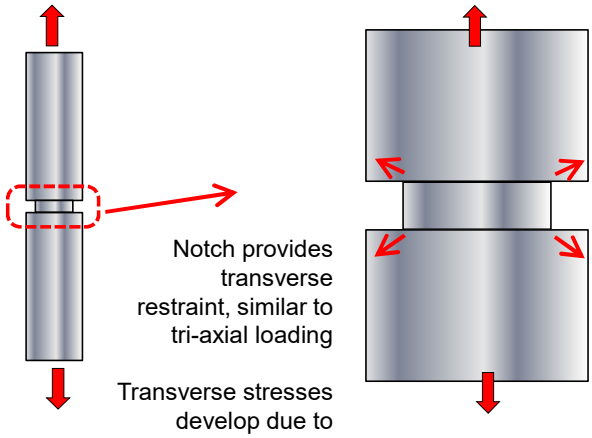
# Rupture

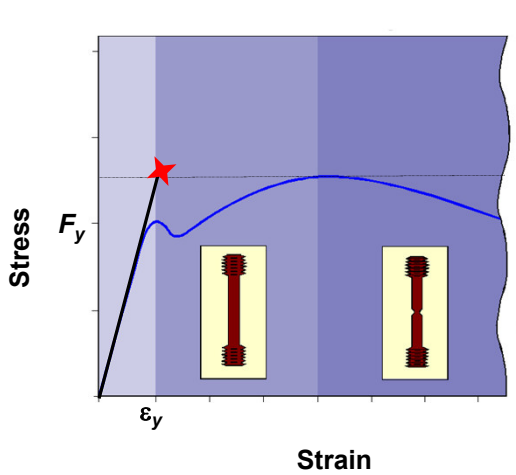


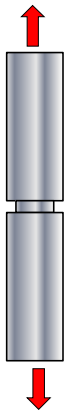
Notch provides transverse restraint, similar to tri-axial loading

Transverse stresses develop due to Poisson's effect

40

# Rupture



Notched specimen develops ultimate strength.

Fails at much lower strain

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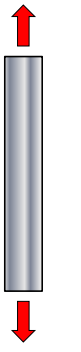
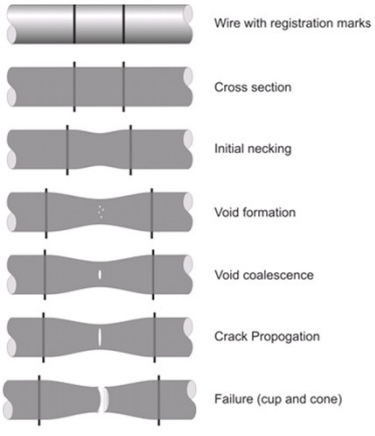
# Restraint



Minimal restraint

Example:
Tensile coupon

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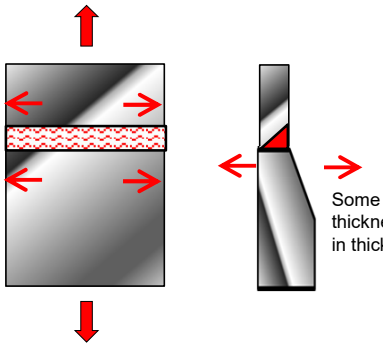
# Restraint



Moderate restraint



Some through-thickness restraint in thicker elements

Example: Column splice flange butt joint

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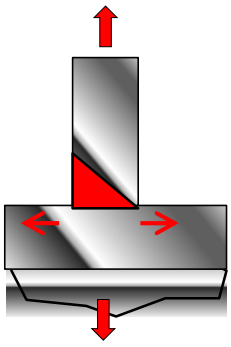
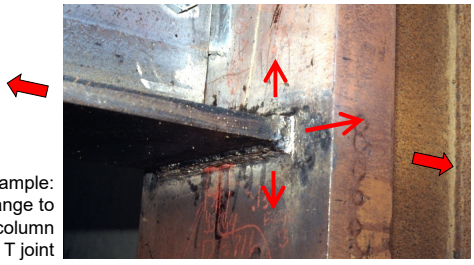
# Restraint



Highly restrained



Example: Beam flange to (thick) column flange T joint

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# Variability and predictability

- Steel yield strength is higher than specified minimum
  - Typically 110%-120%
  - As high as 160%
  - Varies with material and section type
- There is some variability in expected strength

Steel variability is considered in seismic design for "capacity design" procedures

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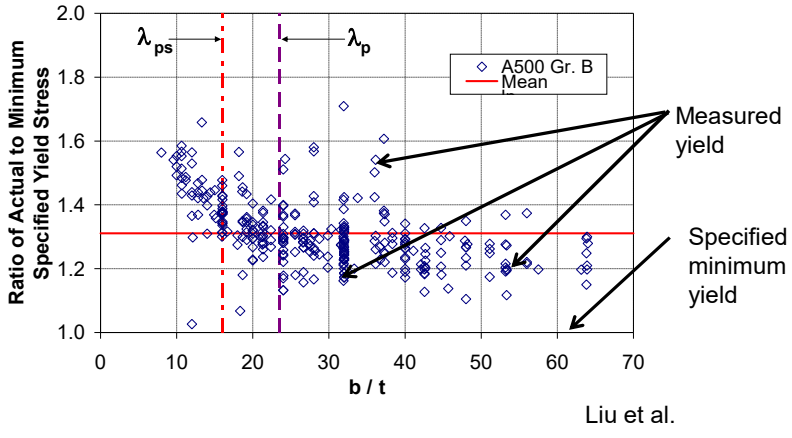
# Variability and predictability

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# Expected strength

- $R_yF_y$
- Expected (mean) yield strength for material
- NOT maximum yield strength
- Determined by AISC using industry-wide data

**TABLE A3.1**
**$R_y$ and $R_t$ Values for Steel and Steel Reinforcement Materials**

| Application | $R_y$ | $R_t$ |
|---|---|---|
| Hot-rolled structural shapes and bars: | | |
| • ASTM A36/A36M | 1.5 | 1.2 |
| • ASTM A1043/A1043M Gr. 36 (250) | 1.3 | 1.1 |
| • ASTM A992/A992M | 1.1 | 1.1 |
| • ASTM A572/A572M Gr. 50 (345) or 55 (380) | 1.1 | 1.1 |
| • ASTM A913/A913M Gr. 50 (345), 60 (415), 65 (450), or 70 (485) | 1.1 | 1.1 |
| • ASTM A588/A588M | 1.1 | 1.1 |
| • ASTM A1043/A1043M Gr. 50 (345) | 1.2 | 1.1 |
| • ASTM A529 Gr. 50 (345) | 1.2 | 1.2 |
| • ASTM A529 Gr. 55 (380) | 1.1 | 1.2 |
| Hollow structural sections (HSS): | | |
| • ASTM A500/A500M Gr. B | 1.4 | 1.3 |
| • ASTM A500/A500M Gr. C | 1.3 | 1.2 |
| • ASTM A501/A501M | 1.4 | 1.3 |
| • ASTM A53/A53M | 1.6 | 1.2 |
| • ASTM A1085/A1085M | 1.25 | 1.15 |
| Plates, Strips and Sheets: | | |
| • ASTM A36/A36M | 1.3 | 1.2 |
| • ASTM A1043/A1043M Gr. 36 (250) | 1.3 | 1.1 |
| • ASTM A1011/A1011M HSLAS Gr. 55 (380) | 1.1 | 1.1 |
| • ASTM A572/A572M Gr. 42 (290) | 1.3 | 1.0 |
| • ASTM A572/A572M Gr. 50 (345), Gr. 55 (380) | 1.1 | 1.2 |
| • ASTM A588/A588M | 1.1 | 1.2 |
| • ASTM A1043/A1043M Gr. 50 (345) | 1.2 | 1.1 |
| Steel Reinforcement: | | |
| • ASTM A615/A615M Gr. 60 (420) | 1.2 | 1.2 |
| • ASTM A615/A615M Gr. 75 (520) and Gr. 80 (550) | 1.1 | 1.2 |
| • ASTM A706/A706M Gr. 60 (420) and Gr. 80 (550) | 1.2 | 1.2 |

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# Toughness

- What is toughness?
- Toughness and cyclic loading
- Temperature
- Thick elements

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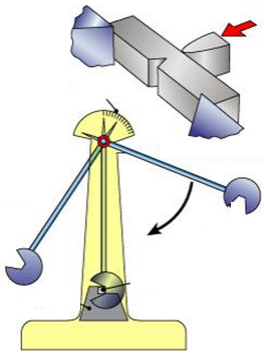
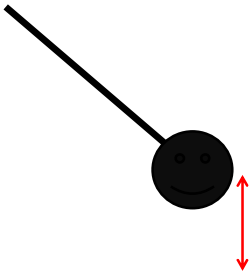
# What is toughness?





Difference in height gives energy required to fracture

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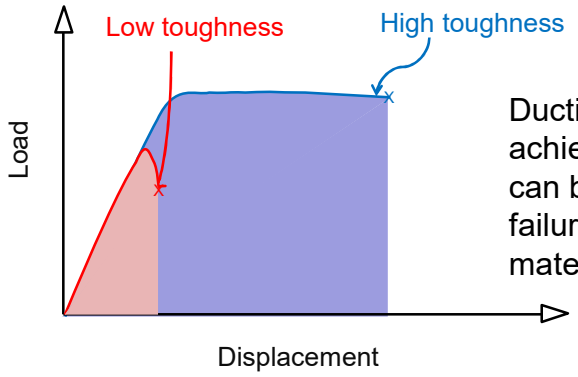
# Toughness and energy absorption




Ductile yielding (or even achieving full strength) can be precluded by failure of low-toughness material

Minimum toughness is required for seismic design at critical locations

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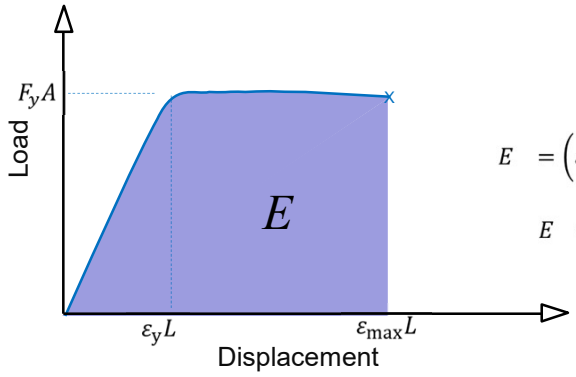
# Toughness and energy absorption




$$E = \left(\varepsilon_{max} - \frac{\varepsilon_y}{2}\right)(F_yA)L$$

$$E \approx \varepsilon_{max}(F_yA)L$$

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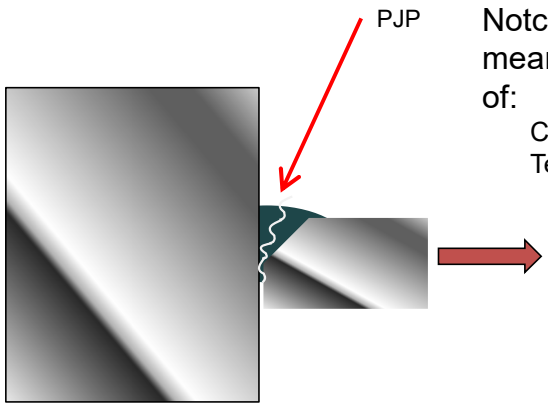
# Toughness and cyclic loading




Notch toughness is only meaningful in presence of:

- Crack
- Tension

PJP welds have reduced design strength to reflect notch effect

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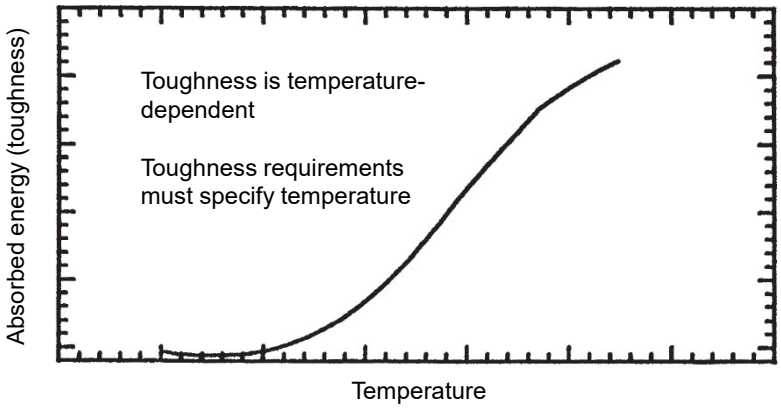
# Toughness and temperature

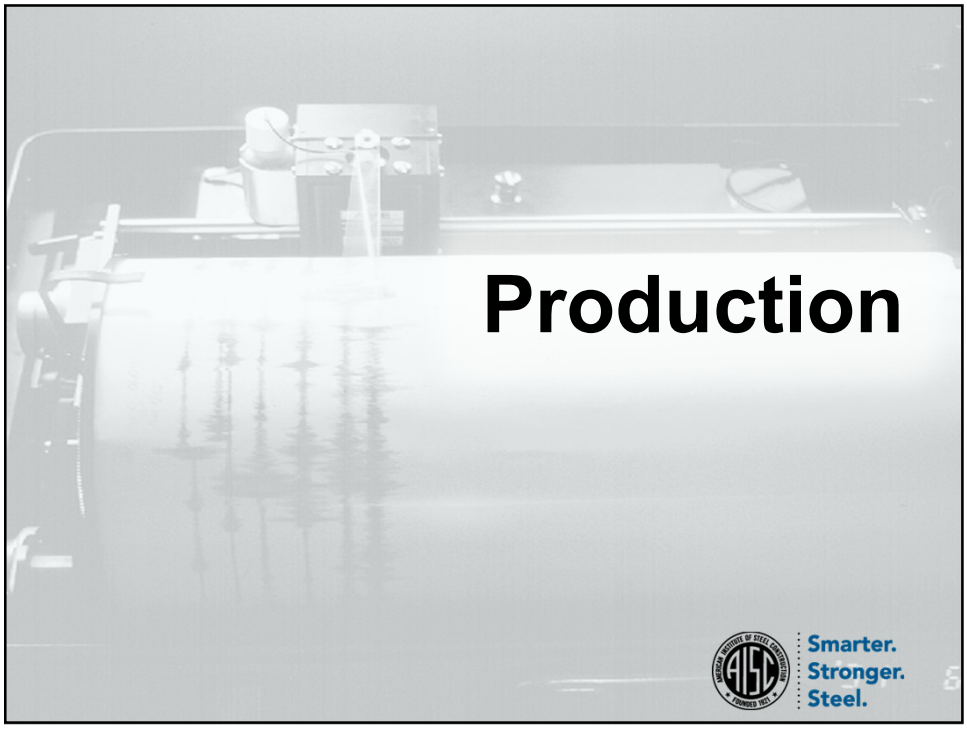



54

## Toughness and thickness

- High notch toughness is necessary for all elements subject to high strains, especially cyclic
- Thinner plates and sections have notch toughness
- Thicker material may have lower toughness due to restraint in through-thickness direction

55

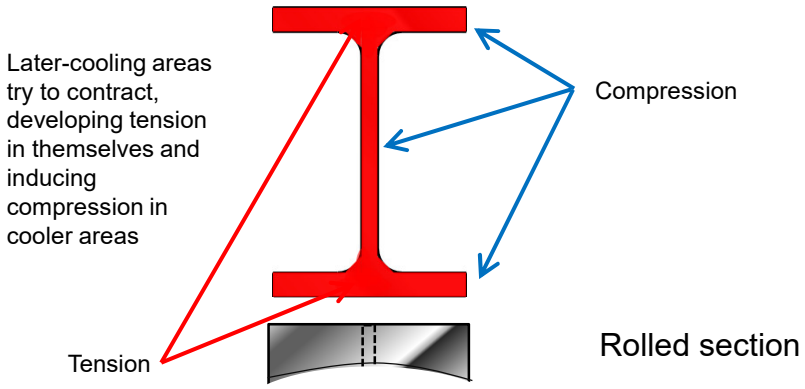


# Production

- Residual stresses
- The “k region”
- Laminations

57

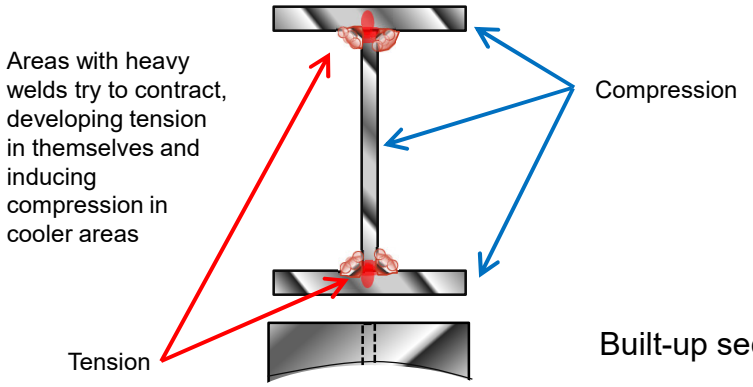
# Residual stresses




Design strengths reflect residual stress where it has an effect

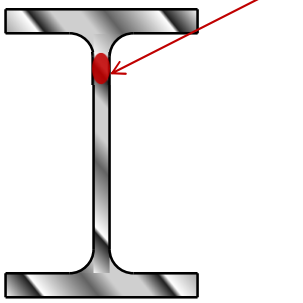
58

# Residual stresses




59

# The “k region”



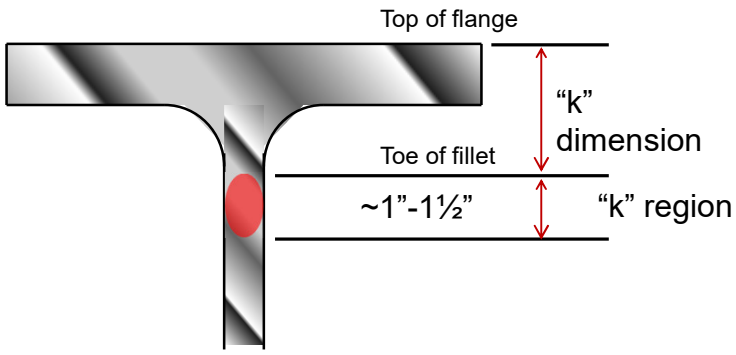
Rotary straightening of flanges strain-ages this area of the web, leading to reduced toughness.

Welds in this area have led to fracture during fabrication.

Welds to this region are proscribed in seismic design

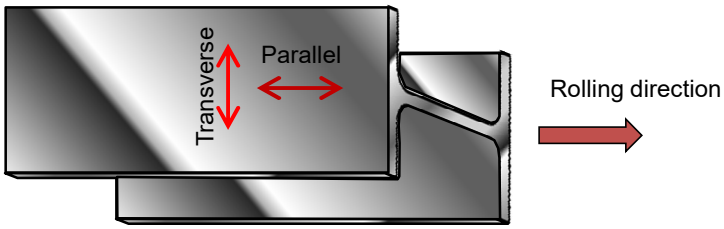
60

# The “k region”




61

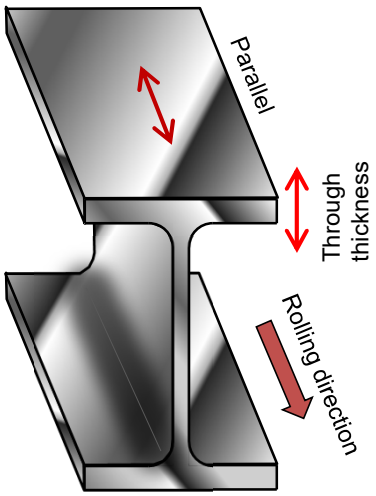
# Rolling




Similar properties in the parallel and transverse directions

62

# Rolling




Through-thickness direction has lower ductility (and toughness)

AKA “thru thickness”

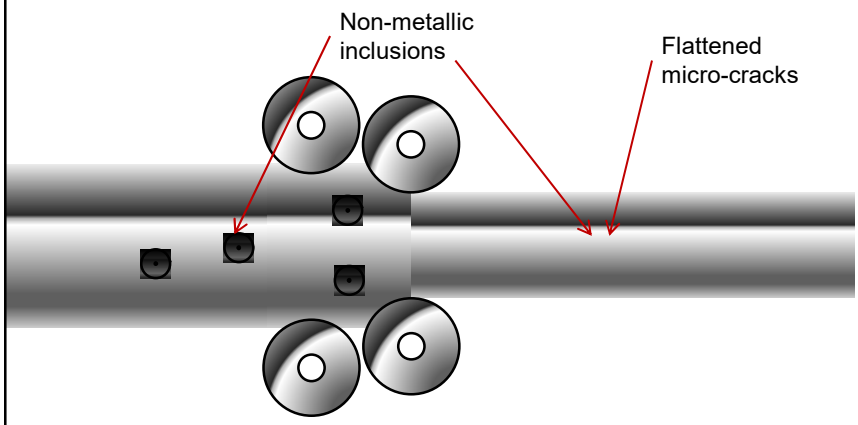
63

# Lamellar tearing

- Through-thickness loading
- High restraint
  - Thick elements
- Initial defects
  - Reduced integrity in through-thickness direction

64

# Lamellar defects




65

# Surface roughness

- Surface defects may initiate cracks
- 500 micro-inches provides sufficient smoothness

Codes require this smoothness at critical locations

66


## Welding

- Forces need to be transferred from member to member
- Welding can provide continuity through steel material
- Attention must be given to detailing
- Joint types
- Weld types
- Heat-affected zone
- Restraint and shrinkage
- Defects

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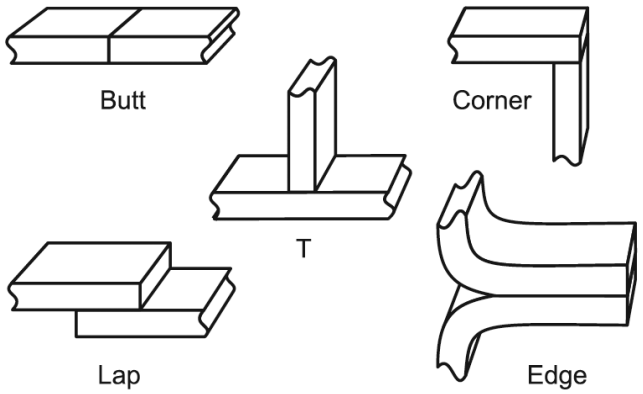
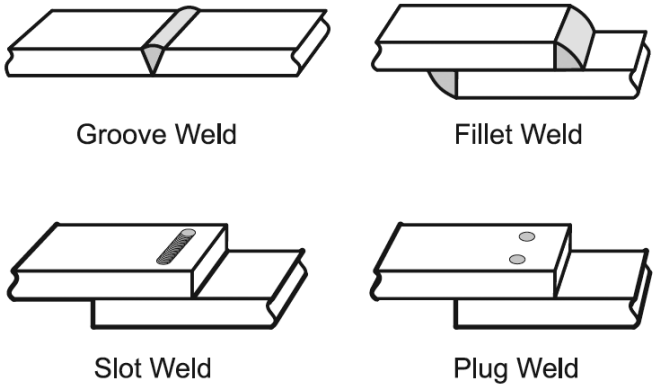
# Joint types



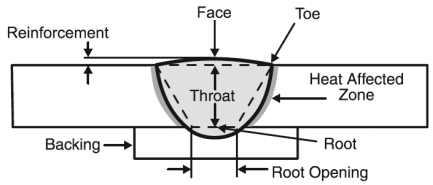

69

# Weld types

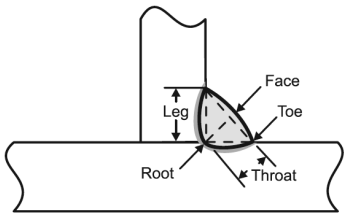



70

# Weld Terminology




Groove welds

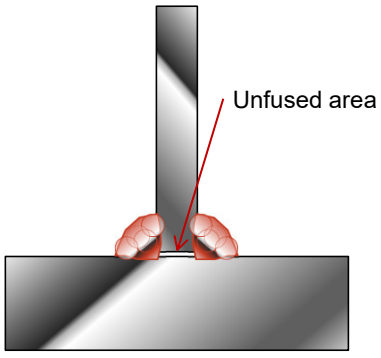



Fillet welds

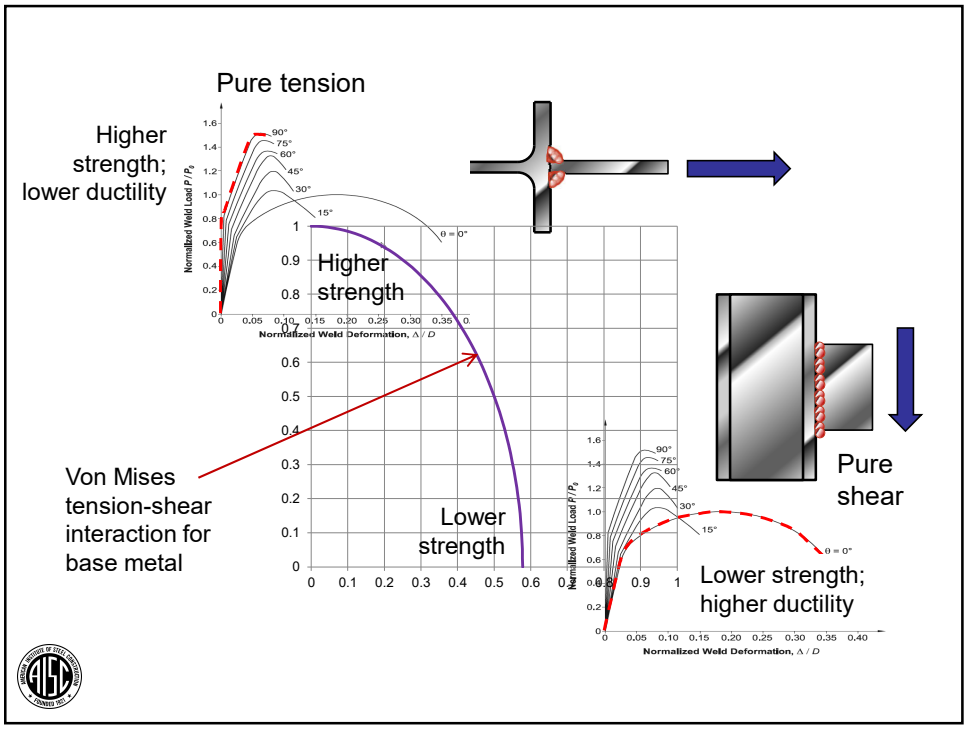
71

# Weld types

- Fillet welds
  - Internal crack
  - Strength is a function of loading angle
  - Some ductility
    - Typically less than base metal
  - Can be sized to develop base metal
    - For ductile joint
    - Similar to CJP

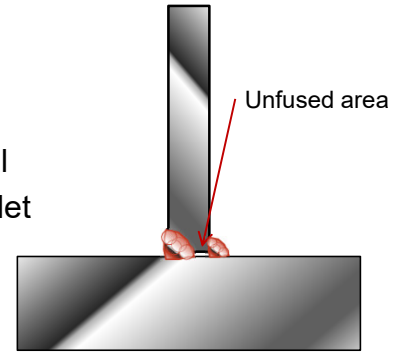



72




# Weld types

- Partial Joint Penetration
  - "PJP"
  - External crack
  - Cannot develop base metal
  - Benefits from reinforcing fillet
    - Internal crack

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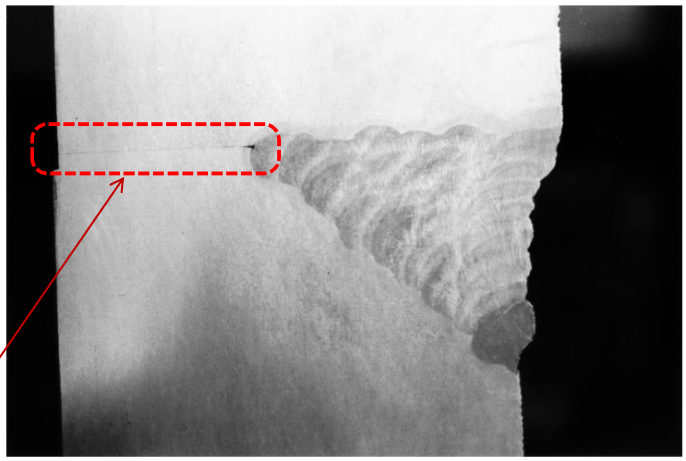
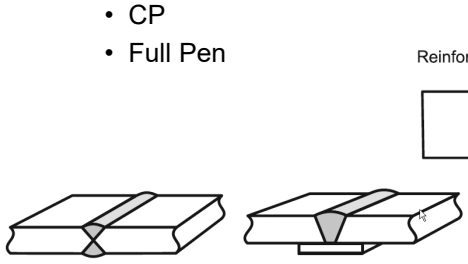
# Partial Joint Penetration weld

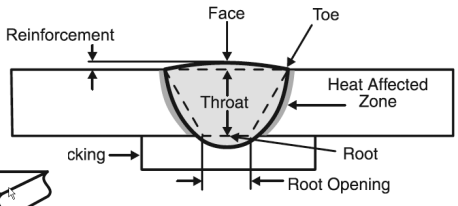



75

# Weld types

- Complete Joint Penetration
  - AKA
    - CJP
    - CP
    - Full Pen



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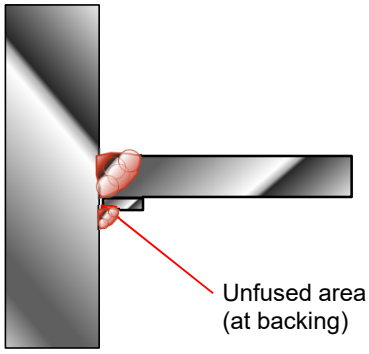
# Weld types

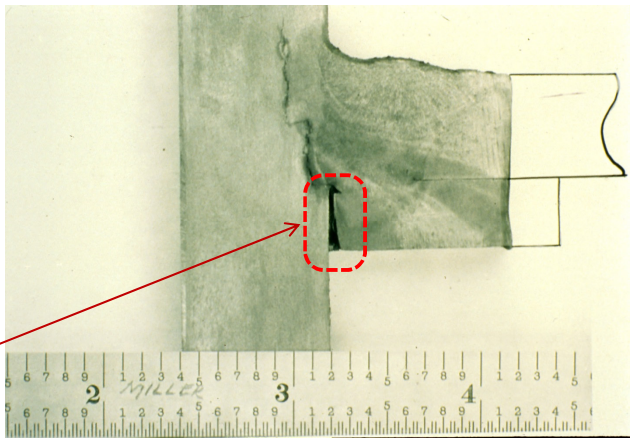
- Complete Joint Penetration
  - Develops base metal
  - 2-Sided
    - Weld tabs
  - 1-Sided
    - Weld tabs and backing
    - Benefits from reinforcing fillet




Codes require backing removal or reinforcement at critical tension locations

77

# Backing

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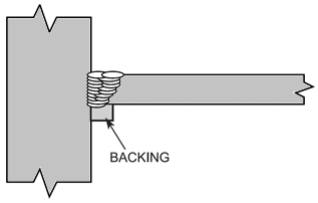
# Backing

- Backing used to support and retain molten filler metal
- Backing – also called "weld backing," "backing bars," "back-up bars", and "backing strips"
- Fusible backing– weld is intended to bond to backing (e.g. steel backing)
- Non-fusible backing– weld not intended to bond to backing (e.g. ceramic and copper)

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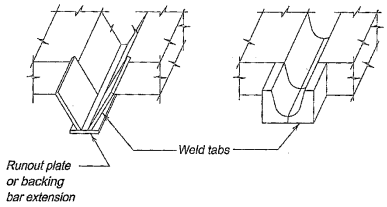
# Weld tabs

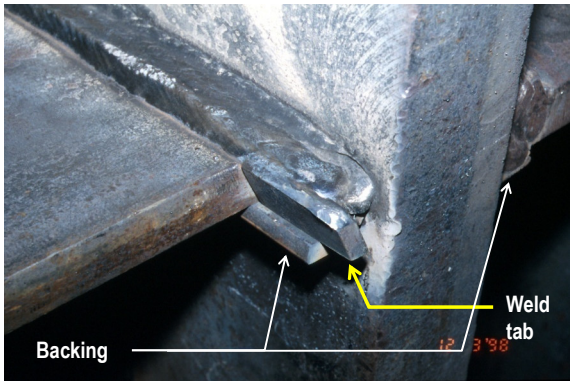
- Weld tabs ("runoff tabs") are extensions of the parts being welded that allow the weld to be started and stopped outside of the joint
- Provide for similar geometry as the preparation
- Generally required to be removed after welding




Codes require weld-tab removal at most locations in the seismic-load-resisting system

80

# CJP

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# Heat-affected zone

- AKA “HAZ”
- Base metal affected by weld heat
- Properties affected by rate of cooling
  - Rapid cooling results in brittle steel
  - Pre-heat slows cooling

82

## Restraint and shrinkage

- Weld shrinkage induces demands
  - Stress
  - Strain
- Good detailing provides length for moderate strain to relieve cooling stresses
- Through-thickness loading is problematic
- Highly restrained conditions do not provide relief

83

## Restraint and shrinkage


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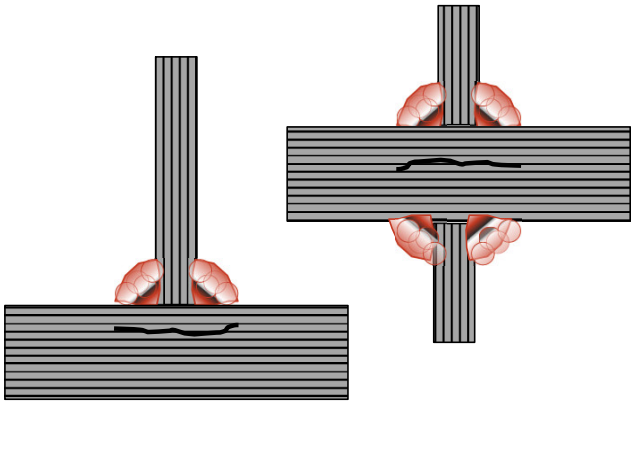
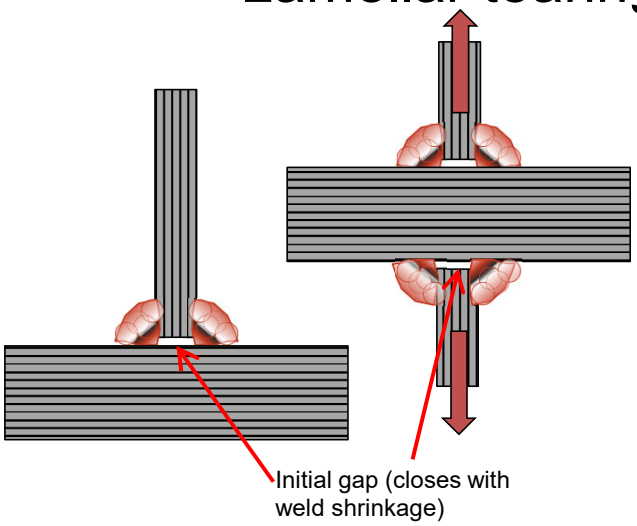
# Lamellar tearing



Weld shrinkage can induce through-thickness loading

85

# Lamellar tearing




Better detailing can reduce welding-induced stresses, but does not address **through-thickness loading**

86

## Weld defects

- Improper fusion
- Inclusions
  - Potential initial cracks
- Hydrogen embrittlement
  - Potential initial cracks
  - Proper procedures reduce hydrogen infiltration
  - Slow cooling allows hydrogen to escape
- Restraint-induced cracking

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## Summary

- Steel material of the right type can provide the foundation for high levels of ductility
- Care must be taken to maintain this ductility
  - At welded joints
  - At locations of high restraint
  - In certain regions affected during rolling and fabrication

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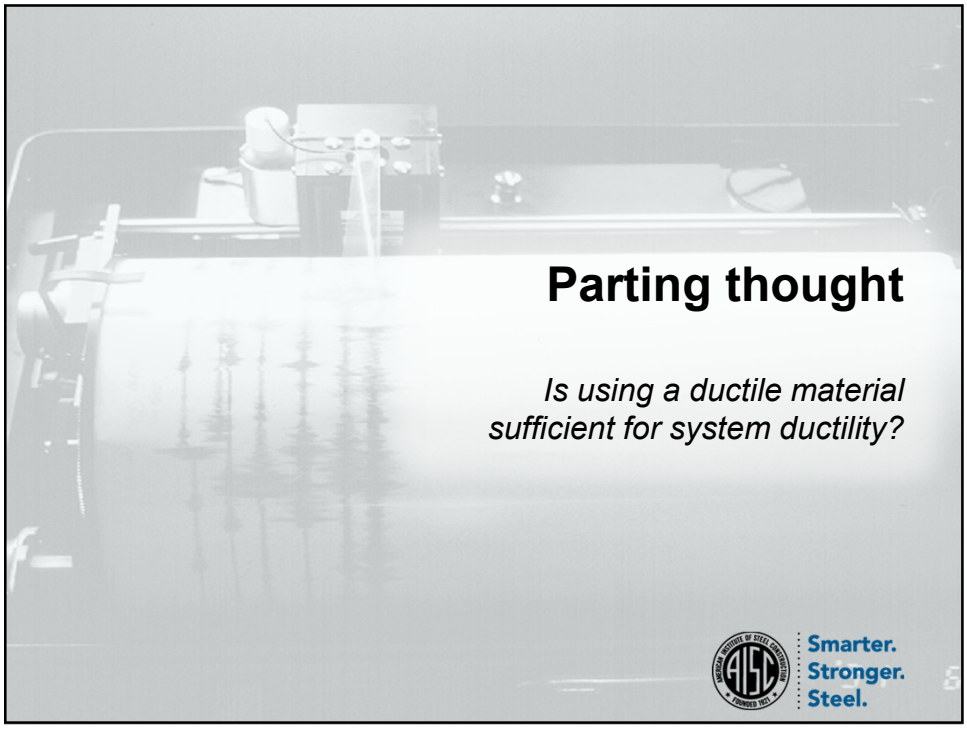
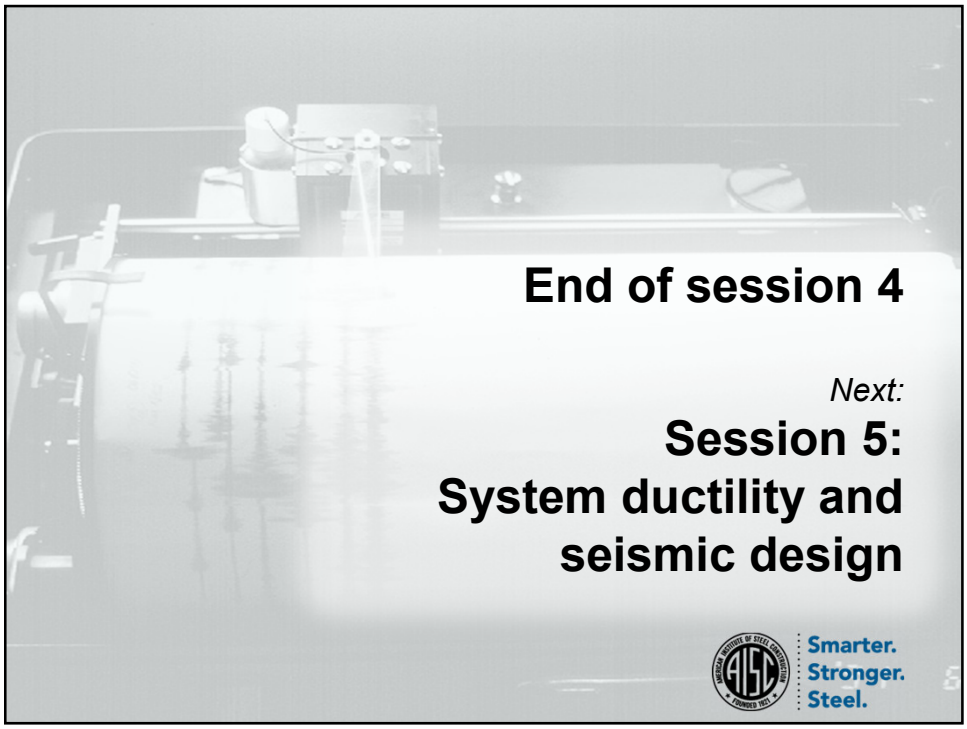
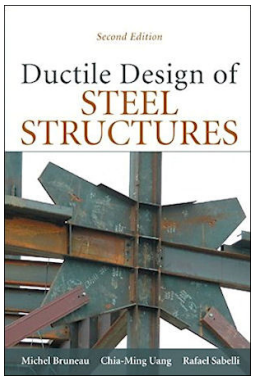
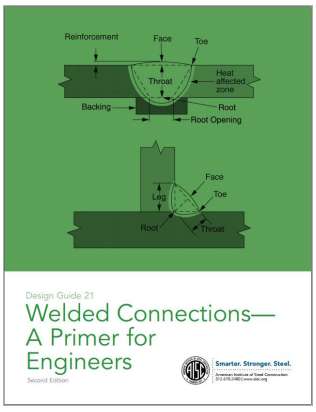


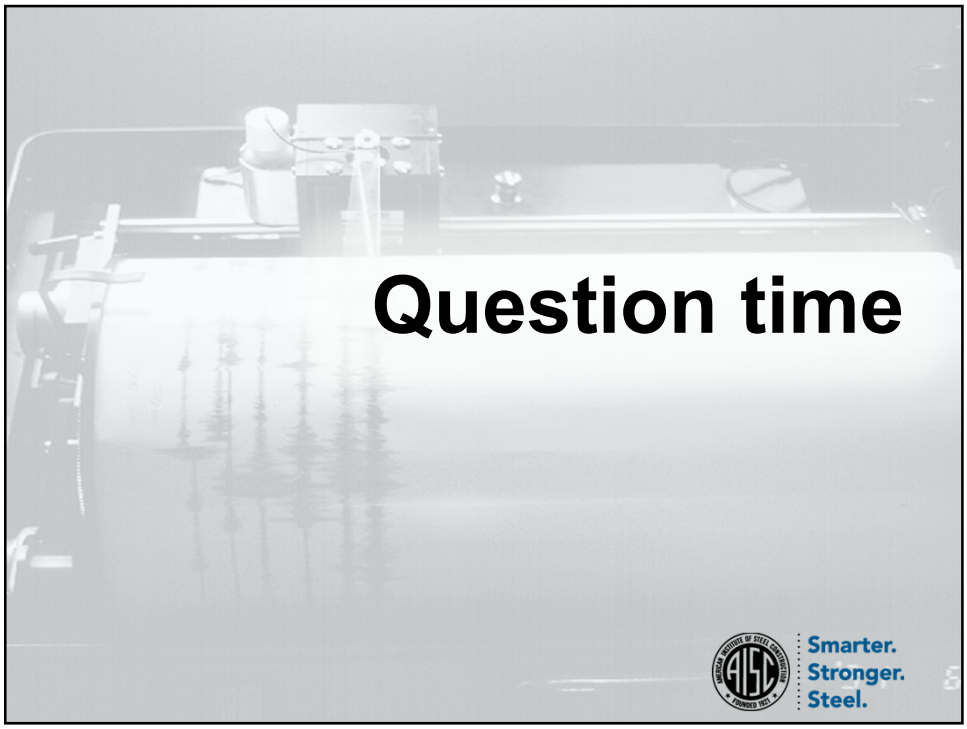



## Additional resources




92

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- Username: Same as AISC website username.
- Password: Same as AISC website password.

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### Attendance and PDH Certificates

- You have two options to receive credit for a given session.
  - Option 1: Watch the live session. Credit for live attendance will be displayed on the Course Resources table within two days of the session.
  - Option 2: Watch the recording and pass the associated quiz.

### Videos and Quizzes

- For each session, find access within two business days after the live air date. (An email will be sent from nightschool@aisc.org.)
- 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.
  - Reinforce what you learn in the lectures and get more out of the course!

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### Course Resources

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

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### Course Resources

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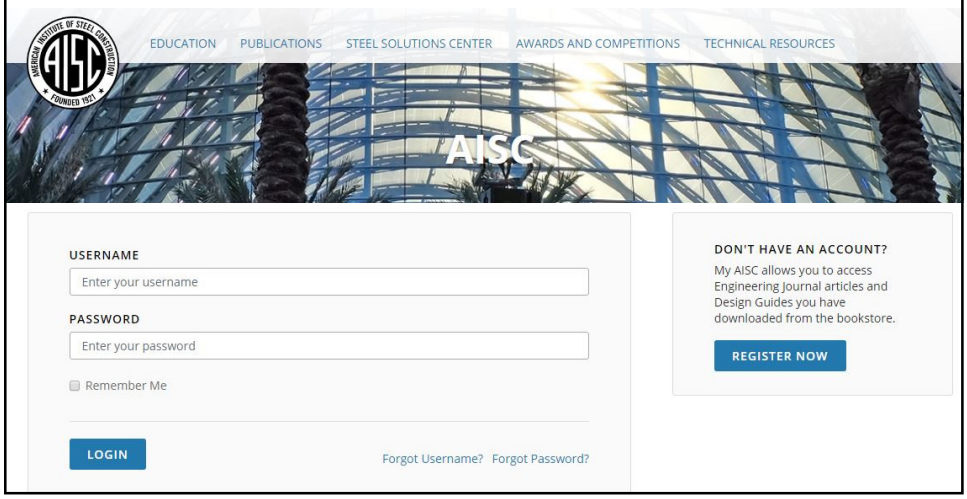


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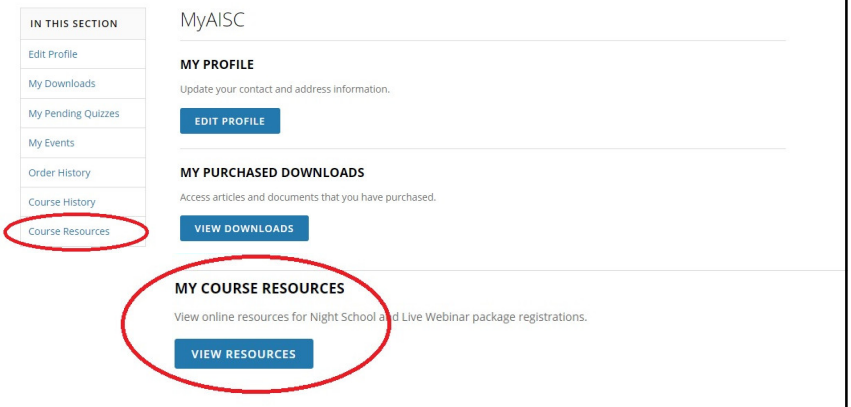


## 8-Session Registrants

### Course Resources

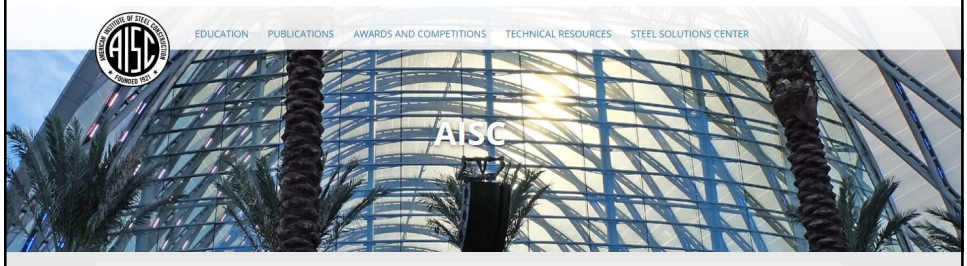

AISC › MY ACCOUNT › COURSE RESOURCES

Course Resources

| Event | Start Date |
|---|---|
| Seismic Design in Steel | 1/1/1900 12:00:00 AM |
| 4-Session Package-Design of Façade Attachments | 5/9/2019 1:30:00 PM |
| NS 15 8-Session Package-Night School 15 - Fundamentals of Connection Design | 10/3/2017 7:00:00 PM |
| NS 16 8-Session Package-Night School 16 - Seismic Design in Steel | 2/5/2018 7:00:00 PM |
| NS 17 4-Session Package-Night School 17: Design of Façade Attachments | 7/16/2018 7:00:00 PM |
| NS 18 8-Session Package-Night School 18: Steel Construction: Mill To Topping Out | 10/15/2018 7:00:00 PM |
| NS 19 8-Session Package-Night School 19: Connection Design | 2/4/2019 7:00:00 PM |
| NS 20 8-Session Package-Night School 20: Classical Methods of Structural Analysis | 6/3/2019 7:00:00 PM |
| 8-Session Package-Seismic Design in Steel - Concepts & Examples | 7/16/2018 1:30:00 PM |

## 8-Session Registrants

### Course Resources

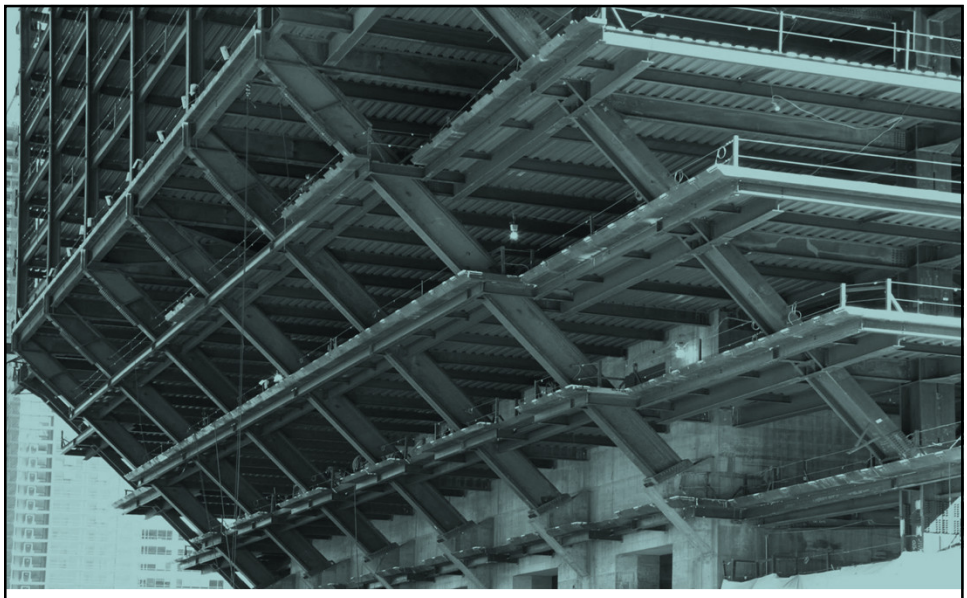



AISC › MY ACCOUNT › COURSE RESOURCES › NS24 8-SESSION PACKAGE RESOURCES

Night School 24: Modern Methods for Learning Structural Stability

**8-SESSION PACKAGE RESOURCES**

| Event | Date | Handouts | Video | Quiz | Attendance |
|---|---|---|---|---|---|
| NS24.1 - Compression Members - The Fundamentals | Oct 6 2020 7:00PM EDT | Handouts | Available 10/08/2020 5:00PM EDT | Available 10/08/2020 5:00PM EDT | Pending |
| NS24.2 - Compression Members - Practical Considerations | Oct 13 2020 7:00PM EDT | Handouts | Available 10/15/2020 5:00PM EDT | Available 10/15/2020 5:00PM EDT | Pending |
| NS24.3 - Behavior of Flexural Members - The Fundamentals | Oct 20 2020 7:00PM EDT | Handouts | Available 10/22/2020 5:00PM EDT | Available 10/22/2020 5:00PM EDT | Pending |
| NS24.4 - Flexural Members - Practical Considerations | Oct 27 2020 7:00PM EDT | Handouts | Available 10/29/2020 5:00PM EDT | Available 10/29/2020 5:00PM EDT | Pending |
| NS24.5 - Stability of Beam-Columns - The Fundamentals | Nov 10 2020 7:00PM EST | Handouts | Available 11/12/2020 5:00PM EST | No longer available | Pending |
| NS24.6 - Stability of Beam-Columns - Practical Consideration | Nov 17 2020 7:00PM EST | Handouts | Available 11/19/2020 5:00PM EST | No longer available | Pending |
| NS24.7 - Behavior of Structural Systems - The Fundamentals | Dec 1 2020 7:00PM EST | Handouts | Available 12/03/2020 5:00PM EST | No longer available | Pending |
| NS24.8 - Structural Systems - Practical Considerations | Dec 8 2020 7:00PM EST | Handouts | Available 12/10/2020 5:00PM EST | No longer available | Pending |
| NS24 - Final Exam | N/A | | | No longer available | |



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