


AISC Night School


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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


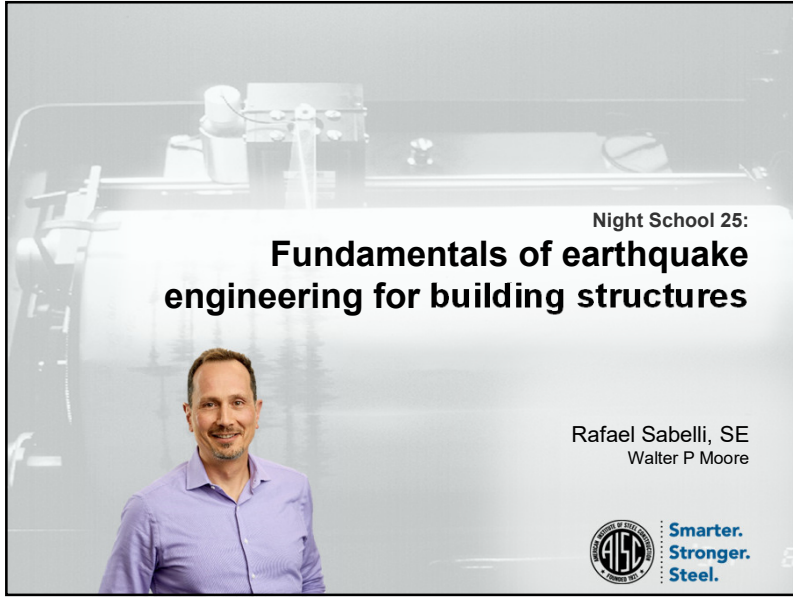
February 22, 2021

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.


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



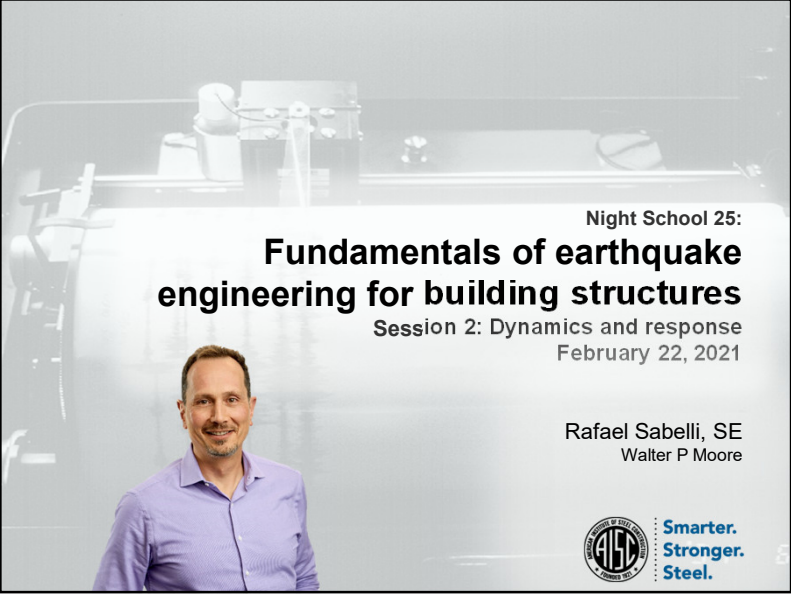
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Course outline

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




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Night School 25:
Fundamentals of earthquake engineering for building structures
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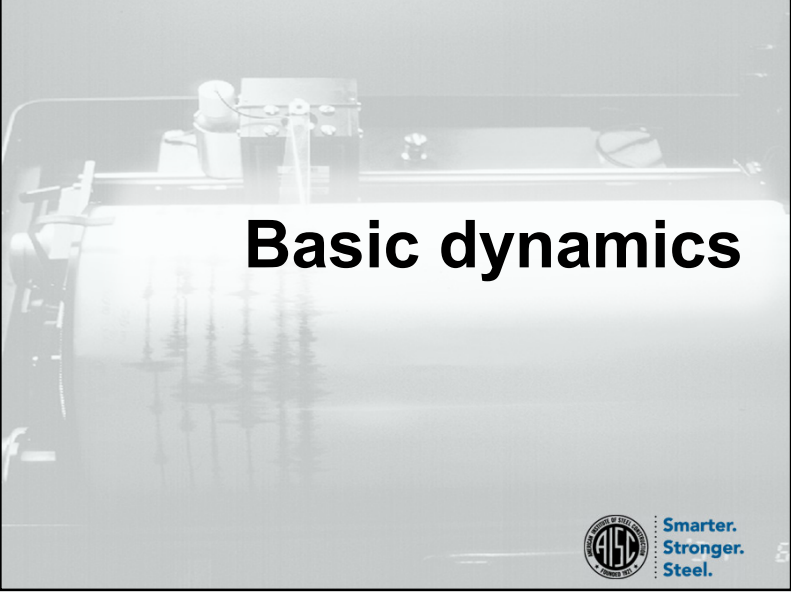
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Session topics


- 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



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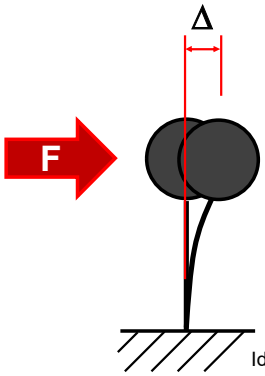
Basic dynamics

- 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
 $\Delta =$ 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

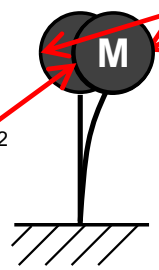

Imposed displacement = Δ
 Release at $t=0$

$E_e = \frac{1}{2}K\Delta^2$

Elastic stored energy

$E_k = \frac{1}{2}Mv^2$

Kinetic energy

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$E = E_e + E_k$

$E_e = \frac{1}{2} K[x(t)]^2$

Elastic strain energy

$E_k = \frac{1}{2} M[v(t)]^2$

Kinetic energy

x = displacement

v = velocity

M = mass = W/g

W = weight

g = acceleration of gravity

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


$E_e = \frac{1}{2} K\Delta^2$

$E_k = 0$

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

$E_k = \frac{1}{2} Mv_{max}^2$


$E_e = 0$



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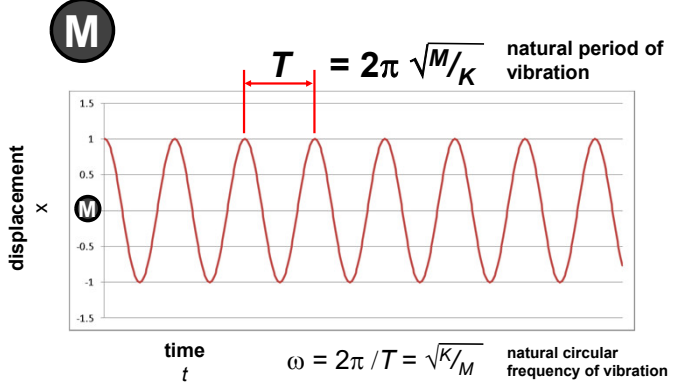
Harmonic motion

x = function of time, t
 v = dx/dt
 Solve differential equation:
 $E_e(t) + E_k(t) = E_e(0)$
 $\frac{1}{2} K x(t)^2 + \frac{1}{2} M (\frac{dx}{dt})^2 = \frac{1}{2} K \Delta^2$
 $x(t) = \Delta \cos[(\frac{K}{M})^{1/2} t]$
 $x = \Delta$ at $t = 0$
 $t = 2\pi (M/K)^{1/2}$
 $t = 4\pi (M/K)^{1/2}$ etc.




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Harmonic motion



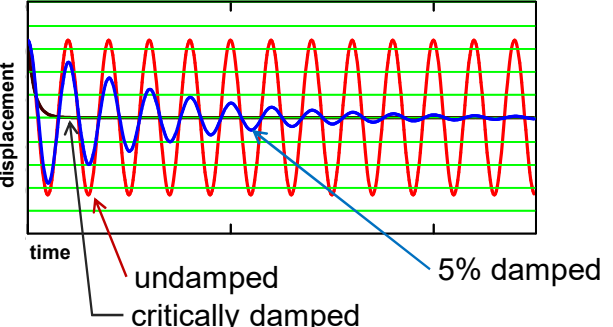
$T = 2\pi \sqrt{M/K}$ natural period of vibration
 $\omega = 2\pi / T = \sqrt{K/M}$ natural circular frequency of vibration

Building period is a fundamental property used in seismic design




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Damping



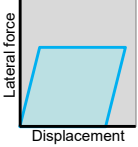

undamped
 critically damped
 5% damped



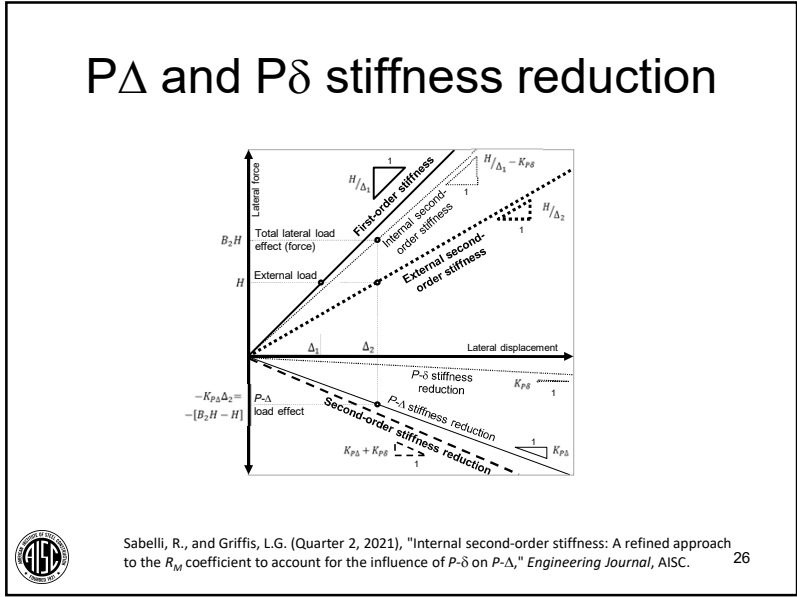
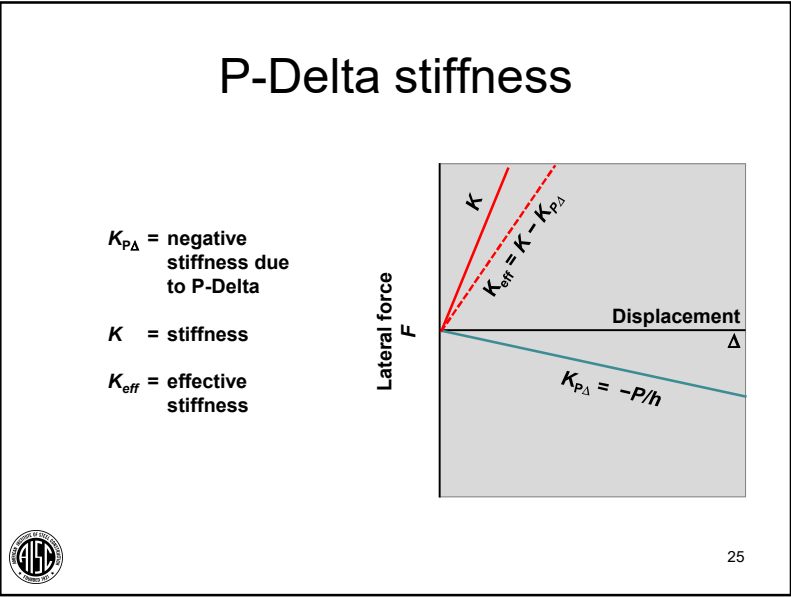
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Damping

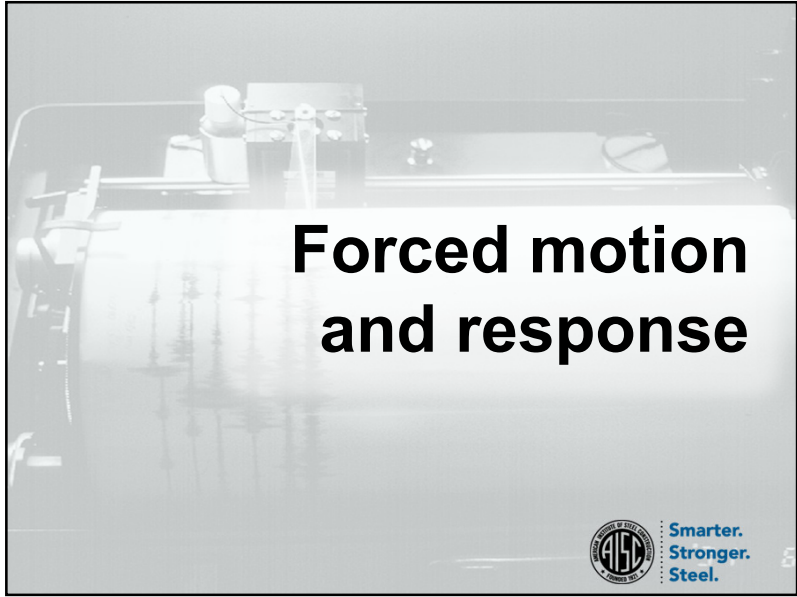
- Friction
 - Structural elements slipping
 - Bolts
 - Nonstructural items sliding, rubbing
- Damage
 - Less energy returned than goes in
 - Non-structural damage
 - Partition cracking
 - Structural damage

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- ### 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

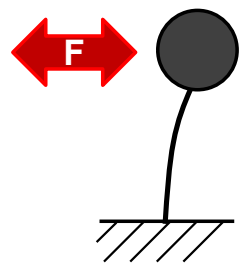


What is *response*?

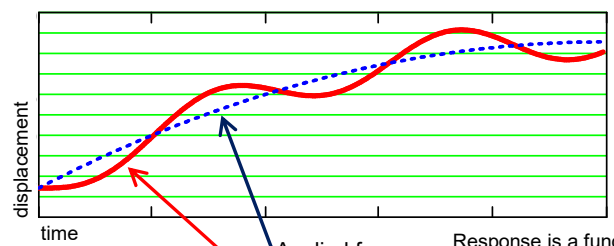
- Any quantity of interest arising from the application of load
 - Displacements
 - Internal Forces
 - Accelerations
 - Velocities
 - etc.



Forced motion



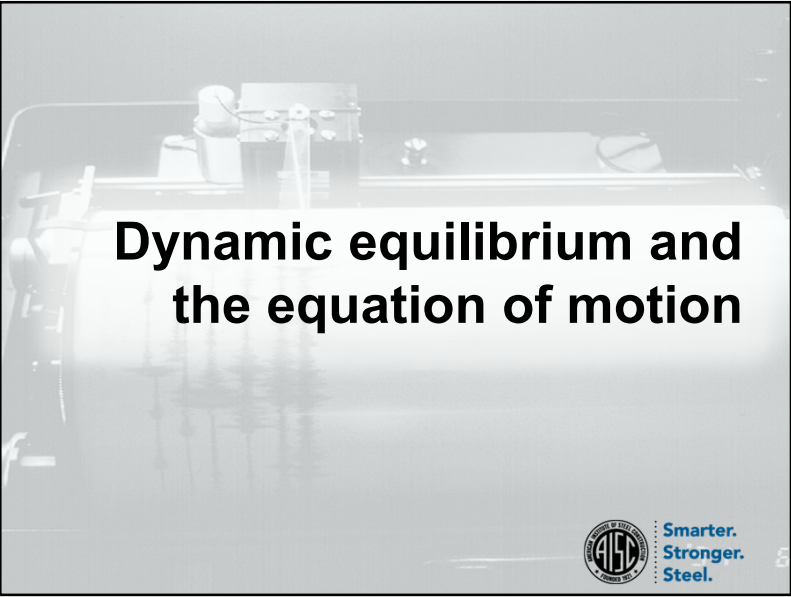
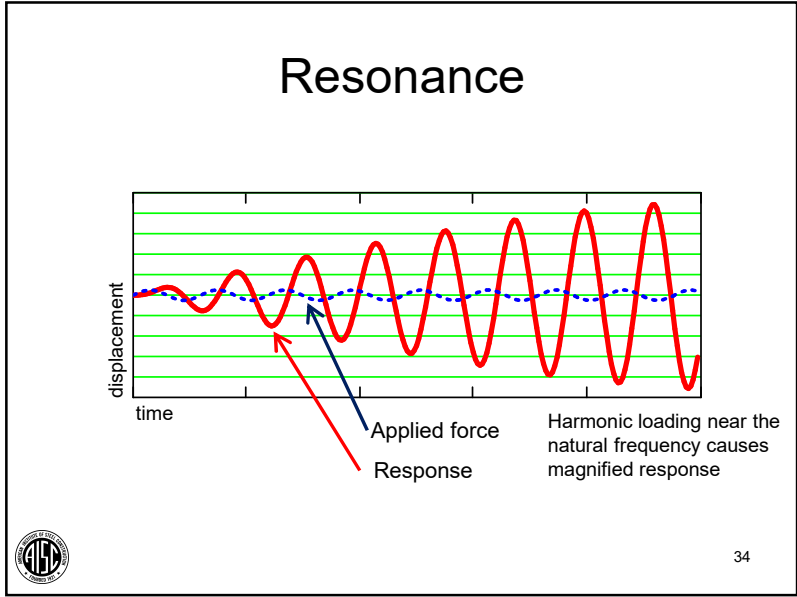
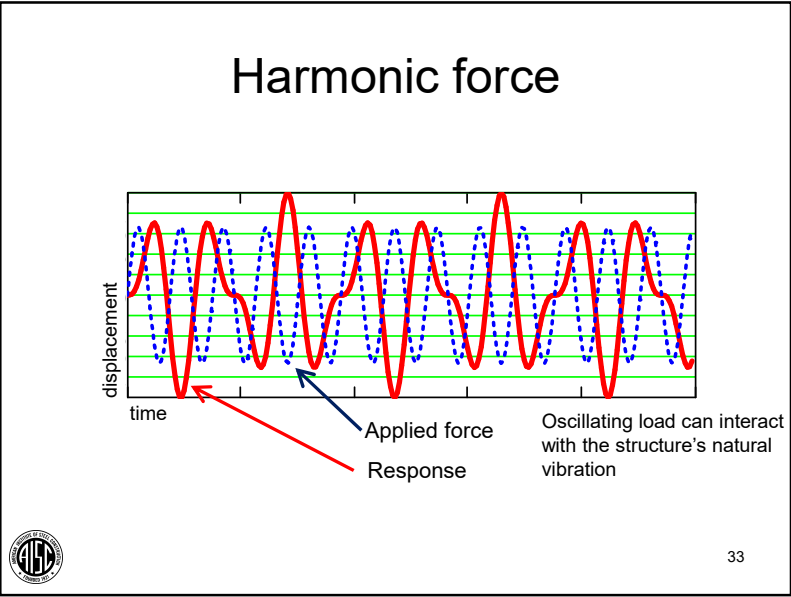
Forced motion




Applied force
Response

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






- ### 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

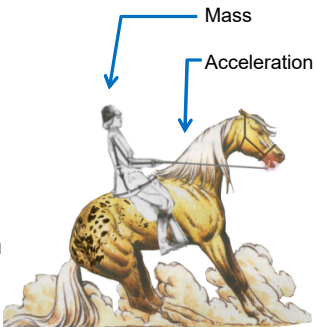

- $Ma(t)+Cv(t)+Kx(t) = - F(t)$
 - M = mass
 - C = damping coefficient
 - K = stiffness
 - t = time
 - $x(t)$ = displacement
 - $v(t)$ = velocity $= dx/dt$
 - $a(t)$ = acceleration $= dv/dt = d^2x/dt^2$
 - $F(t)$ = applied force



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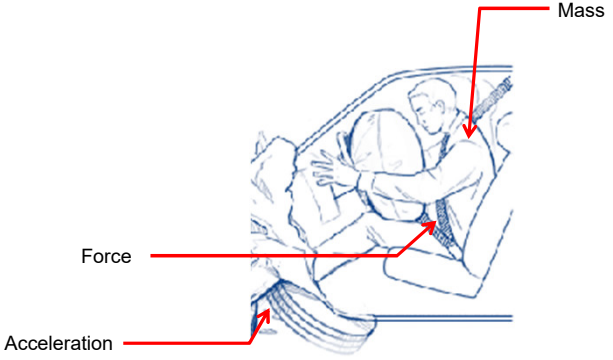

The equation of motion

- C = damping coefficient
 - Critical damping
 - $C_c = [4KM]^{1/2}$
- $F(t)$ = applied force
 - Inertial force
 - $F(t) = Mg(t)$
 - $g(t)$ = ground acceleration history

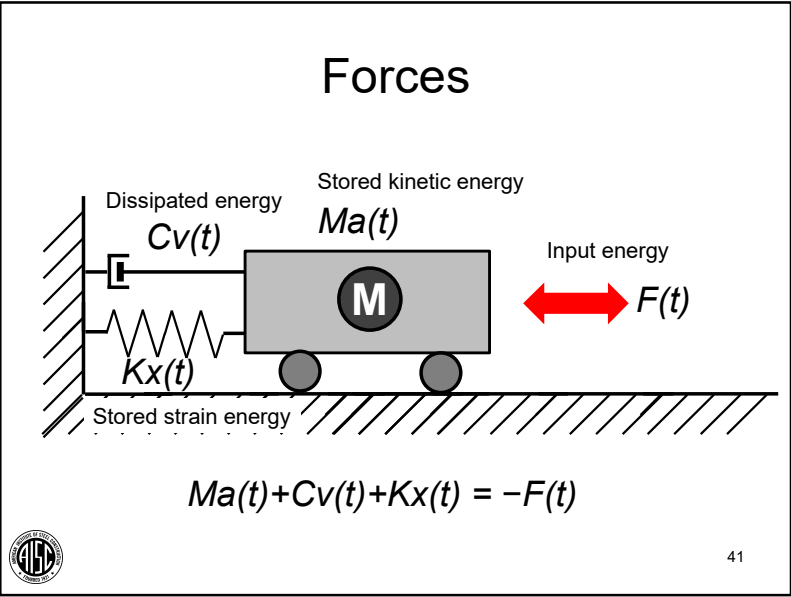



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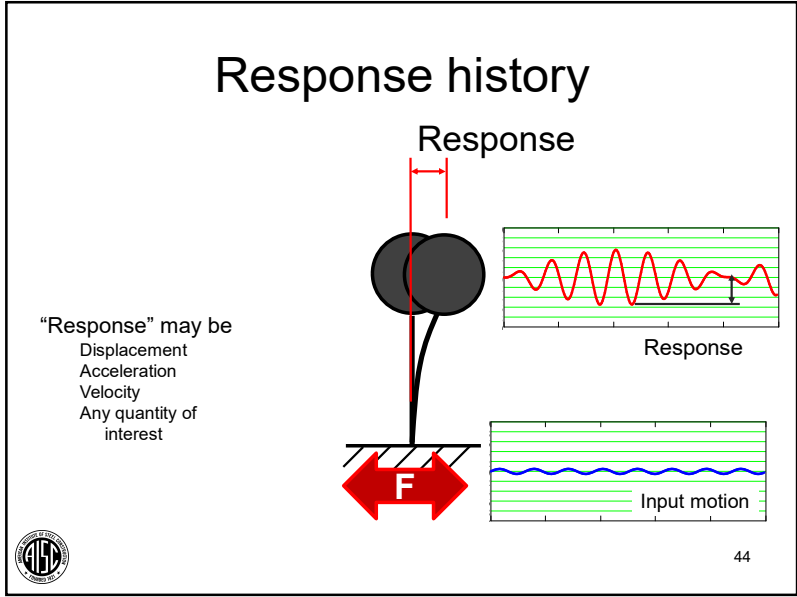
Inertial force

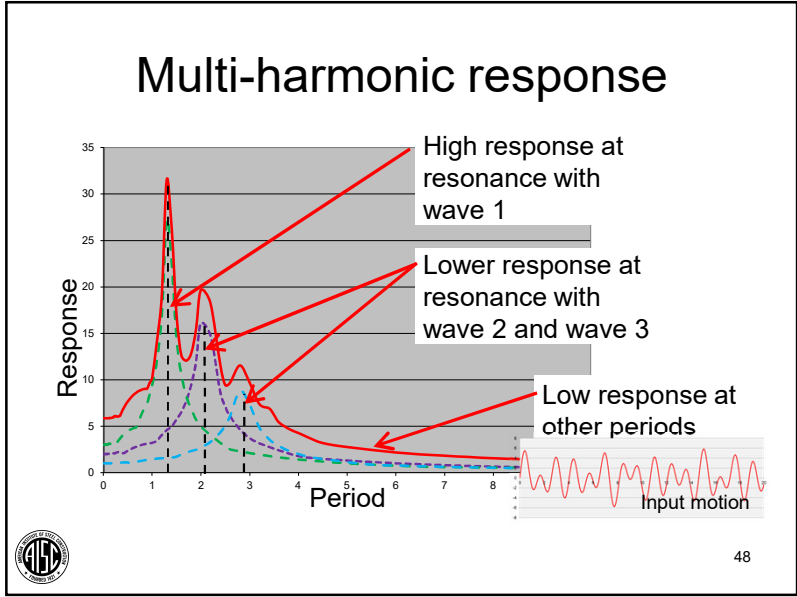
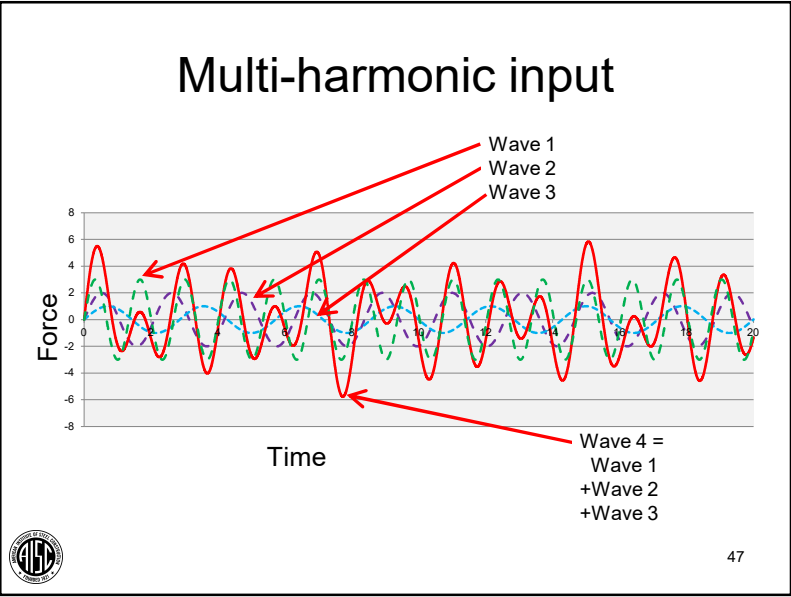
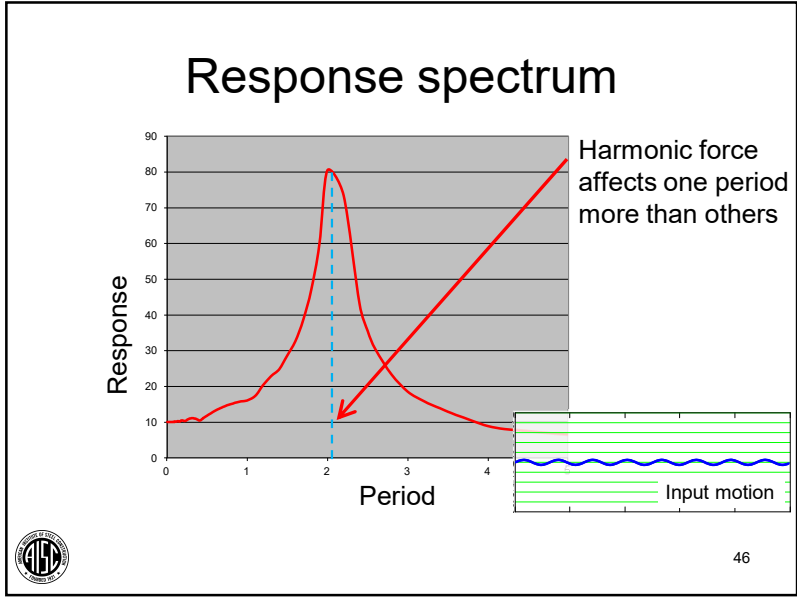
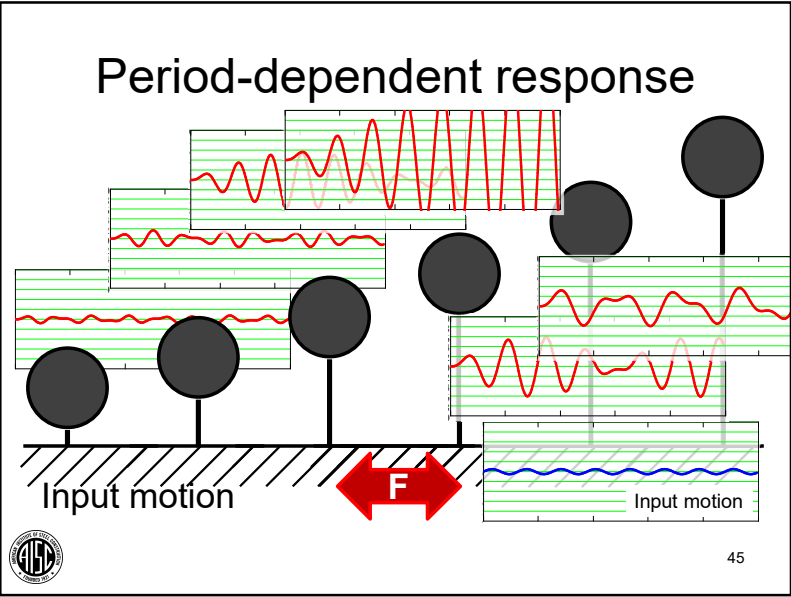



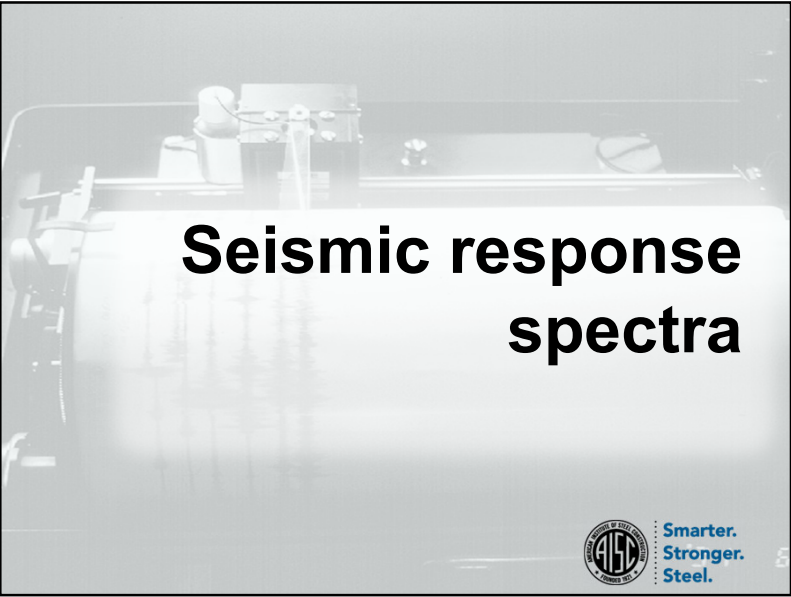
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- ### Response spectra
- Response history
 - Period-dependent response
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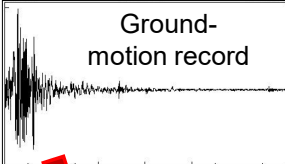


Seismic response spectra

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

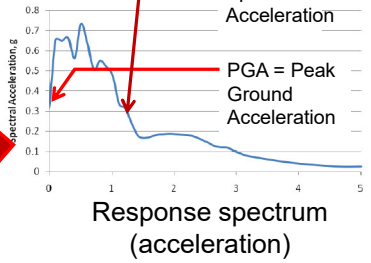

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Seismic response spectrum



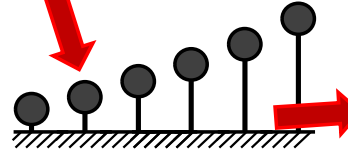
Ground-motion record

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




Spectral Acceleration

Response spectrum (acceleration)



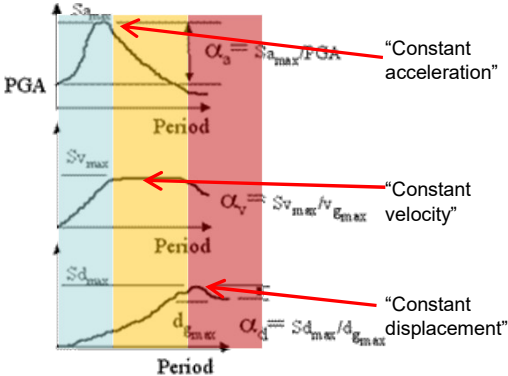
Acceleration response spectra are used in design


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Acceleration, velocity, and displacement spectra

(Pseudo) acceleration response spectrum

PGA



$\alpha_a = S_{a,max} / PGA$ "Constant acceleration"

Period

$\alpha_v = S_{v,max} / v_{g,max}$ "Constant velocity"


Period

$\alpha_d = S_{d,max} / d_{g,max}$ "Constant displacement"

Period


(Pseudo) velocity response spectrum

Displacement response spectrum


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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
 - $M \cdot PS_a / K = S_d$
 - Good match to spectral acceleration
 - $PS_a \sim S_a$
 - $PS_a < S_a$ if high damping



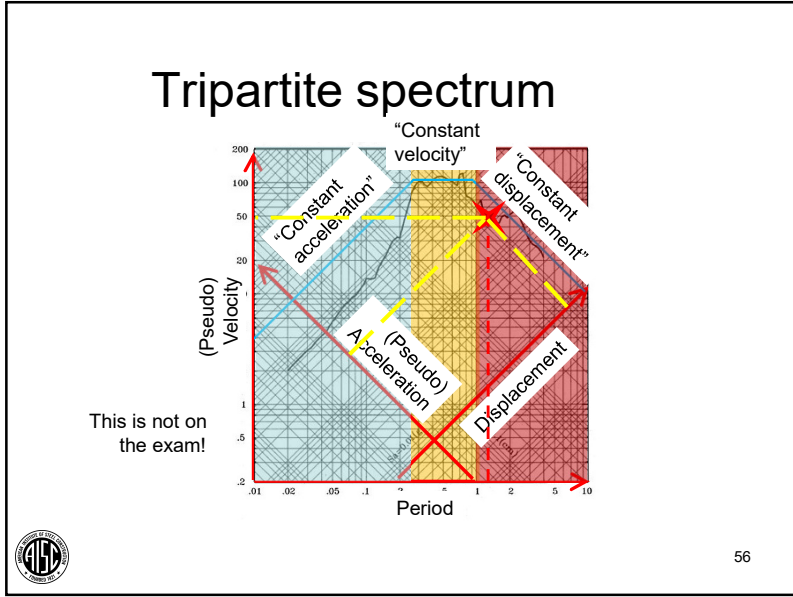
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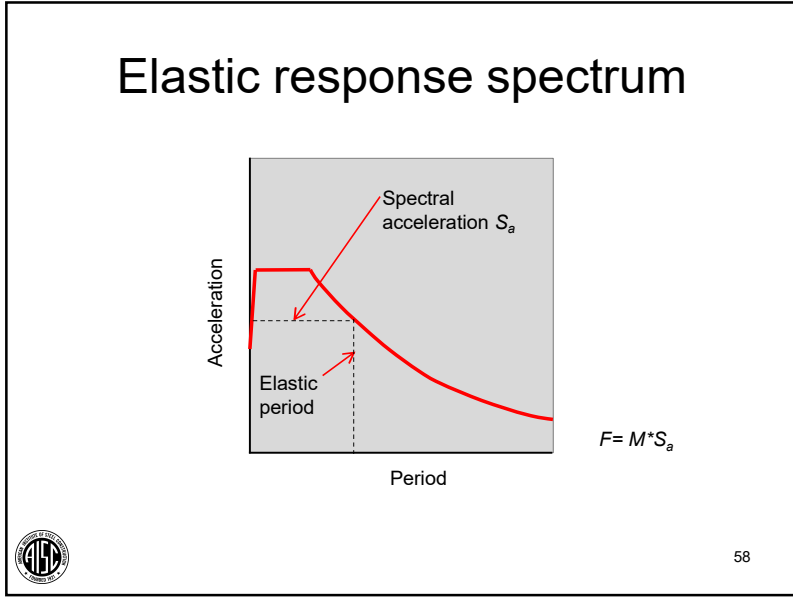
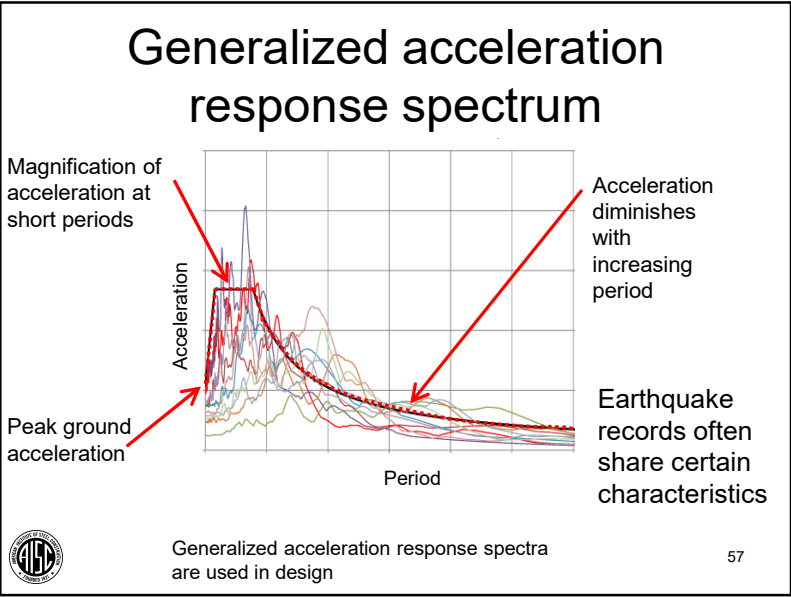
Acceleration, velocity, and displacement spectra

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

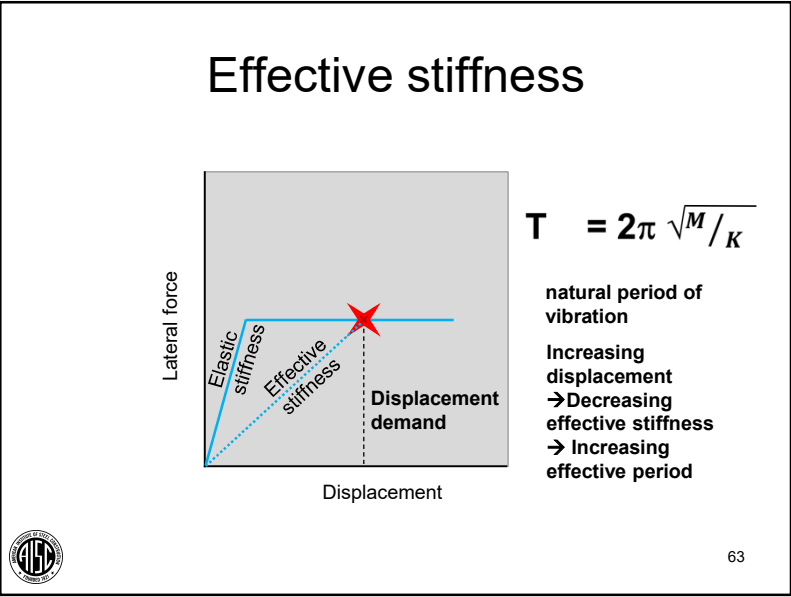
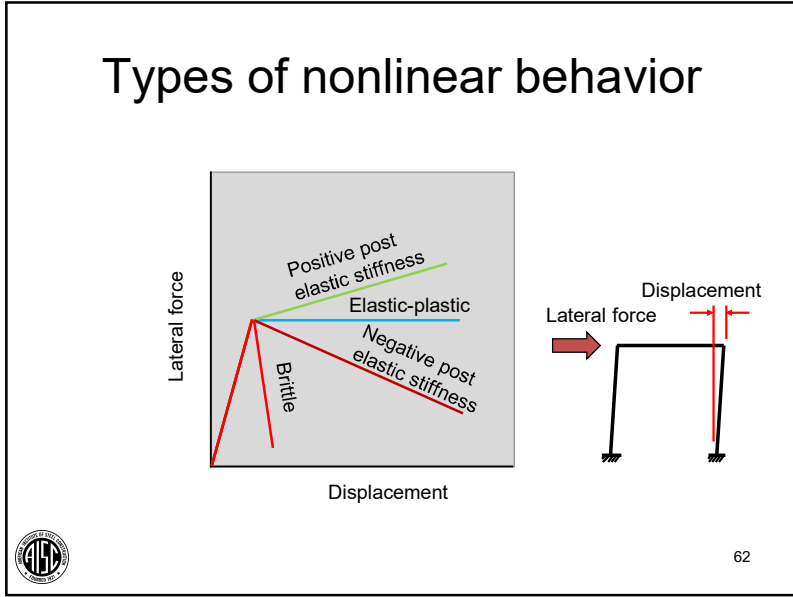
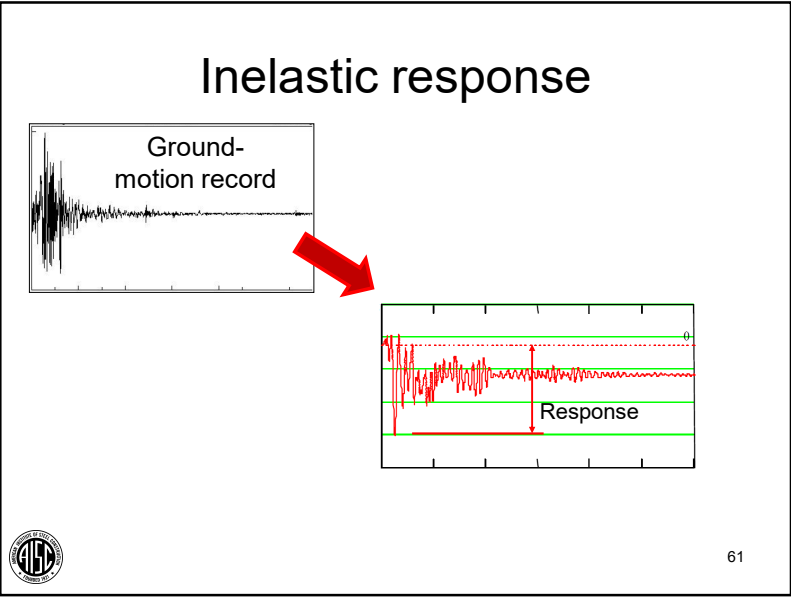


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- ### Inelastic response
- Concept
 - Types of nonlinear behavior
 - Effective stiffness and period
 - Energy dissipation
 - Damping
- 60



- ### 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

Lateral force

Displacement

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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

Lateral force

Displacement

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

Acceleration

Period

Effective period (at maximum response)

Elastic period

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

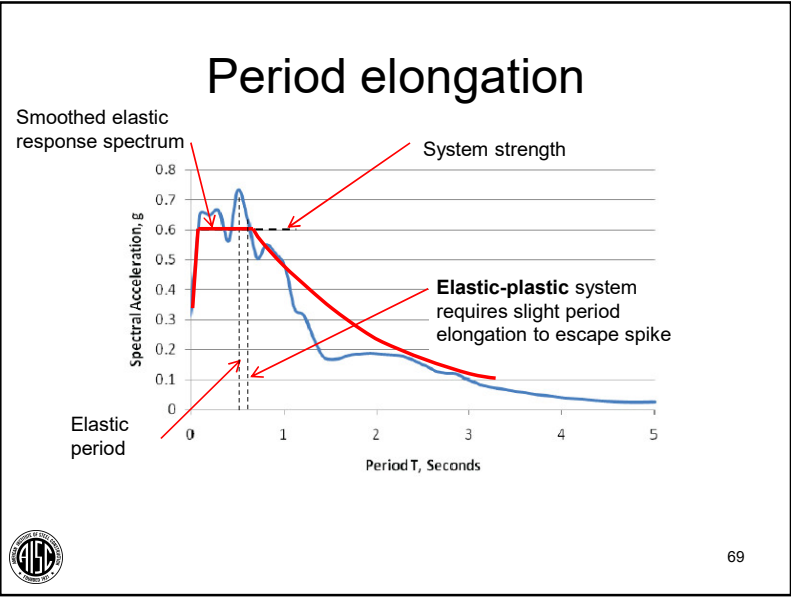
Period

Period

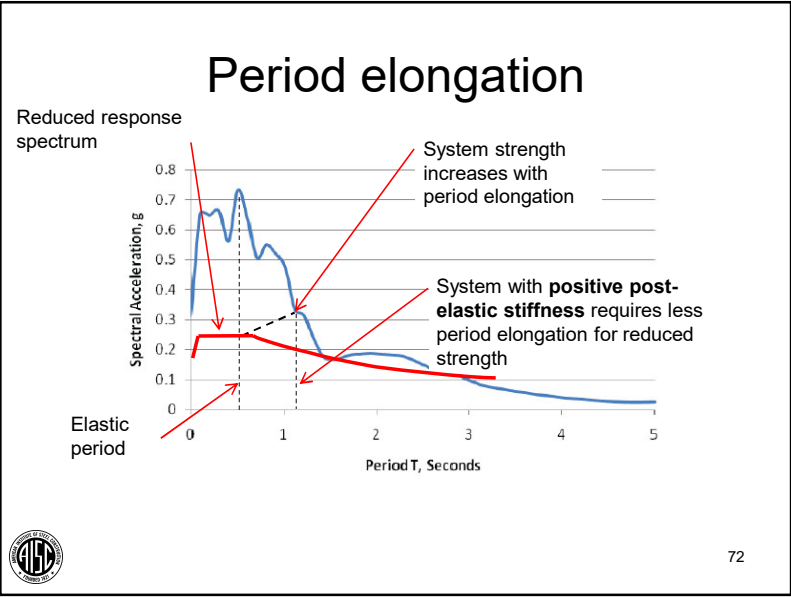
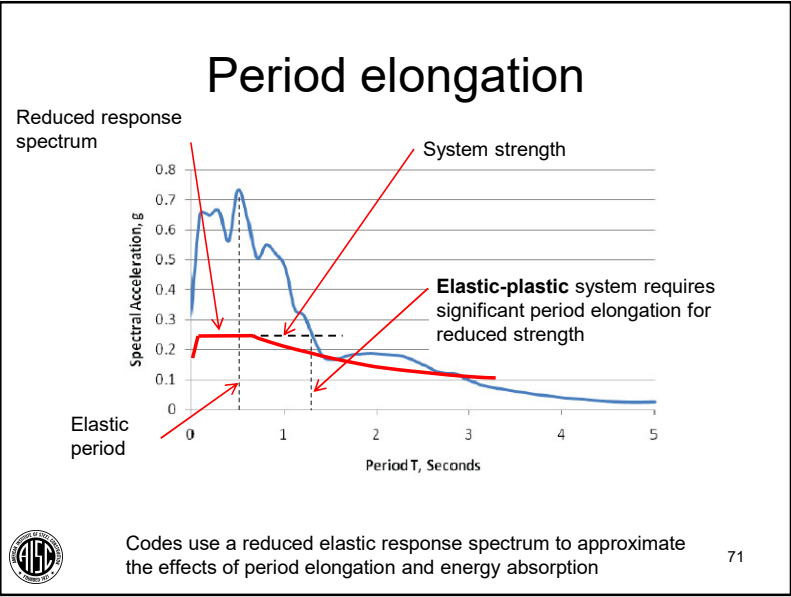
$\alpha_d = S_{a_{max}} / PGA$

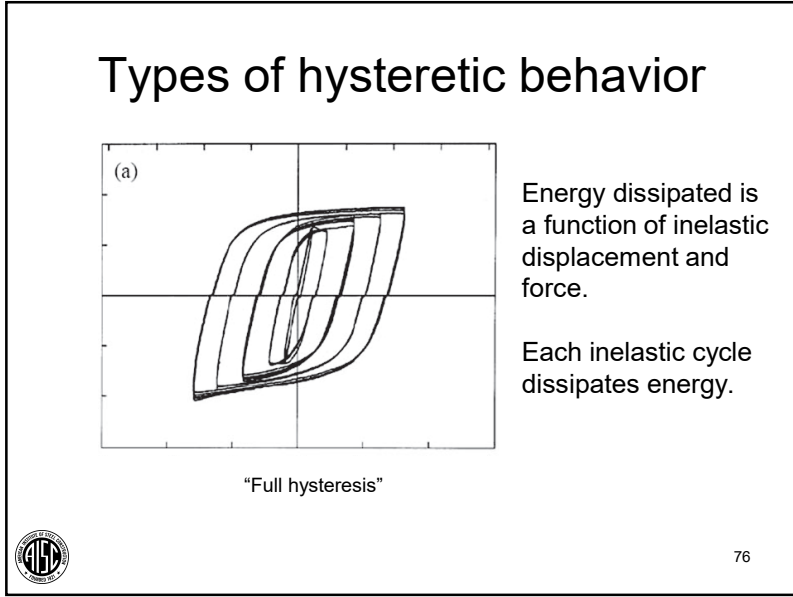
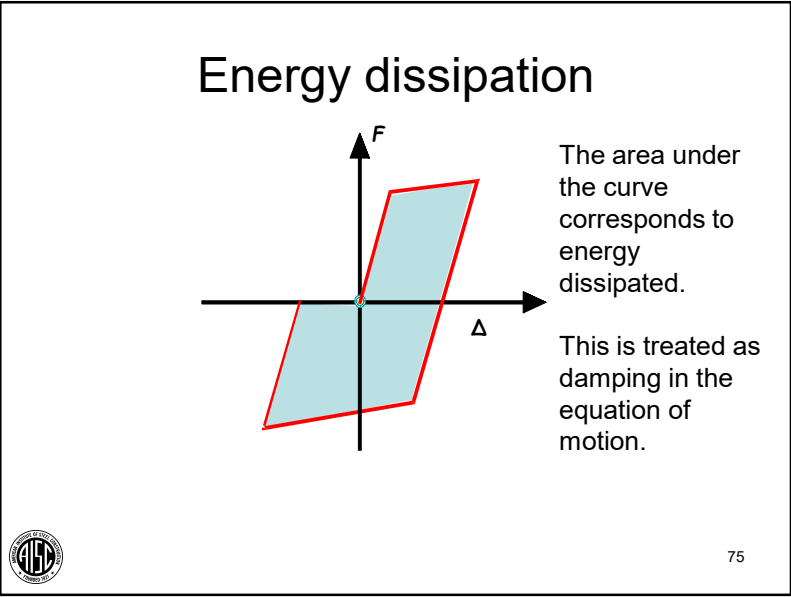
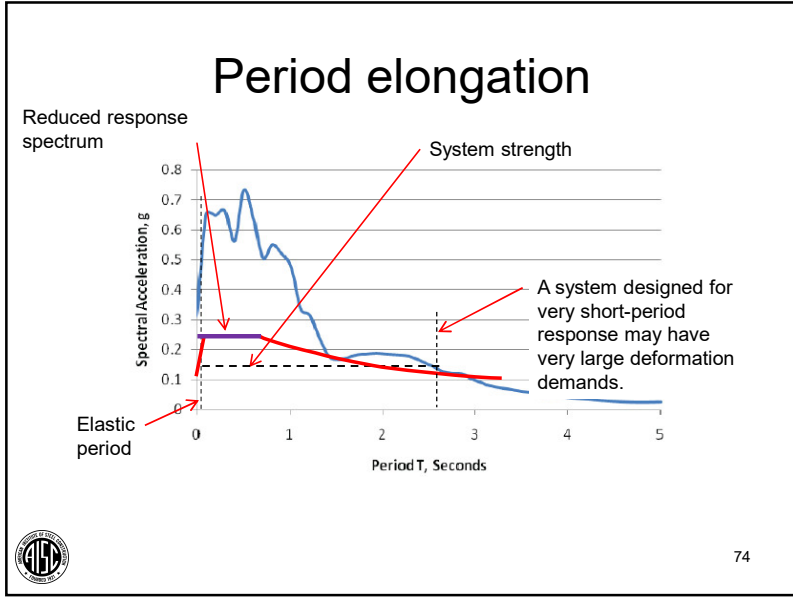
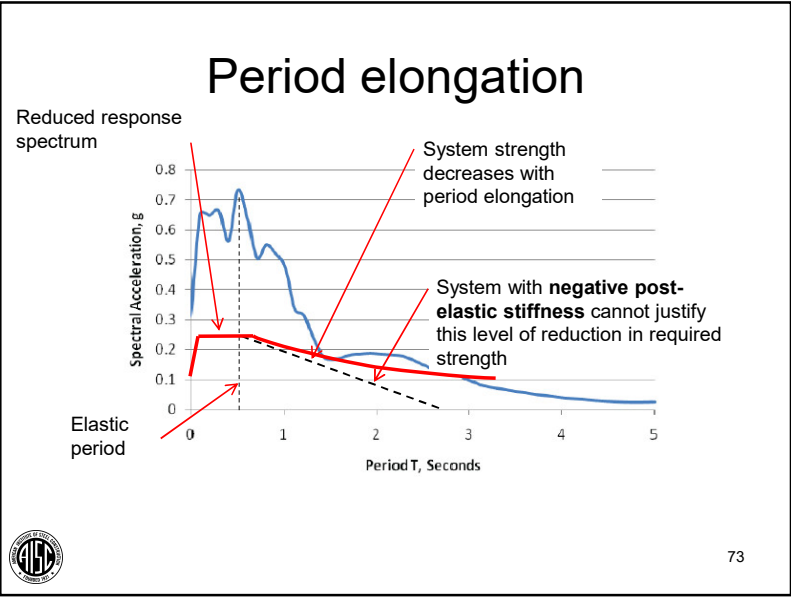
$\alpha_d = S_{d_{max}} / d_{g_{max}}$

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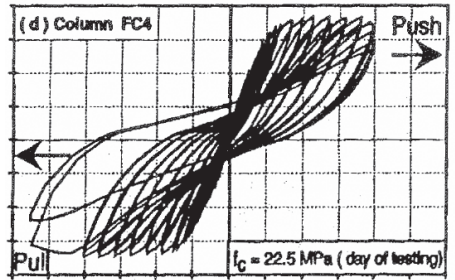


- ### Reduced design spectrum
- Elastic response spectrum
 - Accelerations corresponding to elastic response spectrum
 - Uneconomical design
 - Inelastic response
 - Accelerations corresponding to *reduced* elastic response spectrum
 - Implicitly allows for structural damage
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Types of hysteretic behavior

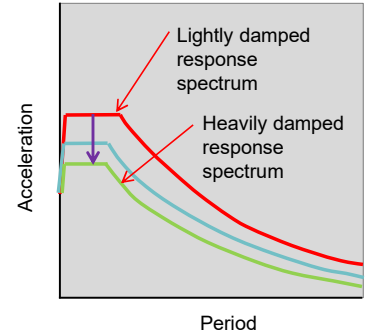


Energy dissipated is a function of hysteresis shape.
 Pinched loops contain less area; less energy is dissipated.

"Pinched hysteresis"



Damping and response

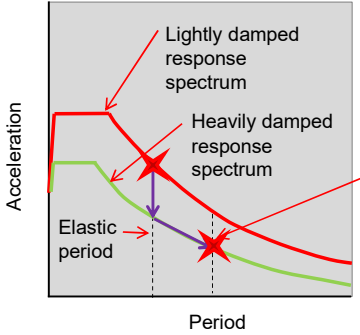


Response reduction due to damping permits use of reduced design forces

Inelasticity increases damping
 Increased damping reduces response



Reduced response



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

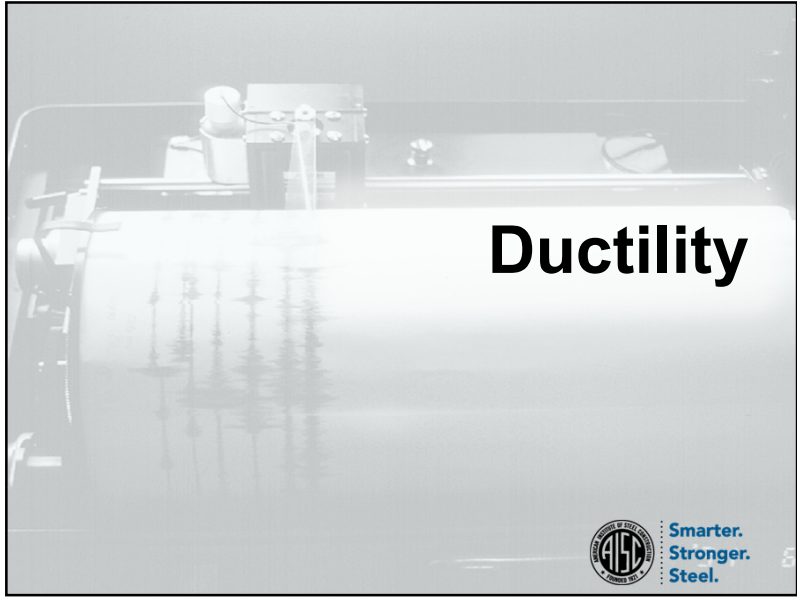
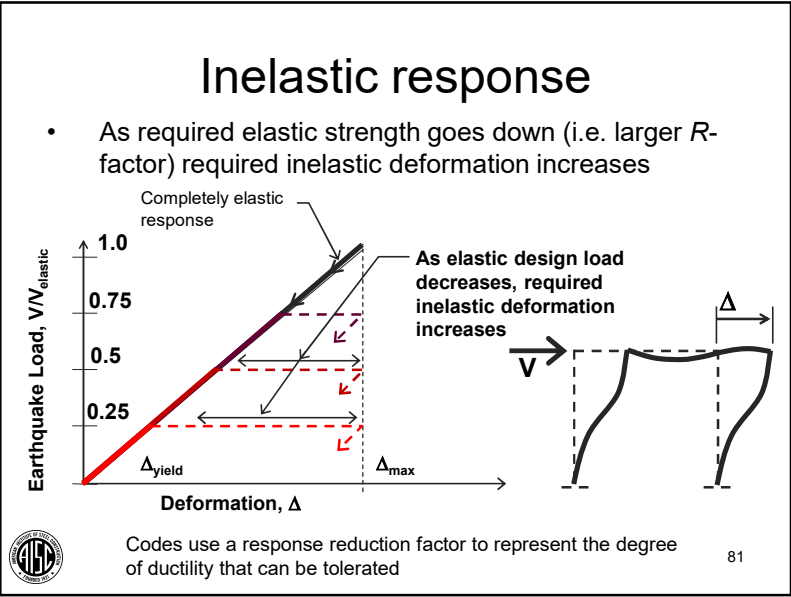
Codes use a reduced elastic response spectrum to approximate the effects of period elongation and energy absorption



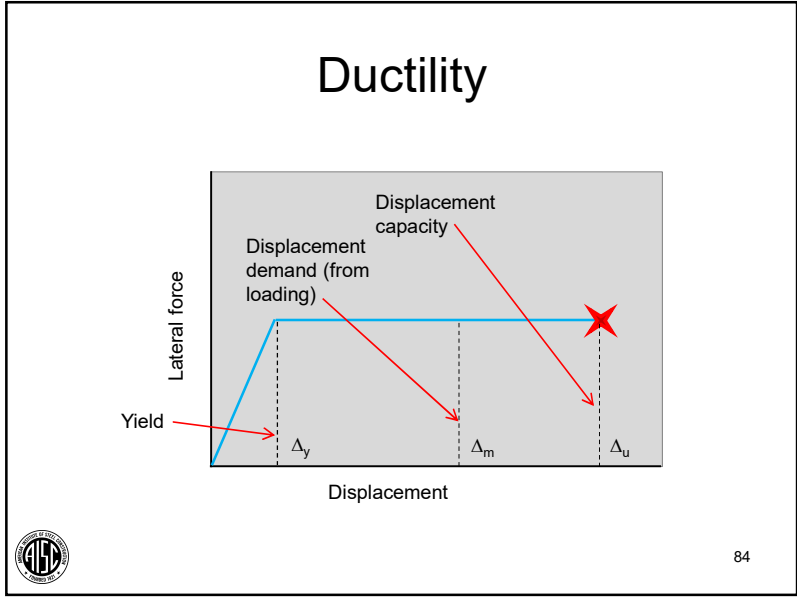
Reduced design spectrum

- 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






- ### Ductility
- Definition
 - o Capacity and demand
 - Force reduction
 - Inelastic response spectra
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Ductility


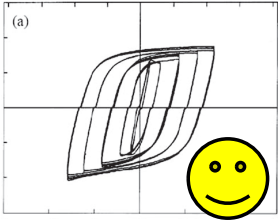

- Demand
 - $\mu = \Delta_m / \Delta_y$
 - Describes the inelastic deformation demand relative to elastic limit
- Capacity
 - $\mu = \Delta_u / \Delta_y$
 - Describes the inelastic deformation capacity relative to elastic limit
- Both concepts employed in this course



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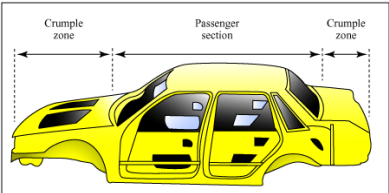
Ductility

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



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)

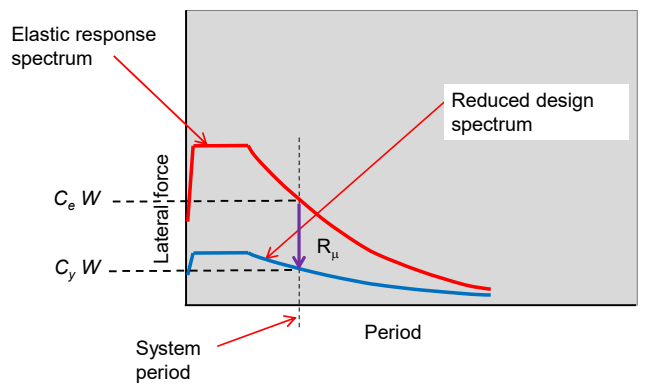


Force reduction

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



Inelastic response spectrum



“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?



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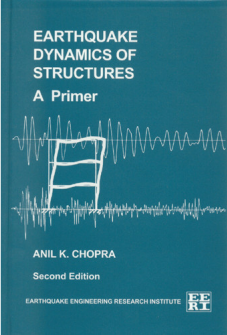
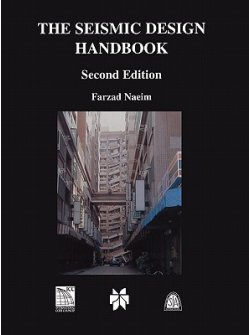
End of session 2


Next:
**Session 3:
Building dynamics
and response**



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Additional resources



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Question time



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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.



8-Session Registrants

CEU / PDH Certificates

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



8-Session Registrants

CEU / PDH Certificates

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



8-Session Registrants

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.



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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Course Resources

Go to www.aisc.org and sign in.



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Course Resources



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Course Resources

Event	Start Date
Seismic Design in Steel	1/12/1990 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 8-Session Package: Night School 17: Design of Seismic Attachments	7/26/2018 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	7/26/2018 1:30:00 PM

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Course Resources


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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 10/06/2020 5:00PM EDT	Available 10/06/2020 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 10/20/2020 5:00PM EDT	Available 10/20/2020 5:00PM EDT	Pending
NS24.4 - Flexural Members - Practical Considerations	Oct 27 2020 7:00PM EDT	Handouts	Available 10/28/2020 5:00PM EDT	Available 10/28/2020 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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