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Fundamentals of earthquake engineering for building structures

Session 2: Dynamics and Response

February 22, 2021 | Rafael Sabelli

Smarter.
Stronger.
Steel.

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Course Description

Session 2: Dynamics and Response

February 22, 2021

This lecture will focus on the dynamics and response to earthquakes. It will include a review of single-degree-of-freedom dynamics. An explanation of harmonic response spectra and a discussion of earthquake response spectra and inelastic response will be discussed. The lecture will include a review of factors affecting response reduction.

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Learning Objectives

- Describe the basic dynamics of building structures.
- Describe seismic response spectra and the development of generalized response spectrum.
- Describe inelastic response and effective stiffness.
- Describe energy dissipation and hysteretic behavior.

Night School 25:

Fundamentals of earthquake engineering for building structures

Rafael Sabelli, SE
Walter P Moore

Smarter.
Stronger.
Steel.

Course outline

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

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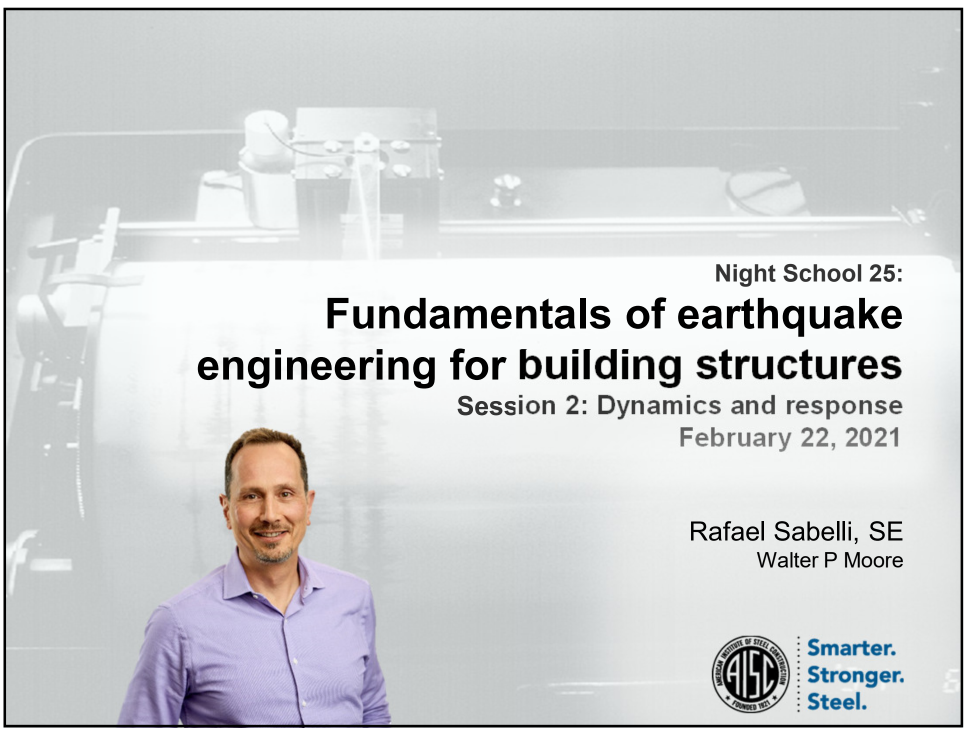

Session topics

- Basic dynamics
- Forced motion and response
- Dynamic equilibrium and the equation of motion
- Response spectra
- Seismic response spectra
- Inelastic response
- Ductility

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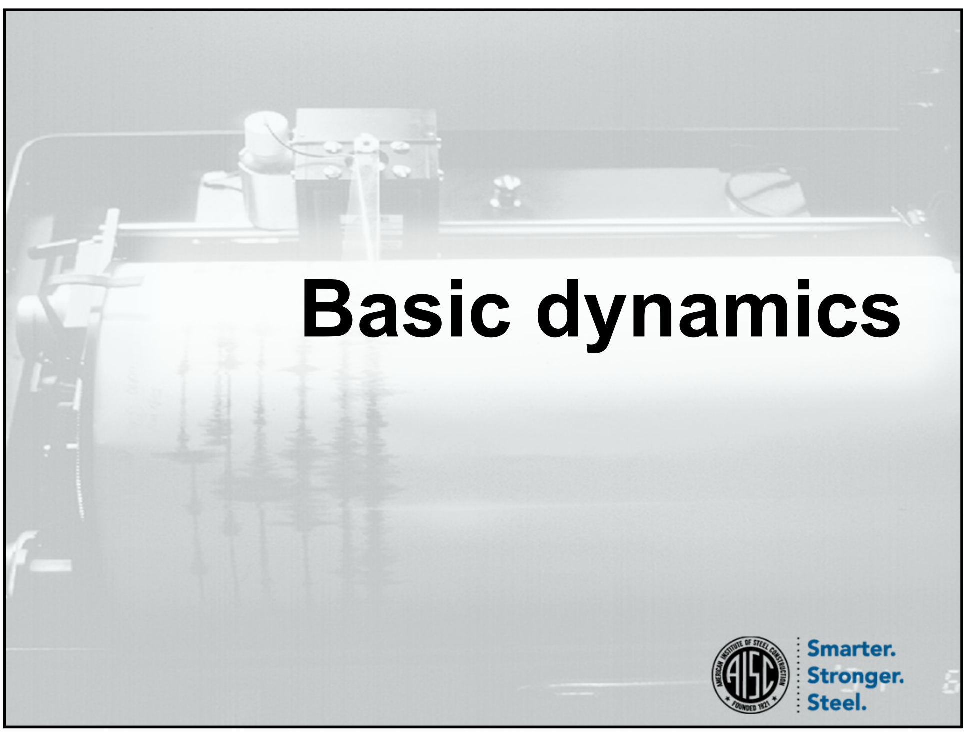

Basic dynamics

- Structures have dynamic characteristics
  - Natural frequencies of vibration
  - Modes of vibration
  - Damping of movement
- Dynamic characteristics arise from
  - Mass
  - Stiffness
  - Damping

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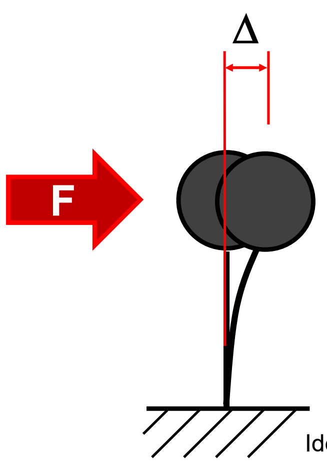
Stiffness



$$K=F/\Delta$$

F= force
Δ= displacement
K= stiffness

Idealized system with
mass and stiffness

Codes treat buildings as simple, single-degree-of-freedom oscillators for basic seismic calculations such as base shear

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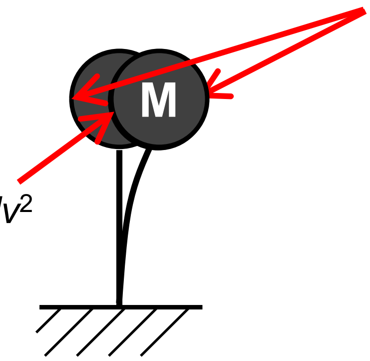
Energy, mass, and motion

Imposed displacement = Δ
Release at t=0

$E_e = ½K\Delta^2$

Elastic stored energy



$E_k = ½Mv^2$

Kinetic energy

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$E = E_e + E_k$

$E_e = ½\, K[x(t)]^2$

Elastic strain energy

$E_k = ½\, M[v(t)]^2$

Kinetic energy

at $v=0$, $x=x_{max}=\Delta$

$E_e = ½\, K\Delta^2$

$E_k=0$

at $x=0$, $v=v_{max}$

$E_k = ½\, Mv_{max}^2$

$E_e=0$

x	= displacement
v	= velocity
M	= mass= W/g
W	= weight
g	= acceleration of gravity

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Harmonic motion

x = function of time, t

$v = {}^{dx}/_{dt}$

Solve differential equation:

$E_e(t)+E_k(t) = E_e(0)$

$\tfrac{1}{2}\,K\,x(t)^2 + \tfrac{1}{2}\,M({}^{dx}/_{dt})^2 = \tfrac{1}{2}\,K\,\Delta^2$

$x(t) = \Delta \cos[({}^{K}/_{M})^{1/2}\,t]$

$x = \Delta$ at

$t = 0$

$t = 2\pi\,({}^{M}/_{K})^{1/2}$

$t = 4\pi\,({}^{M}/_{K})^{1/2}$ etc.

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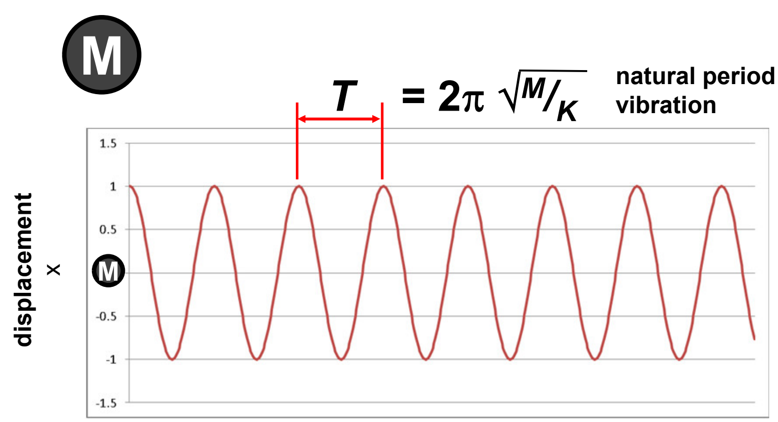
Harmonic motion



$T = 2\pi\sqrt{{}^{M}/_{K}}$ **natural period of vibration**

time
t

$\omega = 2\pi/T = \sqrt{{}^{K}/_{M}}$ **natural circular frequency of vibration**

Building period is a fundamental property used in seismic design

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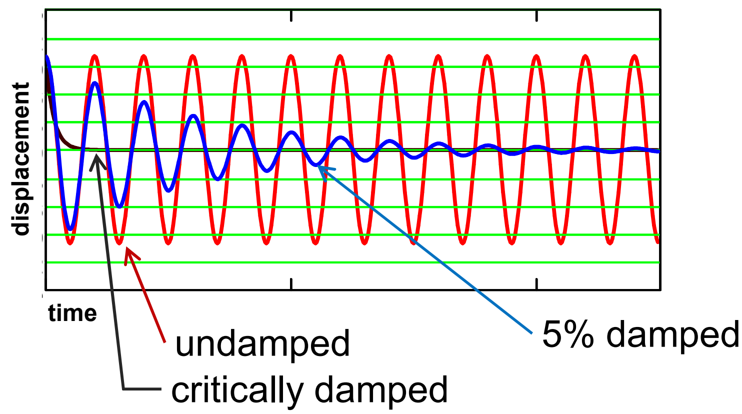
Damping



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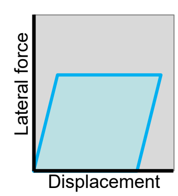
Damping

- Friction
  - Structural elements slipping
    - Bolts
  - Nonstructural items sliding, rubbing
- Damage
  - Less energy returned than goes in
  - Non-structural damage
    - Partition cracking
  - Structural damage



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Damping

- Displacement-dependent sources
- Acceleration-dependent sources
- Idealized as velocity-dependent
- Expressed as a % of critical damping
- Typical steel-framed buildings
  - 2-3%
  - 5% used to include some structural damage
  - Low levels do not affect natural period

Codes use 5% damping to determine forces

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Energy, mass, and *damped* motion

$E = \frac{1}{2} K\Delta^2$ at v=0

$E = \frac{1}{2} Mv^2 - E_{damping}$ at x=0

$T_D = T / \sqrt{1 - \xi^2}$

T_D = damped natural period
T = undamped natural period
ξ = damping coefficient (% of critical damping)

If ξ = 5%

T_{damped} = 1.001 T

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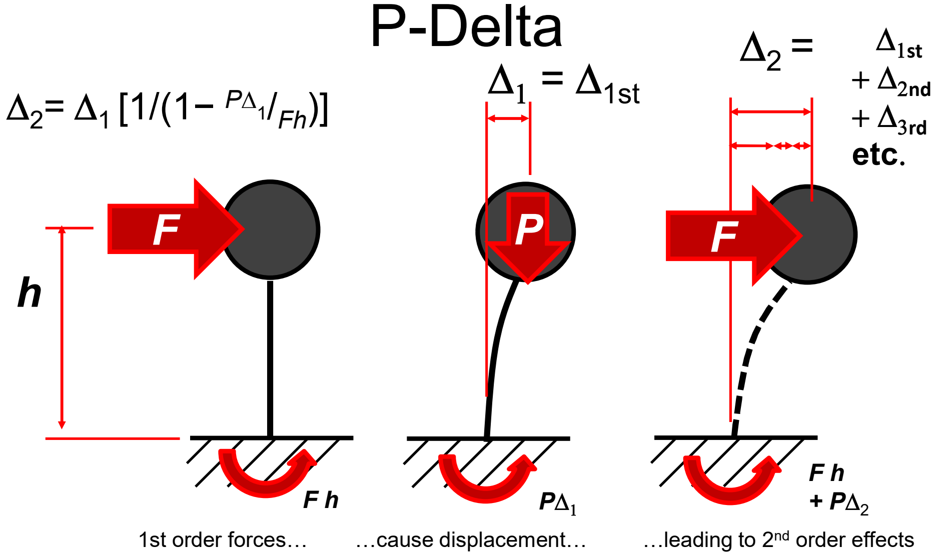
P-Delta



Δ_2 is equilibrium displacement

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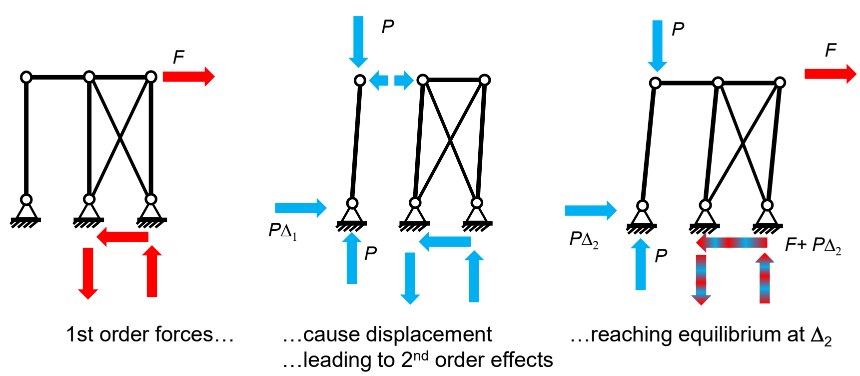
P-Delta



$$\Delta_2 = \Delta_1 [1/(1 - {}^{P\Delta_1}/_{Fh})]$$

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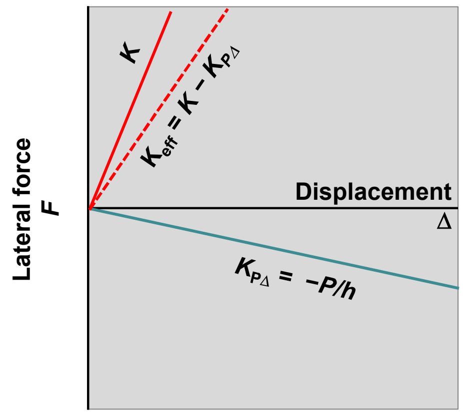
P-Delta stiffness

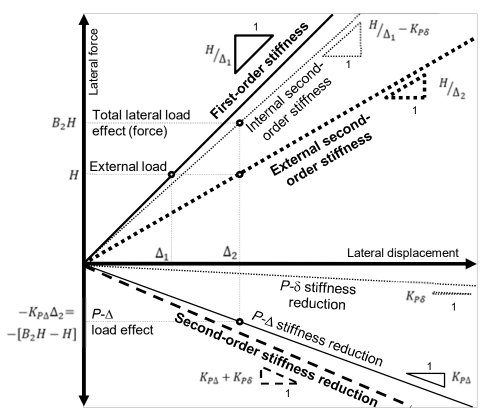
$K_{P\Delta}$ = negative stiffness due to P-Delta

K = stiffness

K_{eff} = effective stiffness



PΔ and Pδ stiffness reduction



Sabelli, R., and Griffis, L.G. (Quarter 2, 2021), "Internal second-order stiffness: A refined approach to the R_M coefficient to account for the influence of P-δ on P-Δ," *Engineering Journal*, AISC.

P-Delta stiffness

- P-Delta reduces effective stiffness
- Reduced stiffness → longer period
  - Typically small effect
  - Not typically considered in design
- P-Delta is a second-order effect
  - Most significant for:
    - Flexible structures
      - Low lateral loads

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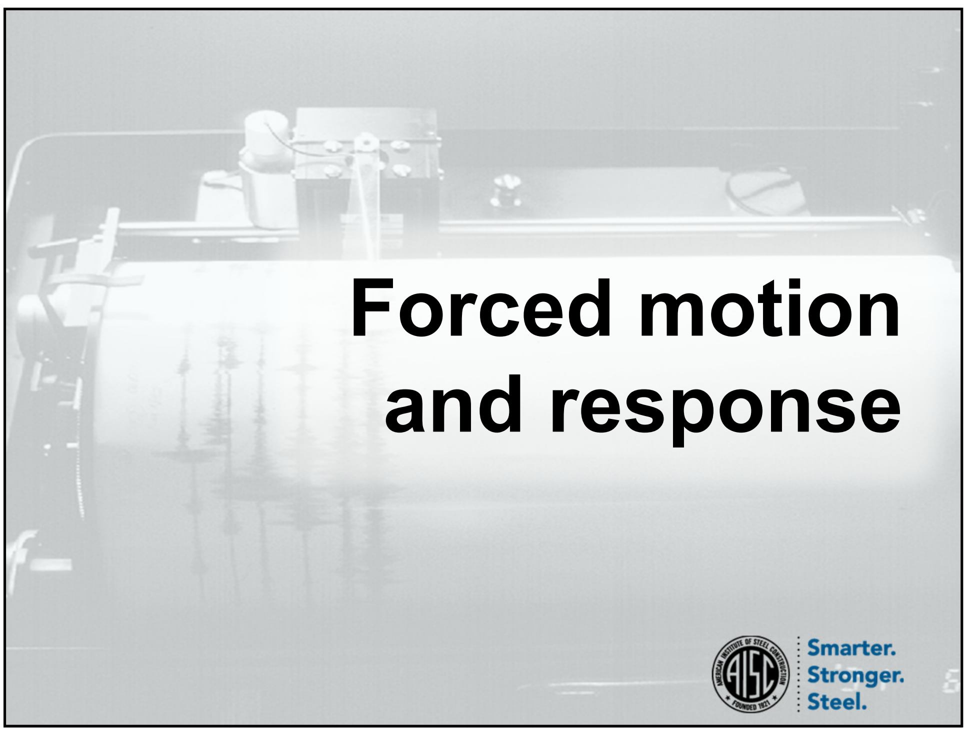

Forced motion and response

- What is “response”?
- Forced motion
- Resonance
- Effect of damping

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What is *response*?

- Any quantity of interest arising from the application of load
  - Displacements
  - Internal Forces
  - Accelerations
  - Velocities
  - etc.

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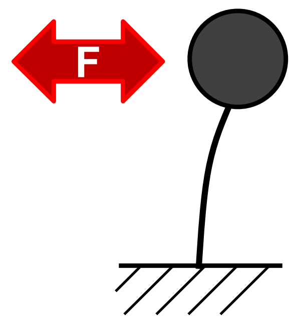
Forced motion



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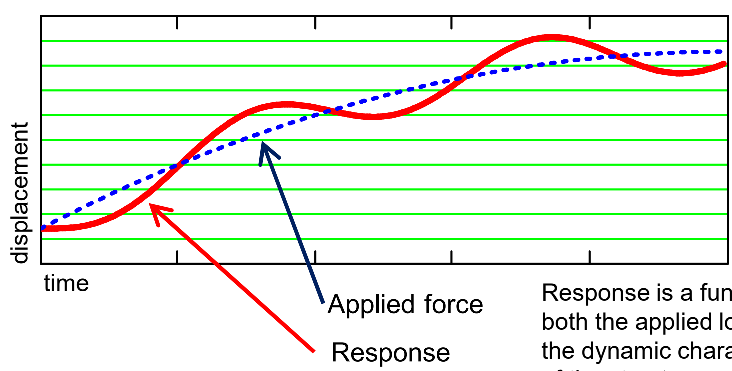
Forced motion



Response is a function of both the applied load and the dynamic characteristics of the structure

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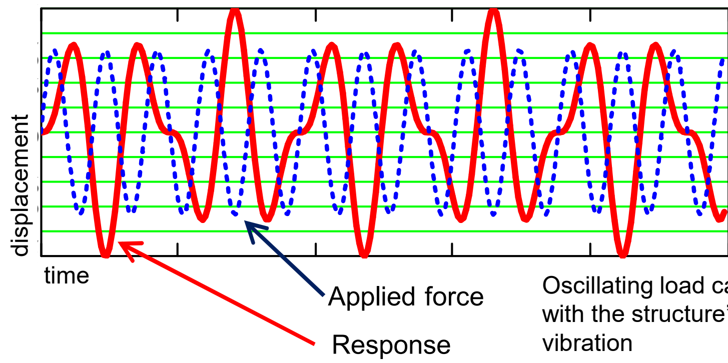
Harmonic force



Oscillating load can interact with the structure's natural vibration

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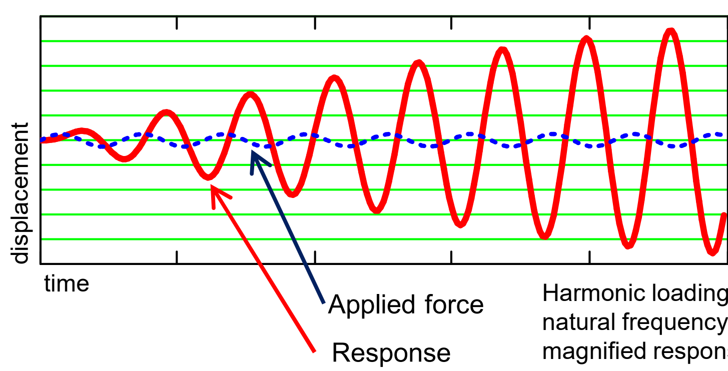
Resonance



Harmonic loading near the natural frequency causes magnified response

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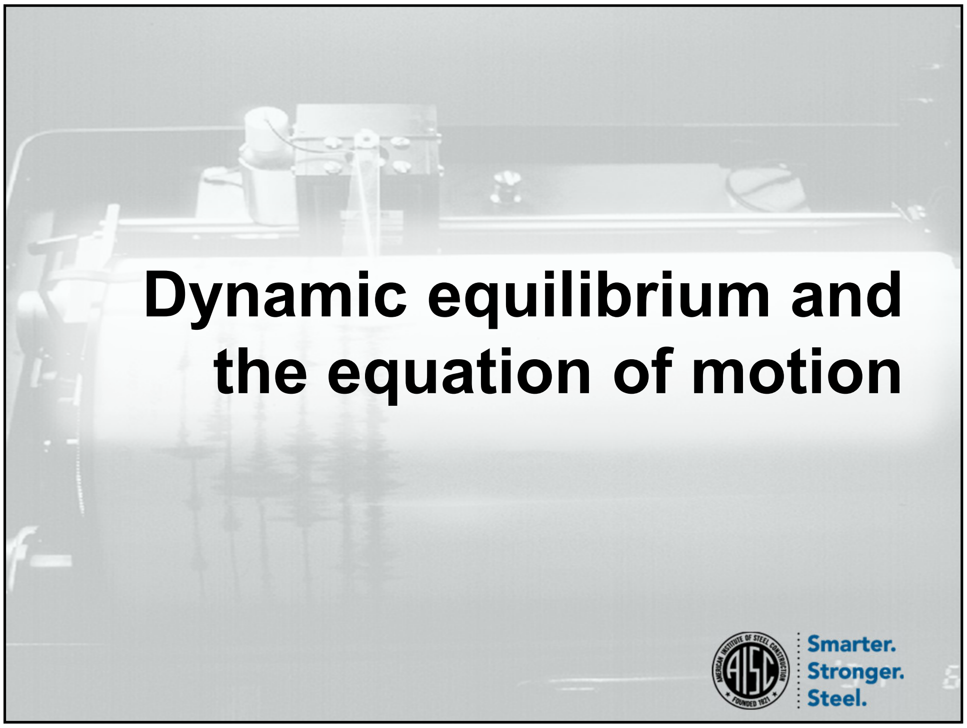

Dynamic equilibrium and the equation of motion

- Basis of response spectra
- Used explicitly in response-history analysis
- Conceptual relation between ground motion and structural demands

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Dynamic equilibrium and the equation of motion

- Dynamic equilibrium
  - External force balanced by
    - Internal force (strain energy) [Temporary storage]
      - May contribute to acceleration of mass or damping later
    - Force lost to damping
      - Heat energy
      - Structural damage
      - Strain energy not returned
    - Acceleration of mass [Temporary storage]
      - May contribute to internal forces and damping later

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The equation of motion

- $Ma(t)+Cv(t)+Kx(t) = -F(t)$
  - M = mass
  - C = damping coefficient
  - K = stiffness
  - t = time
  - x(t) = displacement
  - v(t) = velocity $= {}^{dx}/_{dt}$
  - a(t) = acceleration $= {}^{dv}/_{dt} = {}^{d^2x}/_{dt^2}$
  - F(t) = applied force

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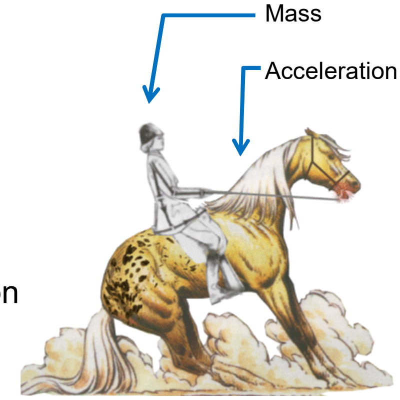
The equation of motion

- C = damping coefficient
  - Critical damping
    - C_c = $[4KM]^{½}$
- F(t) = applied force
  - Inertial force
    - F(t) = Mg(t)
    - g(t) = ground acceleration history



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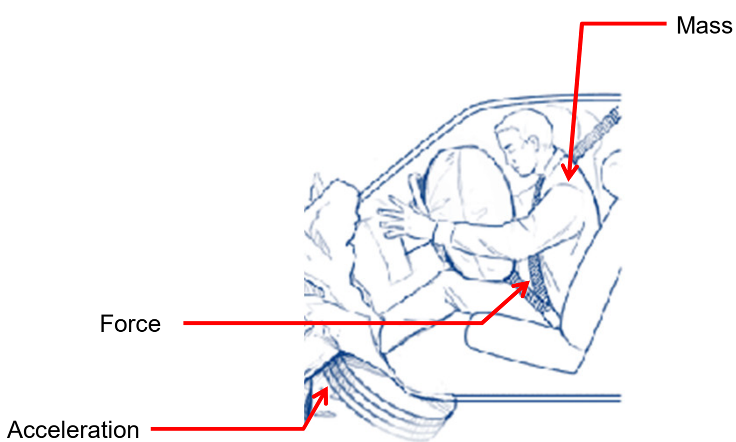
Inertial force



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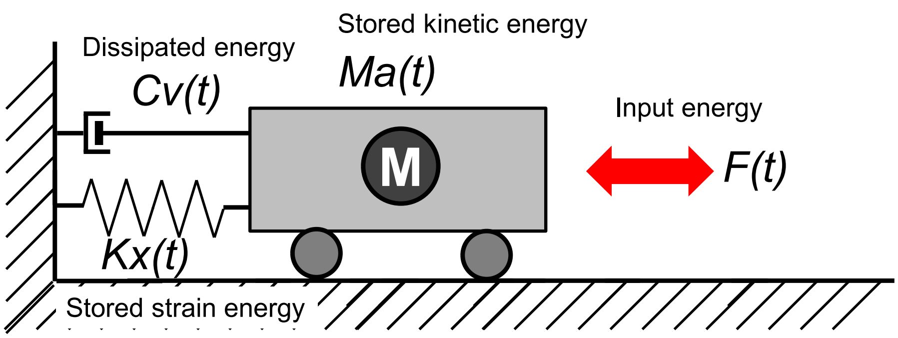
Forces



$$Ma(t)+Cv(t)+Kx(t) = -F(t)$$

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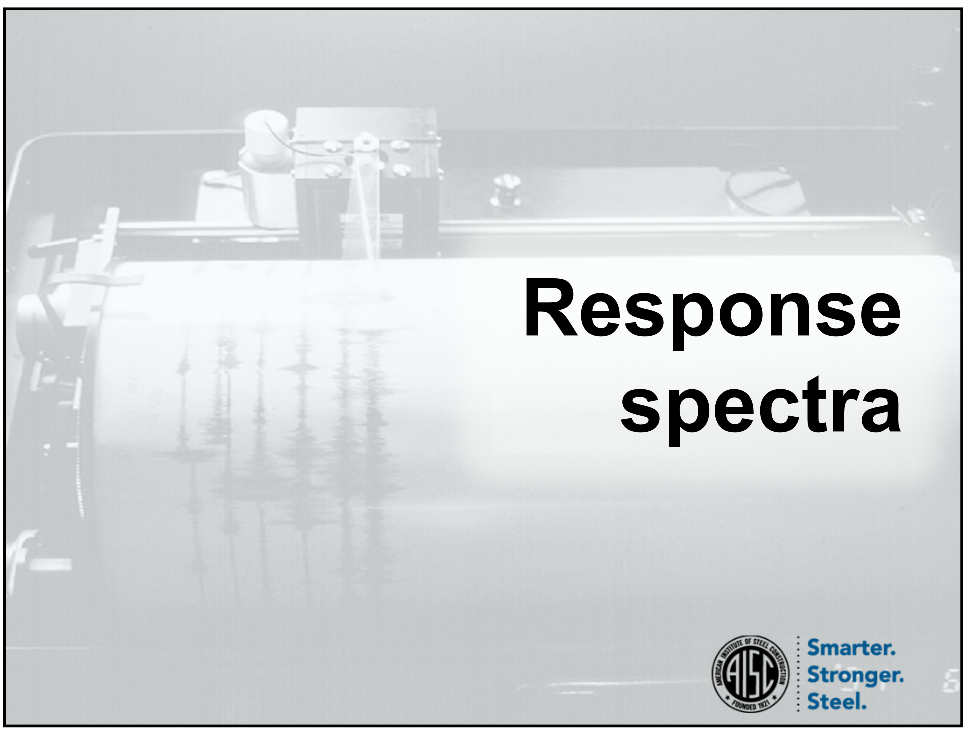

Response spectra

- Response history
- Period-dependent response

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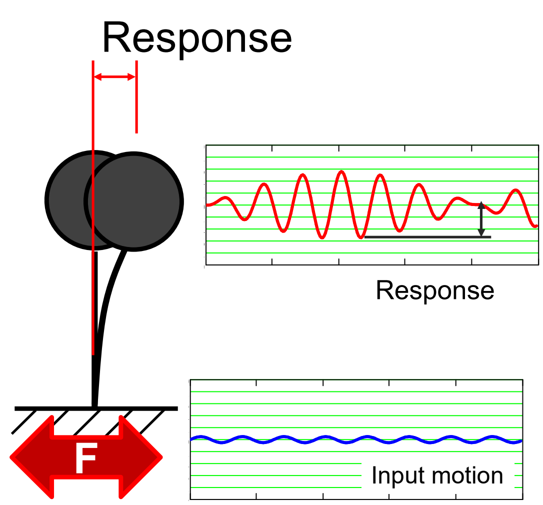
Response history

“Response” may be
Displacement
Acceleration
Velocity
Any quantity of interest



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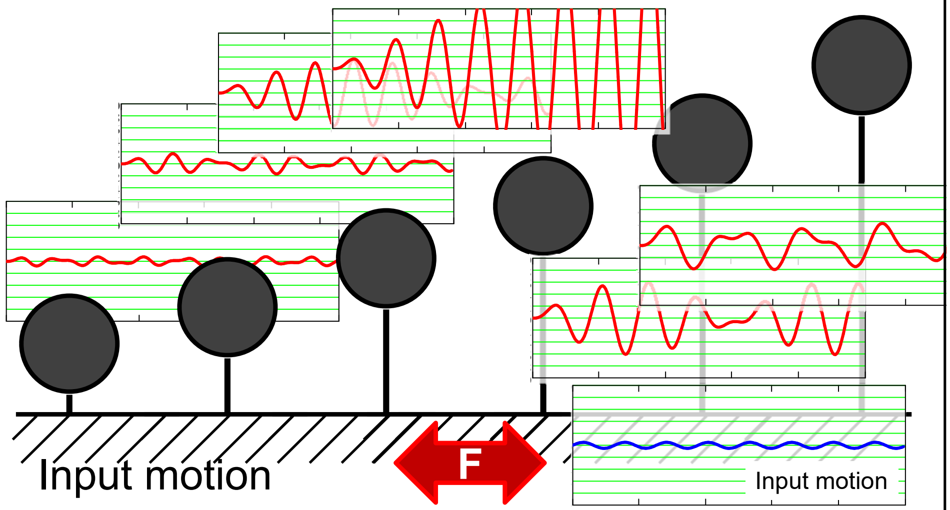
Period-dependent response



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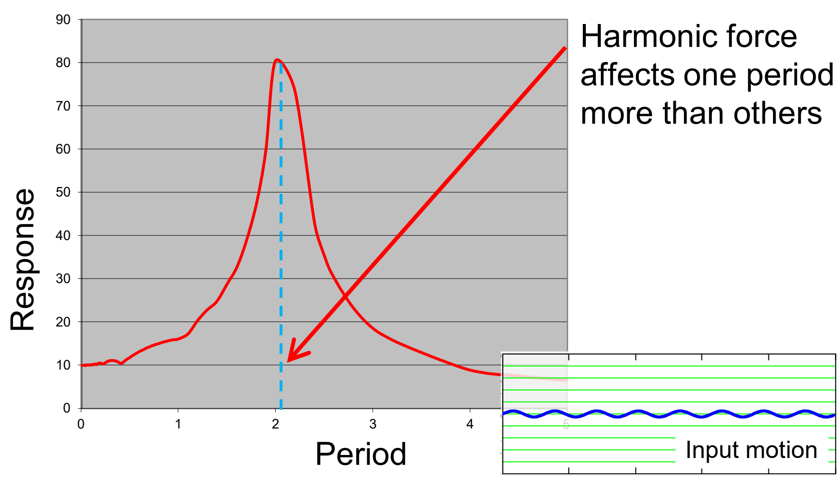
Response spectrum



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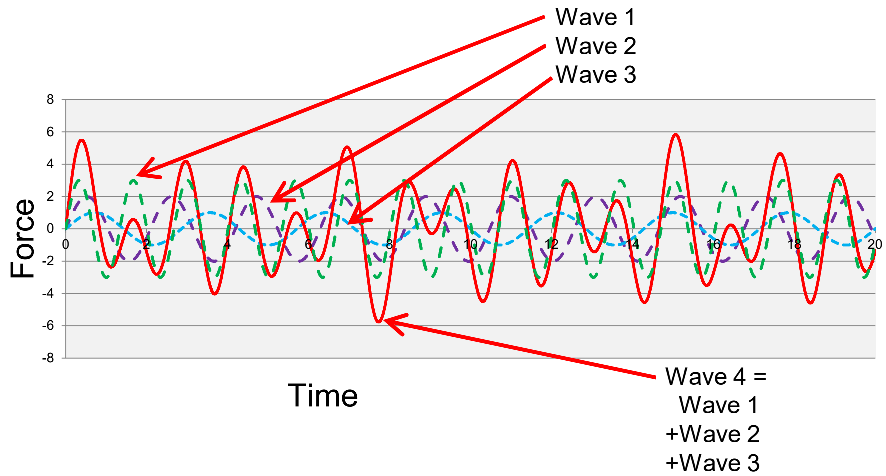
Multi-harmonic input



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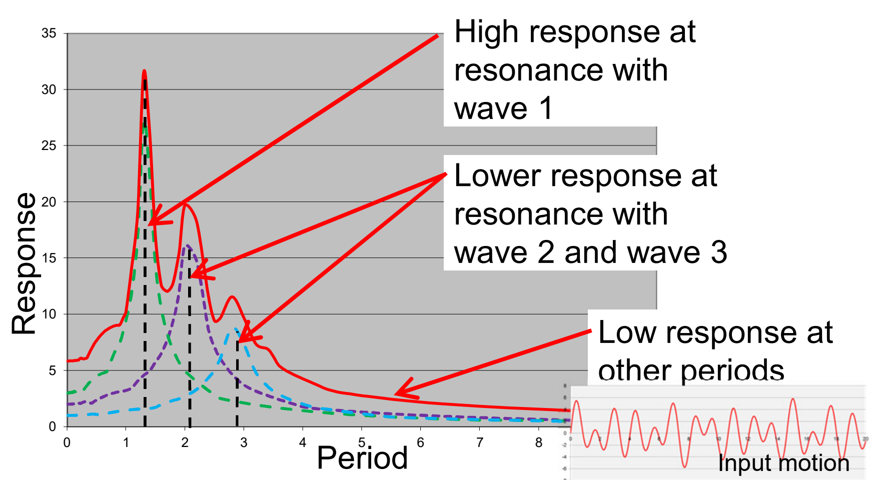
Multi-harmonic response



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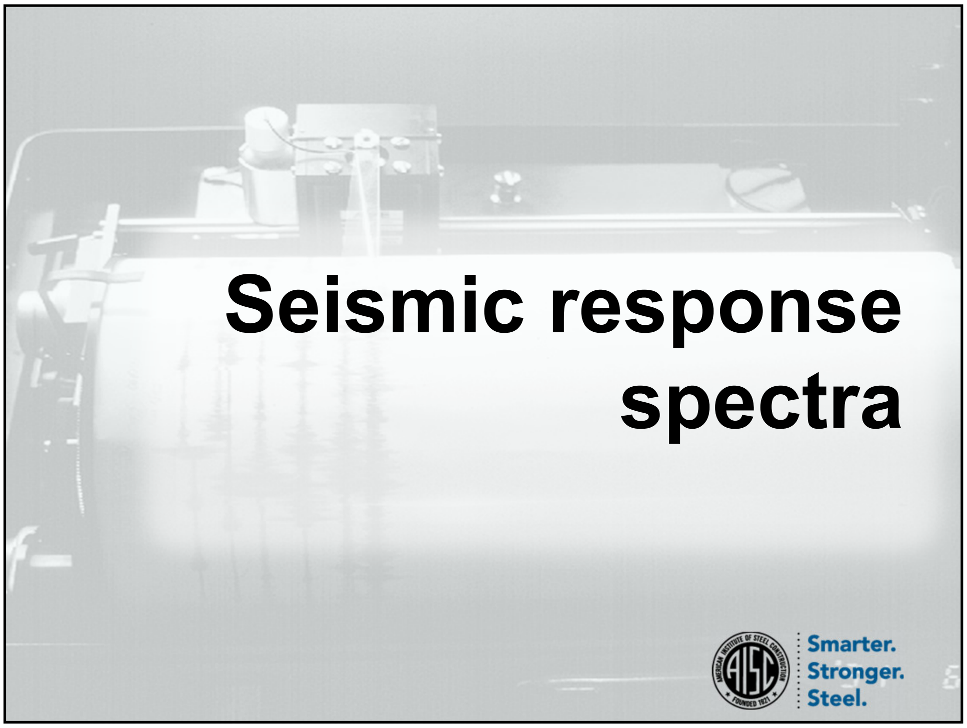

Seismic response spectra

- Earthquake response spectrum
- General seismic response spectrum
- Spectrum types
- Tripartite spectrum

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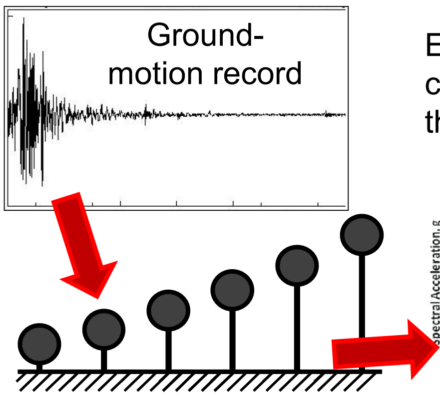
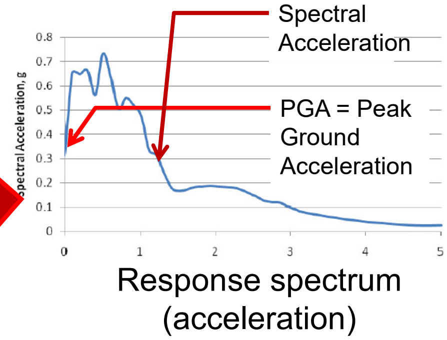
Seismic response spectrum



Earthquake spectra can be characterized by how much they excite different periods



Acceleration response spectra are used in design

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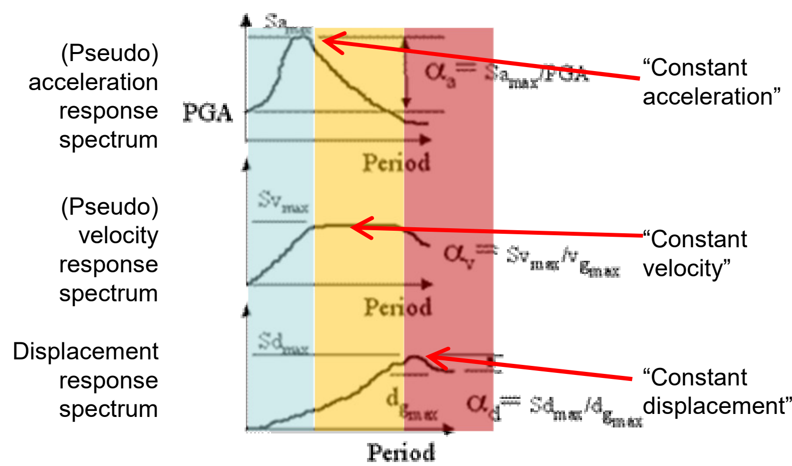
Acceleration, velocity, and displacement spectra



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Acceleration, velocity, and displacement spectra

- *Spectral* displacement
  - Displacement of a damped harmonic isolator
    - One period on the displacement response spectrum
  - S_d

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Acceleration, velocity, and displacement spectra

- Pseudo acceleration
  - Units of acceleration
  - Derived from displacement
    - $PS_a = \omega^2 S_d$
    - Acceleration that results in displacement S_d
      - $M^*PS_a / K = S_d$
  - Good match to spectral acceleration
    - $PS_a \sim S_a$
    - $PS_a < S_a$ if high damping

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Acceleration, velocity, and displacement spectra

- Pseudo-velocity
  - Units of velocity
  - Derived from displacement
    - $PS_v = \omega S_d$
  - Reasonable match for spectral velocity
    - $PS_v \sim S_v$

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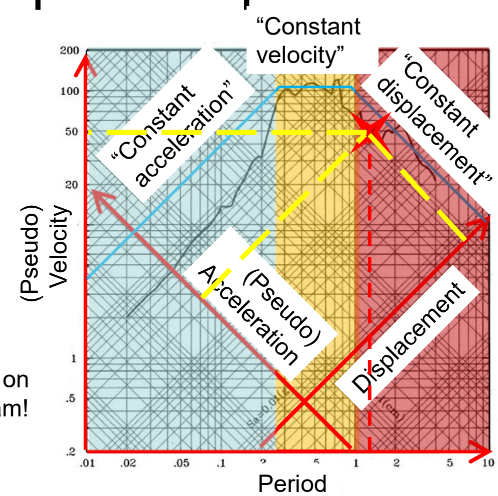
Tripartite spectrum



This is not on the exam!

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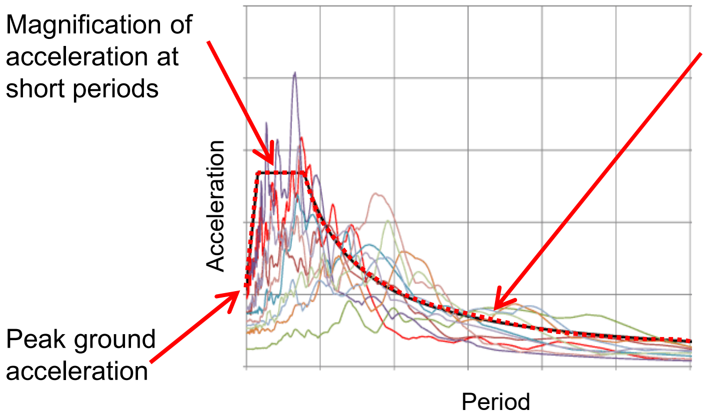
Generalized acceleration response spectrum



Earthquake records often share certain characteristics

Generalized acceleration response spectra are used in design

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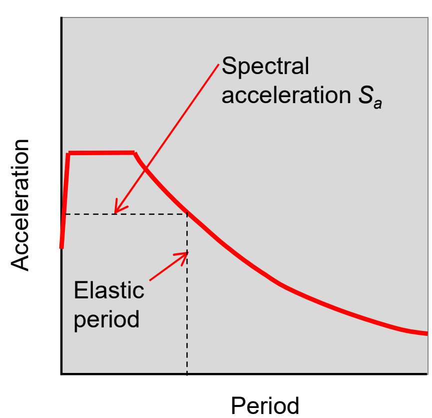
Elastic response spectrum



$F= M^*S_a$

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Inelastic response

- Concept
- Types of nonlinear behavior
- Effective stiffness and period
- Energy dissipation
- Damping

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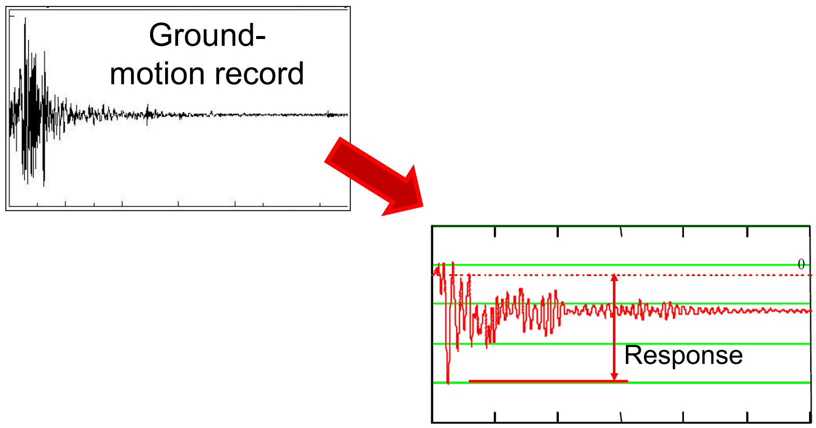
Inelastic response



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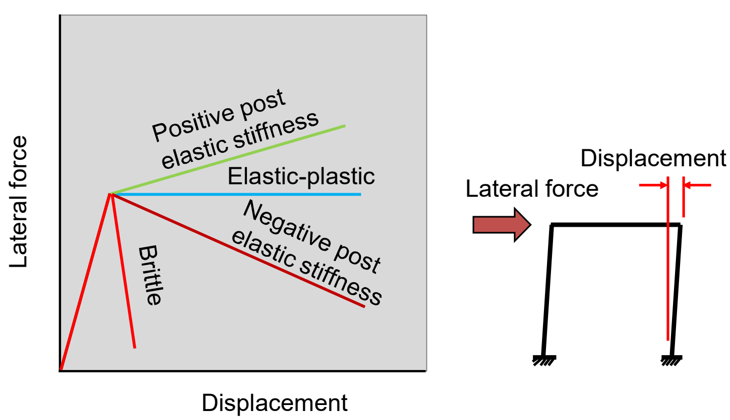
Types of nonlinear behavior



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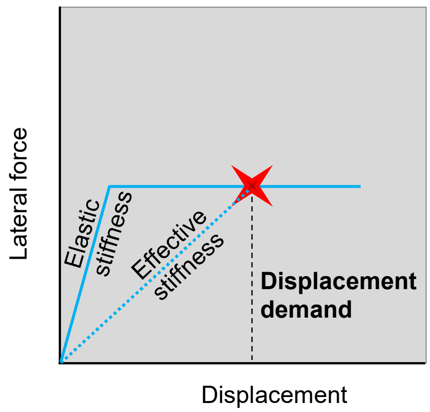
Effective stiffness



$$T = 2\pi \sqrt{M/K}$$

natural period of vibration

Increasing displacement
→Decreasing effective stiffness
→ Increasing effective period

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Effective stiffness

- "Effective stiffness" and "effective period"
  - Concepts presented to aid understanding
    - Effect of inelasticity
    - Reduction of response
  - Not reflected in elastic response spectra
  - Not typically used in design!

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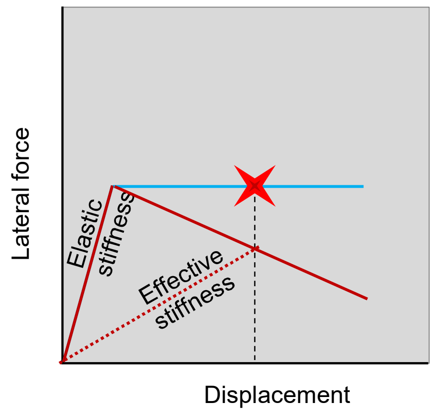
Effective stiffness



$$T = 2\pi \sqrt{M/K}$$

natural period of vibration

Increasing displacement →Decreasing effective stiffness → Increasing effective period

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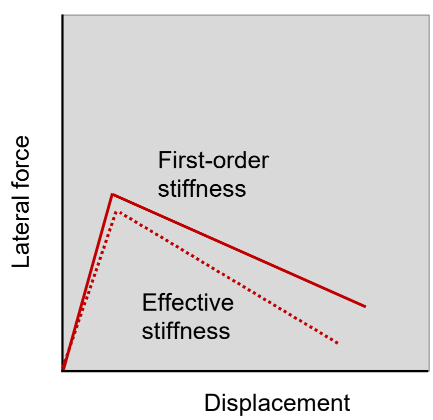
P-Δ effect



$$T = 2\pi \sqrt{M/K}$$

natural period of vibration

P-Δ effect further reduces stiffness.

Positive post-yield stiffness can offset P-Δ effect

Codes limit the flexibility of structures to limit the P-Δ effect

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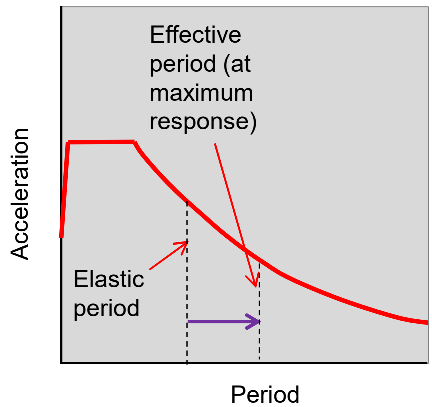
Effective period

Response reduction due to period shift permits use of reduced design forces



Inelasticity increases period

Increased period reduces acceleration response

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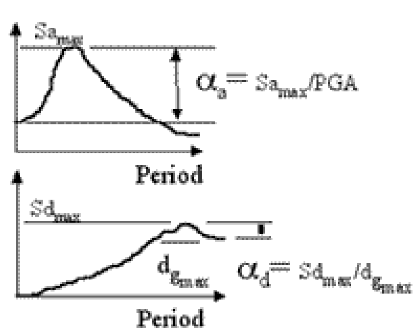
Period elongation

- Inelasticity increases period
    - Increased period reduces acceleration response
    - Increased period increases displacement response



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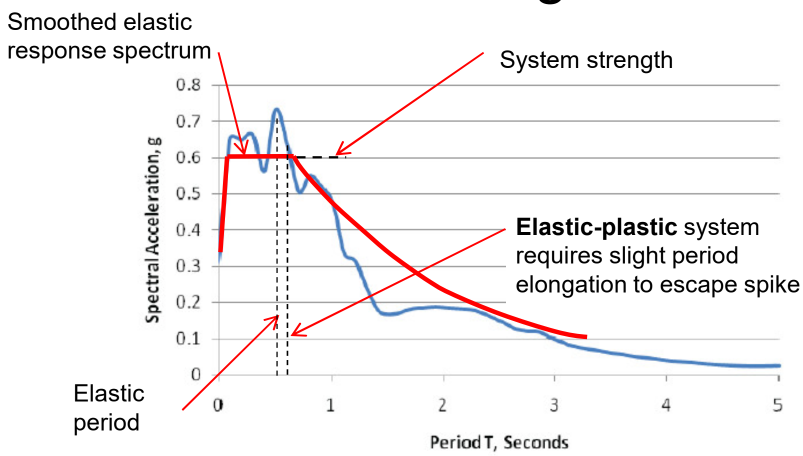
Period elongation



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Reduced design spectrum

- Elastic response spectrum
  - Accelerations corresponding to elastic response spectrum
  - Uneconomical design
- Inelastic response
  - Accelerations corresponding to *reduced* elastic response spectrum
  - Implicitly allows for structural damage

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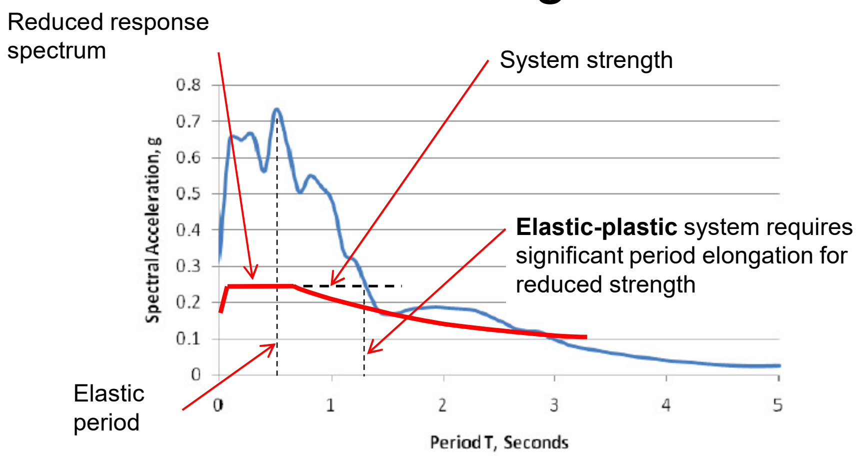
Period elongation



Codes use a reduced elastic response spectrum to approximate the effects of period elongation and energy absorption

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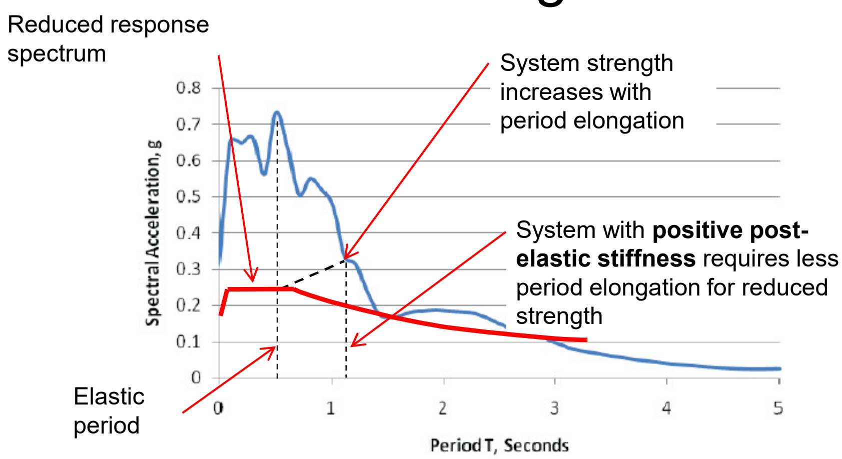
Period elongation



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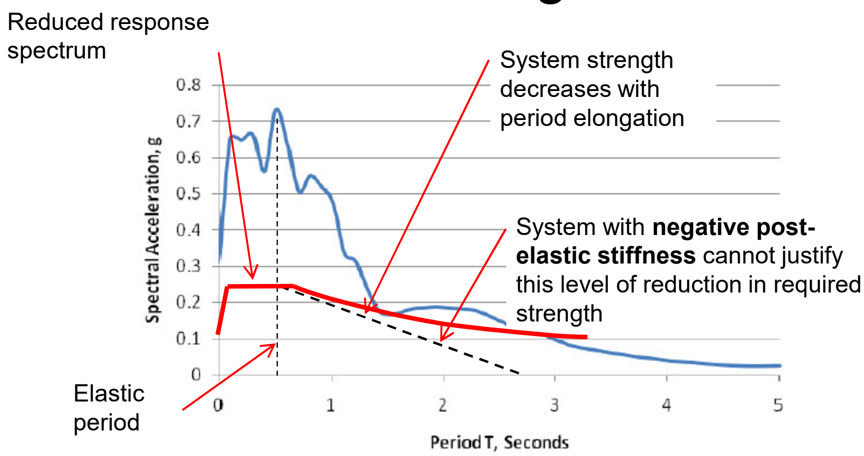
Period elongation



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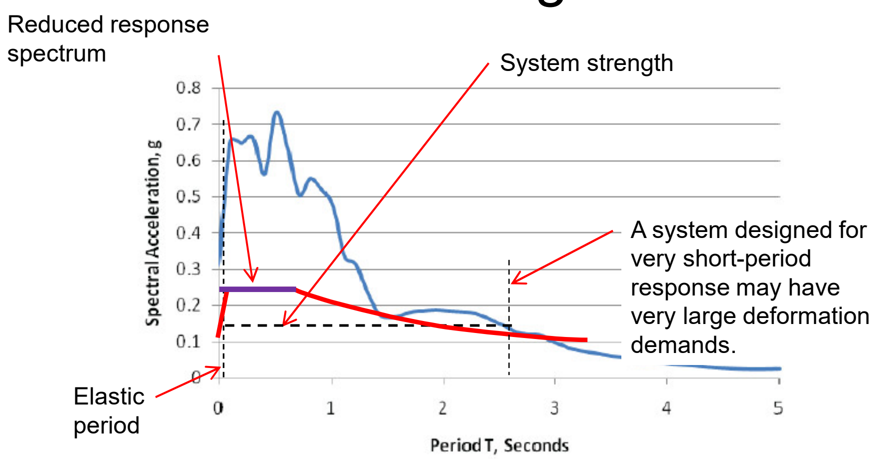
Period elongation



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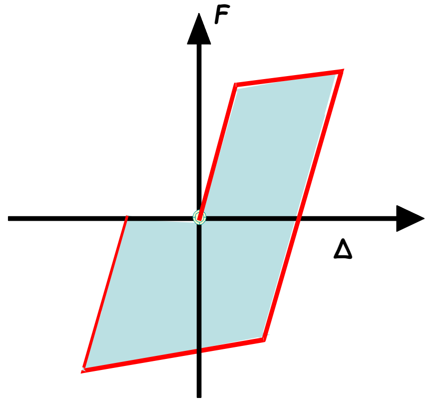
Energy dissipation



The area under the curve corresponds to energy dissipated.

This is treated as damping in the equation of motion.

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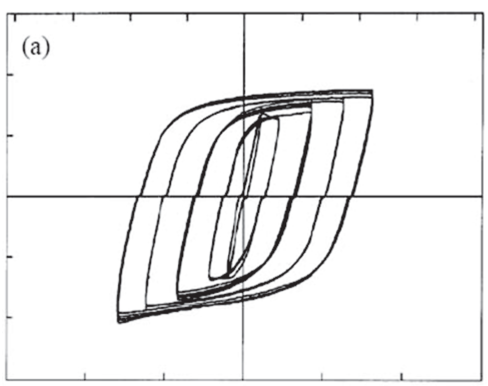
Types of hysteretic behavior



"Full hysteresis"

Energy dissipated is a function of inelastic displacement and force.

Each inelastic cycle dissipates energy.

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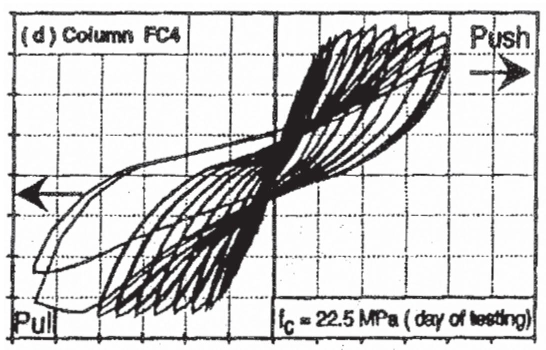
Types of hysteretic behavior



"Pinched hysteresis"

Energy dissipated is a function of hysteresis shape.

Pinched loops contain less area; less energy is dissipated.

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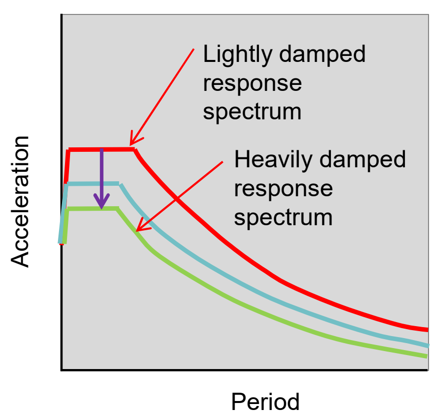
Damping and response

Response reduction due to damping permits use of reduced design forces



Inelasticity increases damping

Increased damping reduces response

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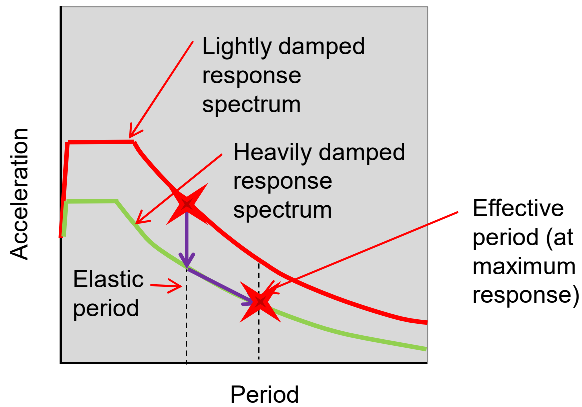
Reduced response



Response reduction due to damping and period shift permit use of reduced design forces (*R* factor)

Codes use a reduced elastic response spectrum to approximate the effects of period elongation and energy absorption

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Reduced design spectrum

- Reduced elastic response spectrum
  - ○ Degree of reduction depends on system characteristics
    - Ductility
      - ○ Displacement capacity
    - Post-elastic stiffness
    - Hysteretic damping
    - Cyclic degradation
  - ○ Approximates inelastic response spectrum
    - Time-history response of inelastic oscillators

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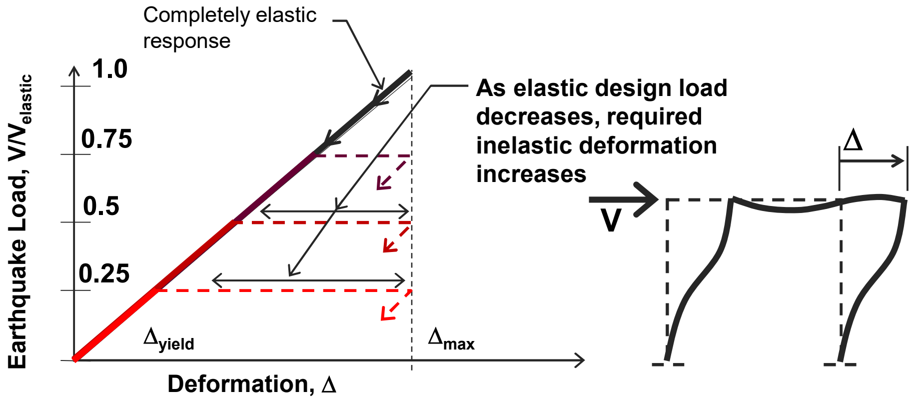
Inelastic response

- As required elastic strength goes down (i.e. larger *R*-factor) required inelastic deformation increases



Codes use a response reduction factor to represent the degree of ductility that can be tolerated

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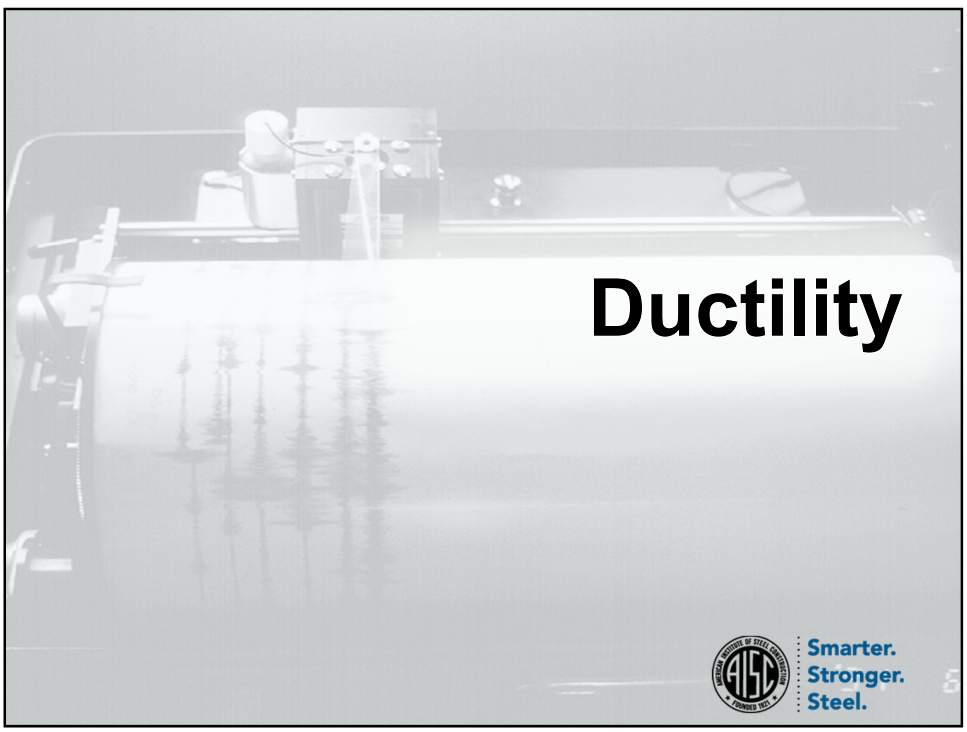

Ductility

Ductility

- Definition
  - Capacity and demand
- Force reduction
- Inelastic response spectra

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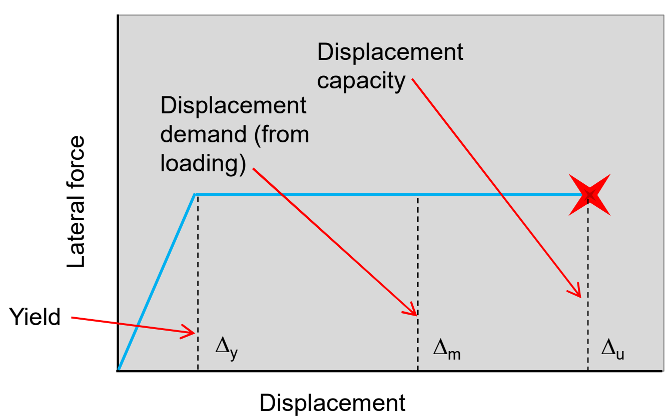
Ductility



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Ductility

- Demand
  - $\mu = \Delta_m / \Delta_y$
  - Describes the inelastic deformation demand relative to elastic limit
- Capacity
  - $\mu = \Delta_u / \Delta_y$
  - Describes the inelastic deformation capacity relative to elastic limit
- Both concepts employed in this course

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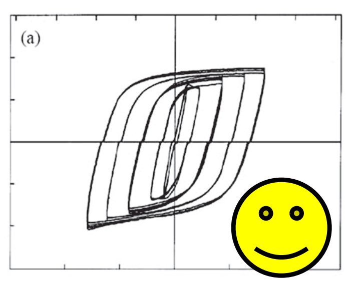
Ductility

- That building experienced a lot of ductility (demand)

- That specimen exhibited a lot of ductility (capacity)



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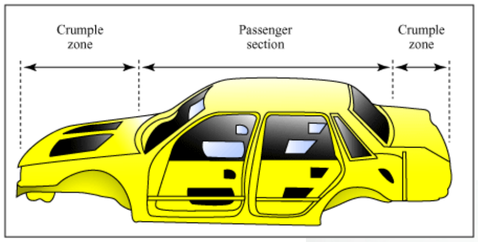
Ductility



Good to have it

Bad to use it

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Force reduction

- $V \; = C_y W$ design base shear
- $C_y = C_e / R_\mu$
  - $C_y W$ = reduced required lateral strength
  - $C_e W$ = required strength of elastic system
  - R_μ = reduction factor due to ductility

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Force reduction

- Constant displacement region
  - R_μ = μ (ductility capacity)
- Constant velocity region
  - R_μ = μ
- Constant acceleration region
  - It's complicated.
  - $R_\mu = \sqrt{2\mu - 1}$
  - Lower at very short periods

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Force reduction

- The designer selects the building strength
  - Based on earthquake demand
    - To match ductility demand and ductility capacity
- Ground motion may occur
  - May not match design assumptions
  - Maximum building forces (primarily) due to building strength
  - Ductility demands due to earthquake intensity and building strength (overload)

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Force reduction

- Elastic structures
  - Earthquake variability
    - Uncertainty in force demand
- Inelastic structures
  - Earthquake variability
    - Uncertainty in ductility demand

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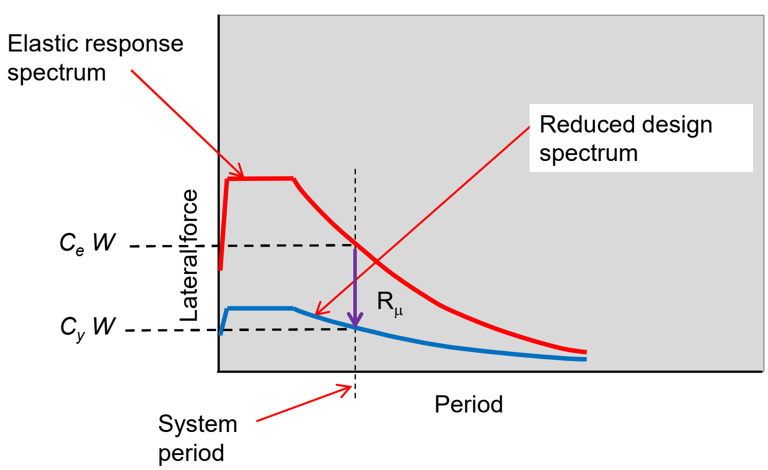
Inelastic response spectrum



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"Equal displacement rule"

- Applies to long period
  - "Constant displacement" region
  - "Constant velocity" region
- Same displacement for all structures of the same elastic stiffness regardless of ductility

$$\Delta = C_e W/K$$

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"Equal displacement rule"

- Elastic system

  $\Delta = C_e W/K$
- Inelastic system

  $\Delta = C_D[C_y W/K]$

  $C_D =$ Displacement amplification factor

  $= R_\mu$
- Short period:

  $\Delta > C_e W/K$ (equal displacement does not apply)

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Summary

- Response to excitation depends on
  - Mass
  - Stiffness
  - Damping
  - Ductility
- Earthquake load can be expressed as a response spectrum
- Ductility allows lower design strength

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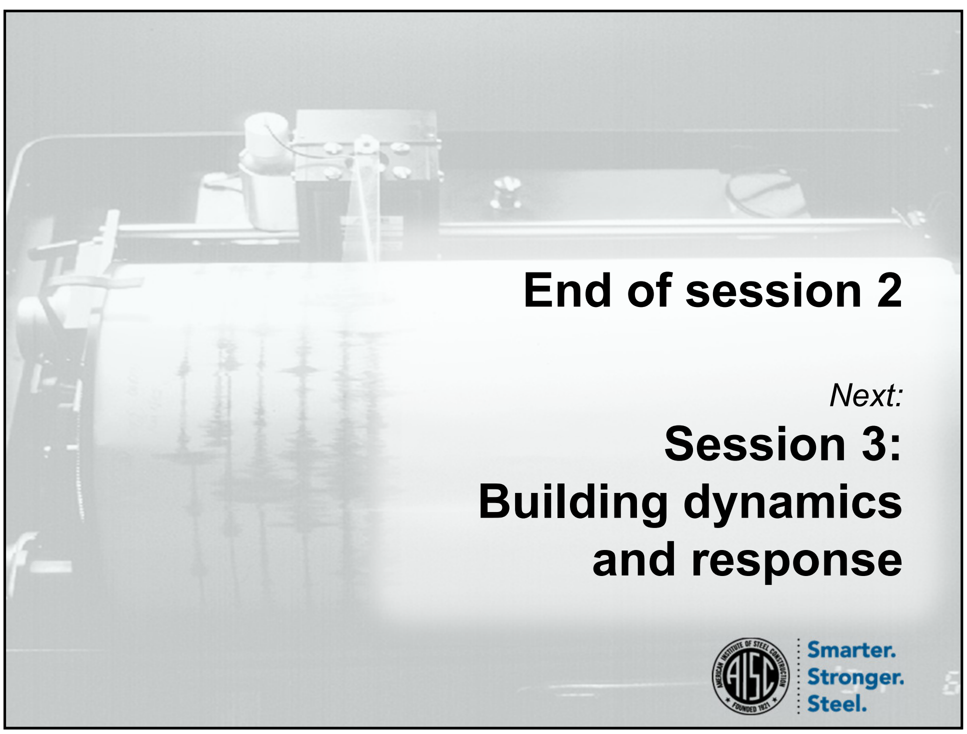
Parting thought
How do real structures compare to the idealized single-degree-of-freedom oscillator?
Smarter.
Stronger.
Steel.


End of session 2
Next:
Session 3:
Building dynamics and response
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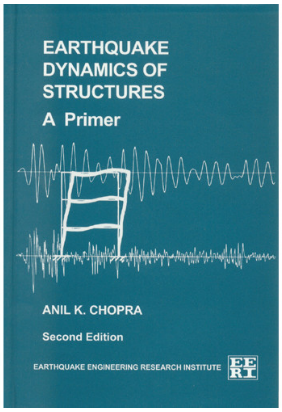
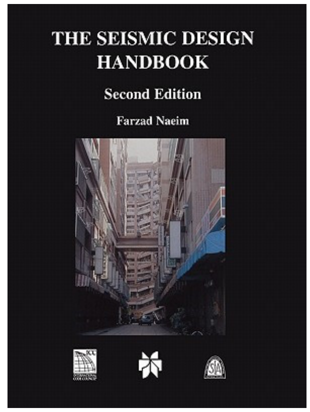
Additional resources





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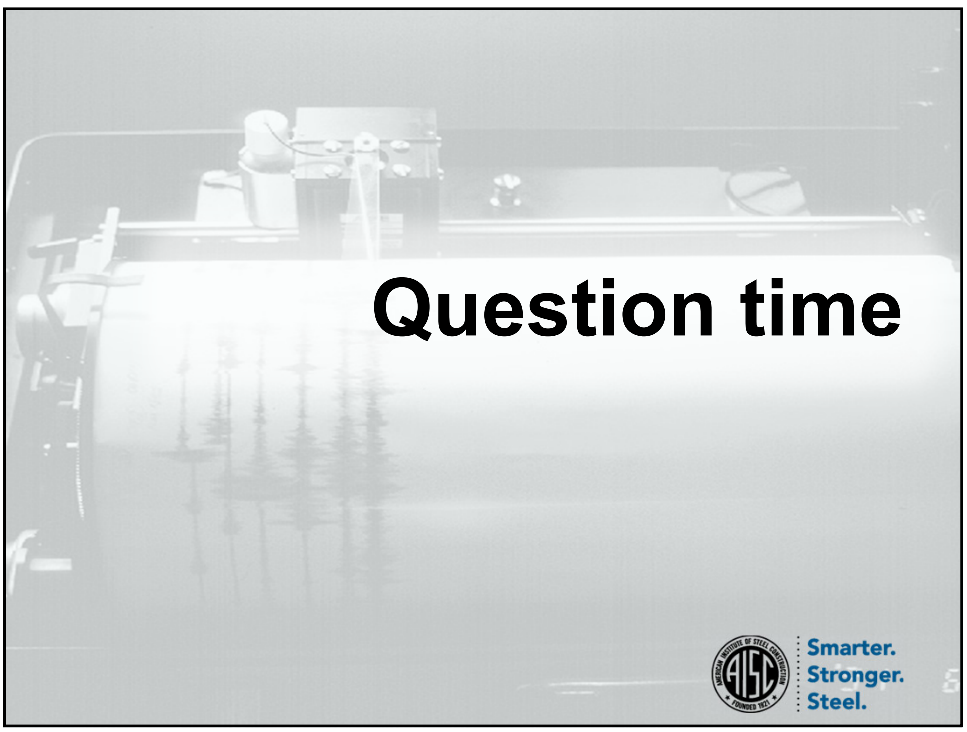
Question time



Single-Session Registrants

CEU / PDH Certificates

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

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8-Session Registrants

CEU / PDH Certificates

One certificate will be issued at the conclusion of the course.

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8-Session Registrants

CEU / PDH Certificates

One certificate will be issued at the conclusion of the course.

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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!

Distribution of Certificates

All certificates will be issued after the course is completed. Only the registrant will receive a certificate for the course.

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8-Session Registrants

Course Resources

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

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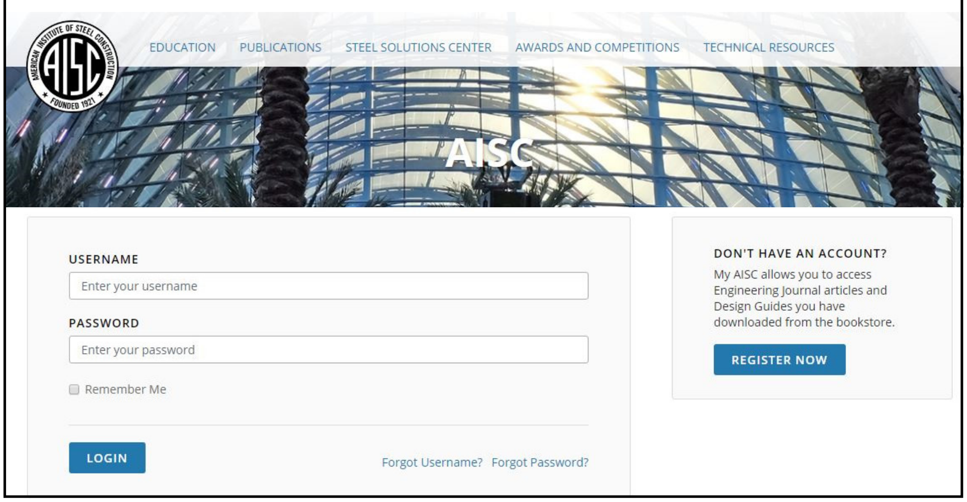
8-Session Registrants

Course Resources

Go to www.aisc.org and sign in.



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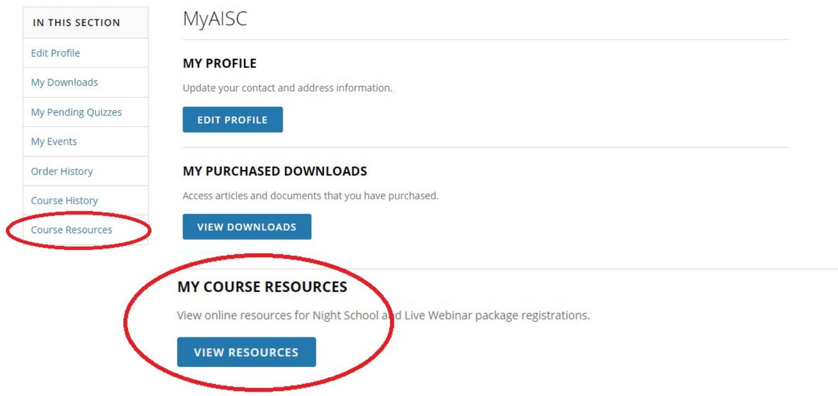
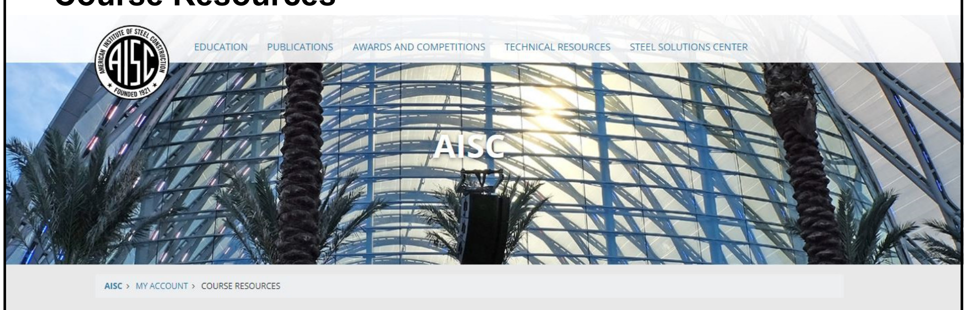
Course Resources

Go to www.aisc.org and sign in.



8-Session Registrants

Course Resources



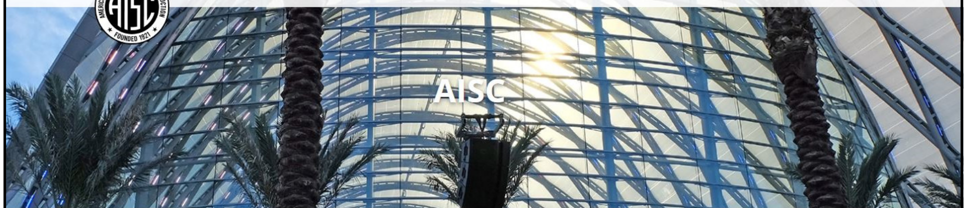
Course Resources

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

EDUCATION PUBLICATIONS AWARDS AND COMPETITIONS TECHNICAL RESOURCES STEEL SOLUTIONS CENTER



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	

AISC | Thank you.

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