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**Fundamentals of earthquake engineering
for building structures**

Session 3: Building Dynamics and Response
March 1, 2021 | Rafael Sabelli





Smarter.
Stronger.
Steel.



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Course Description

Session 3: Building Dynamics and Response

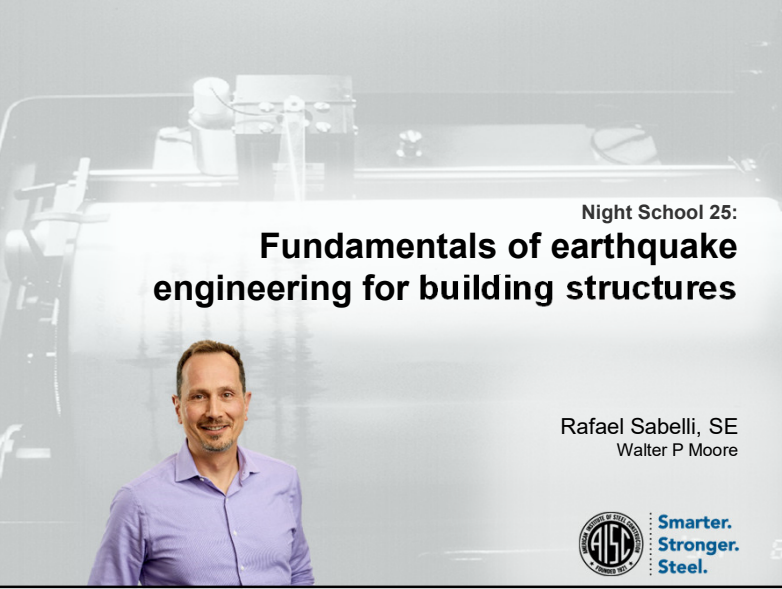

March 1, 2021

This session includes a review of building dynamics and multiple degrees of freedom as well as a review of modal analysis. Inelastic response of multiple-degree-of-freedom systems for building design will be discussed. The lecture presents the development of equivalent lateral force concepts. The use of modal-response-spectrum analysis in the design of structural steel buildings will be discussed.




Learning Objectives

- Describe the modes of deformation for buildings.
- Explain modal response.
- Explain inelastic response.
- List three types of seismic analysis allowed per code.



Night School 25:
Fundamentals of earthquake engineering for building structures


Rafael Sabelli, SE
Walter P Moore



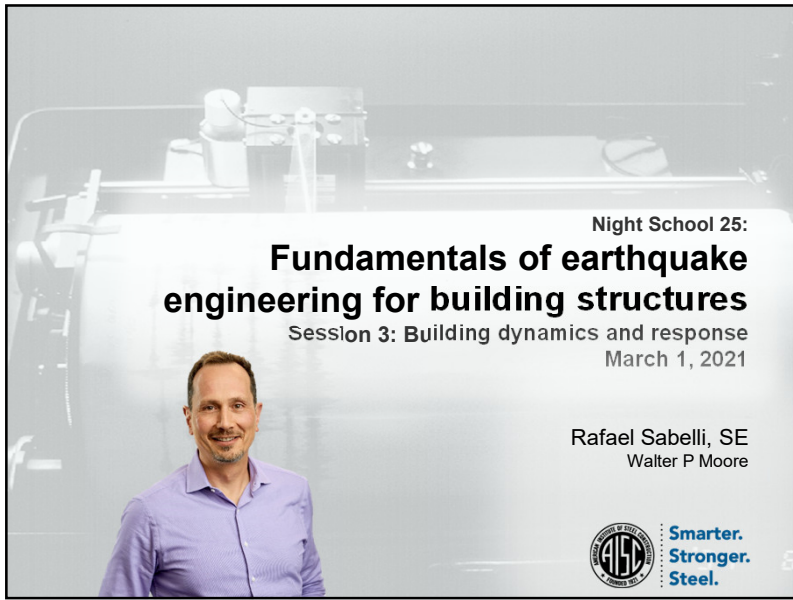
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Course outline

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




9



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Session 3: Building dynamics and response
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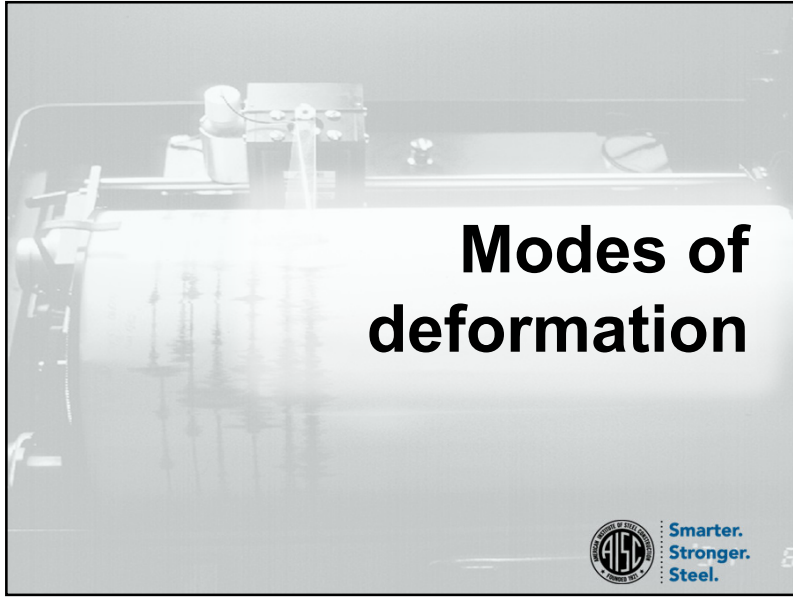
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Session topics


- Modes of deformation
- Modal response
- Inelastic response
- Seismic design



11



Modes of deformation



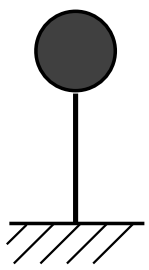
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Modes of deformation

- Buildings
- Degrees of freedom
- 2-dimensional modes
- Modal analysis



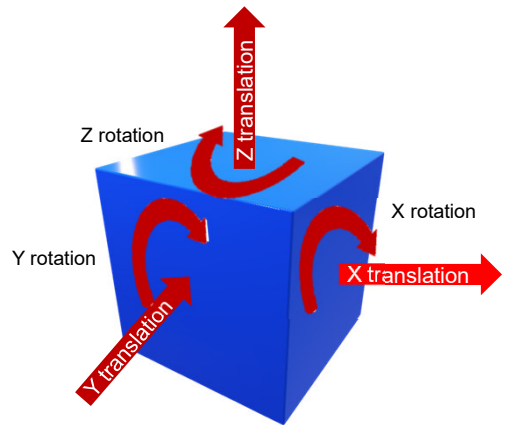
Buildings



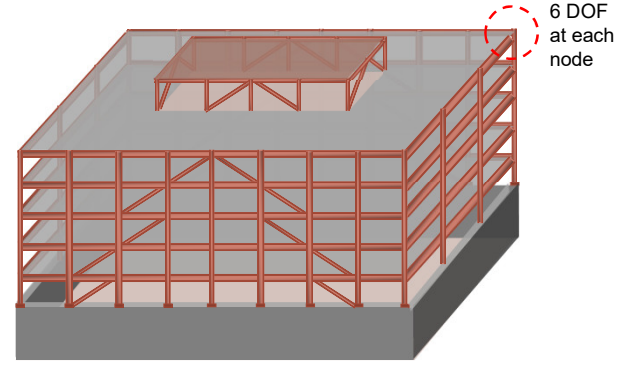
Identify 3 differences:
Mass is distributed vertically.
Mass is distributed horizontally.
Degrees of freedom at every floor.



Degrees of freedom (DOF)



Degrees of freedom (DOF)



Diaphragm degrees of freedom

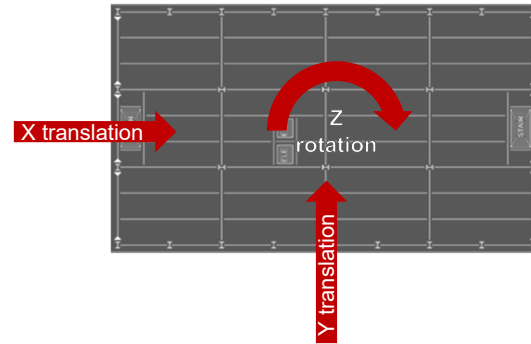
- 3 degrees of freedom (DOF) at each rigid diaphragm
 - X translation
 - Y translation
 - Z rotation
- Many, many DOF at non-rigid diaphragms



Codes require consideration of diaphragm flexibility in some cases

17

Plan degrees of freedom



At rigid diaphragms, X translation, Y translation, and Z rotation of each node is constrained to diaphragm.



Many buildings have diaphragms that are effectively rigid

18

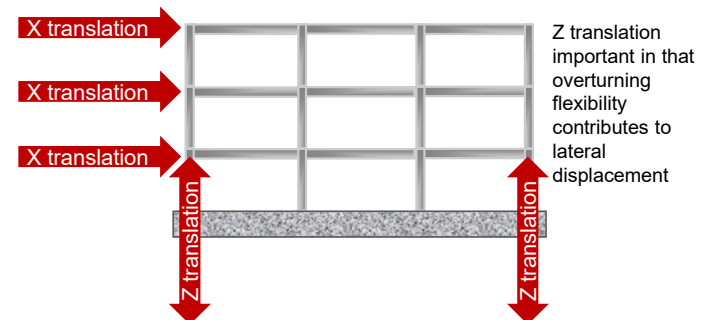
2-dimensional modes

- X-Z plane
 - 3 planar DOF/node
 - Many DOF effectively constrained to move together (rigid diaphragms)
 - X translation most important
 - 1 lateral DOF per story
 - 1 mode of vibration per DOF
 - Eigenvalue solution to free-vibration equation with mass matrix and stiffness matrix



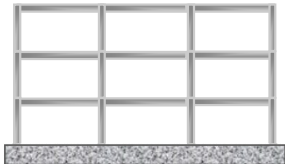
19

Degrees of freedom




20

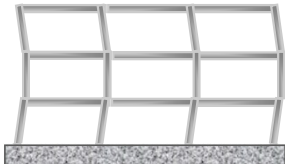
2-dimensional modes



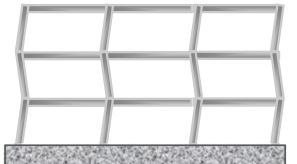
Undeformed




1st mode



2nd mode




3rd mode


21


Natural modes

- Linearly independent
 - Any deformed shape can be expressed as sum of modal shapes (each with a different amplitude)
- Excitable
 - Apply force in modal shape
 - Resulting displacement is in same shape
 - No other mode excited


22

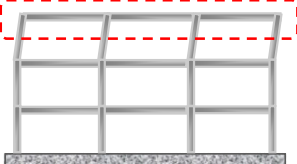
Natural modes

- Effectively “orthogonal”
 - Movement in one mode has no effect in other modes
- One mode per DOF
 - For simplified 2-D model
 - n floors → n modes
- Structures can be analyzed as a group of modes


23

These are not modes

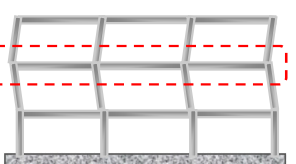
Only one level moves:
 Linearly independent
 Not a natural mode




$$\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$$

Apply force (or displacement) at one level and other levels move.

$$\begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$



$$\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

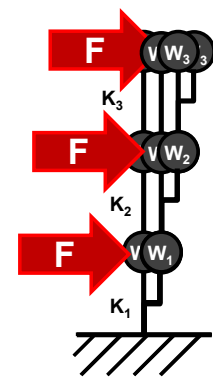

24

Modal analysis

- Lumped-mass and stiffness model
- Modal vectors
- Mass participation
- Orthogonality
- Modal coupling



Lumped-mass and stiffness model



$$\Delta_3 = F/K_3 + F/K_2 + F/K_1$$

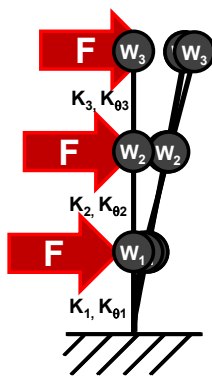
$$\Delta_2 = F/K_2 + F/K_1$$

$$\Delta_1 = F/K_1$$

Overturning projection missing from this simplified model



Lumped-mass and stiffness model



$$\Delta_3 = F/K_3 + F/K_2 + F/K_1 + F(h_3+h_2+h_1)^2/K_{\theta 1} + F(h_3+h_2)^2/K_{\theta 2} + Fh_3^2/K_{\theta 3}$$

$$\Delta_2 = F/K_2 + F/K_1 + F(h_2+h_1)^2/K_{\theta 1} + Fh_2^2/K_{\theta 2}$$

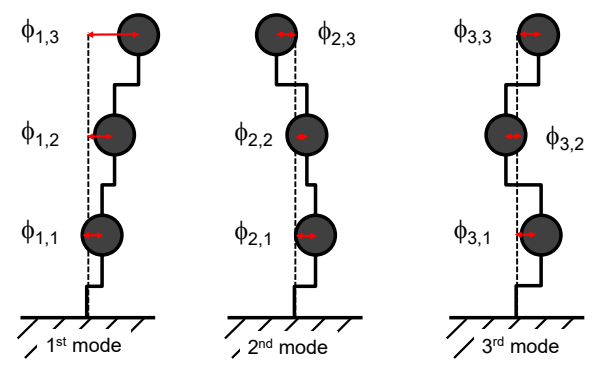
$$\Delta_1 = F/K_1 + Fh_1^2/K_{\theta 1}$$

Complete stiffness matrix required for overturning

Codes use the concept of "story stiffness." Shear stiffness is generally used.



Modal vectors



Modal vectors

- Each mode has a deformed-shape vector
- One row for each lumped mass (i.e., each story)

$\phi_{i,j}$ = Deformation for mode i at level j

- Each mode has its own P - Δ magnification
 - Generally this is simplified (i.e., ignored)
 - One lateral force used



29

Modal period

- Each mode has a period of vibration
 - Relates mass to stiffness
- Longest period mode is the *fundamental mode*
 - Typically most significant in response
 - Tall buildings may be different



30

Modal height

- Each mode has a force-vector shape that results in that deformation shape

$s_{i,j}$ = Force for mode i at level j

- Each modal force vector has an effective height relating overturning to base shear
 - $h_i = \Sigma [s_{i,j} * H_j] / \Sigma s_{i,j}$
 - h_i = modal height for mode i
 - H_j = Height of level j



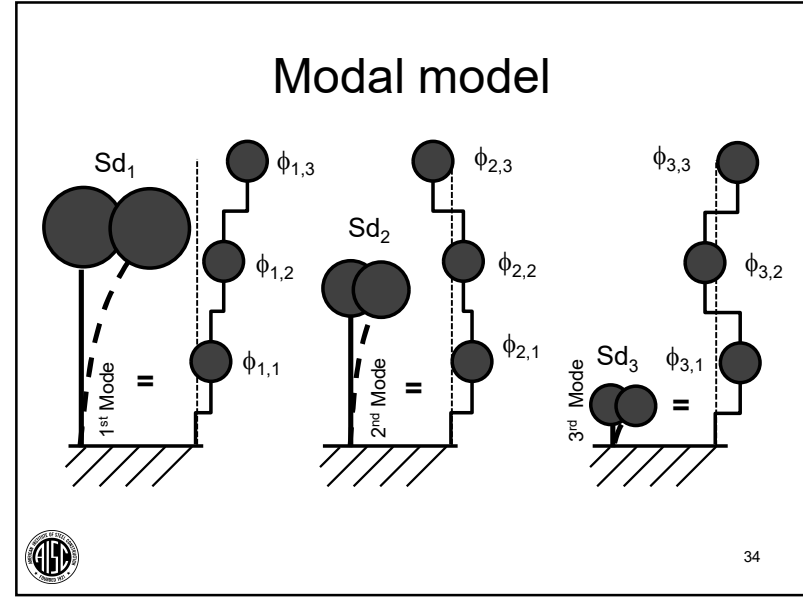
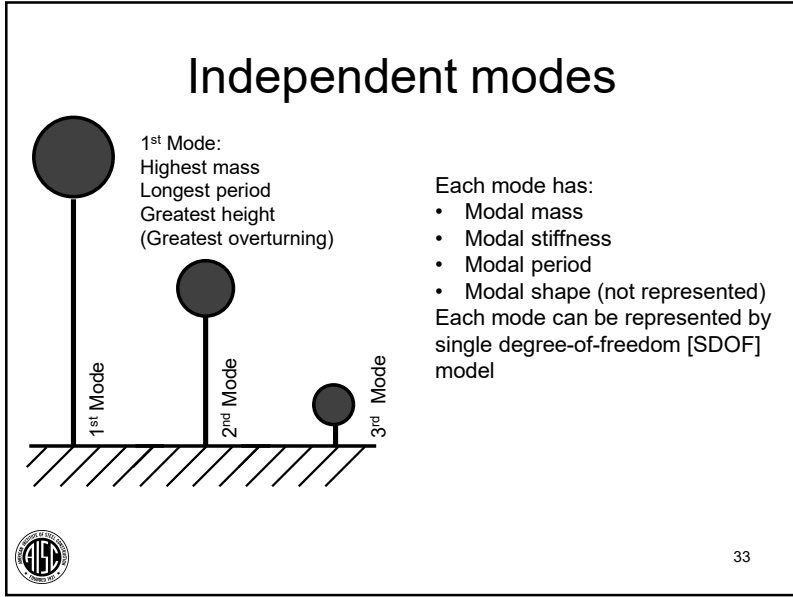
31

Modal mass

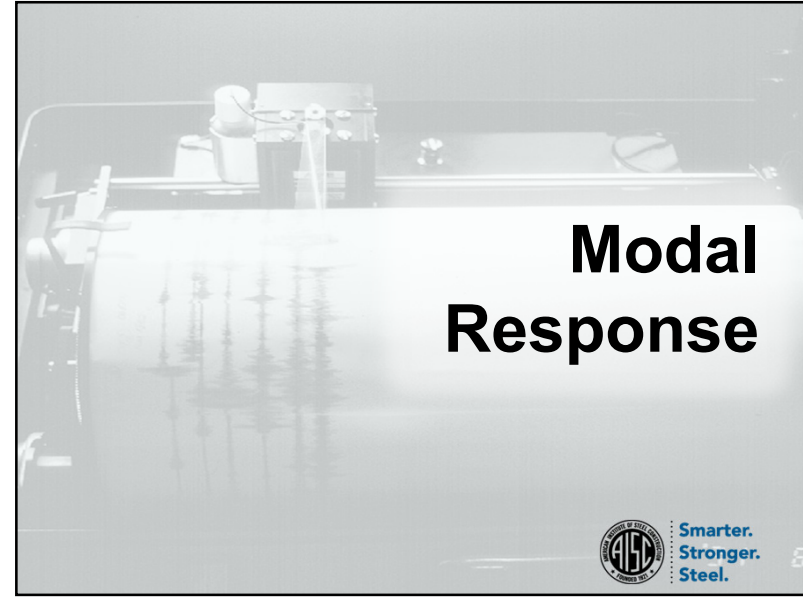
- Each mode has an effective modal mass associated with it
- The sum of all modal masses is the building mass
- Longer-period modes have higher modal mass
 - Modal mass represents importance
 - Models with many DOF often have many short-period modes with little mass



32




- ### Modal model
- Displacement of equivalent SDOF modal model corresponds to displacement in mode shape.
 - Acceleration of equivalent SDOF modal model corresponds to acceleration in mode shape.
 - Combining with modal mass gives forces
-
- 35



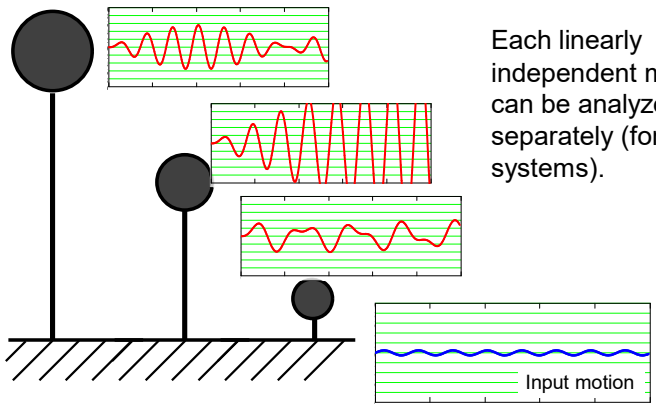
Modal response

- Modal time-history
- Response spectrum
 - Peak responses
 - Modal combination
- Modal stiffness




37

Modal time-history




Each linearly independent mode can be analyzed separately (for elastic systems).



38

Modal time-history

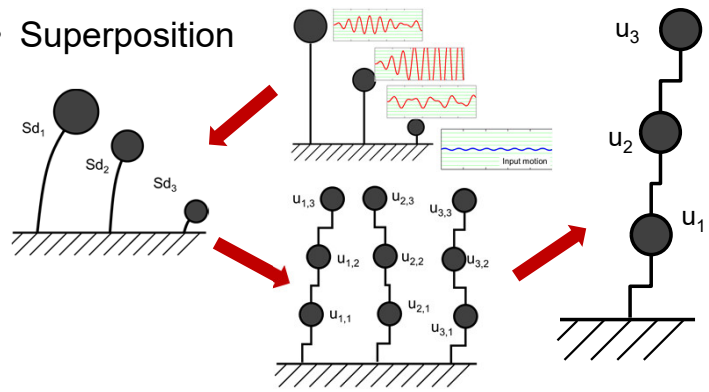

- Superposition
 - $Sd_i(t)$: Time-history response of each SDOF modal model (mode i) is converted to
 - $u_{i,j}(t)$: Time-history response of each floor-level DOF in 2-D model for that mode
 - Floor-level DOF are summed at each time step:

$$u_j(t) = \sum u_{i,j}(t) = u_{1,j}(t) + u_{2,j}(t) + u_{3,j}(t)$$


39

Modal time-history

- Superposition

40

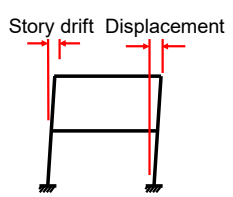

Maxima

- Maximum story drifts cannot be obtained from maximum displacements

$$\delta_j(t) > \max[u_j(t)] - \max[u_{j-1}(t)]$$

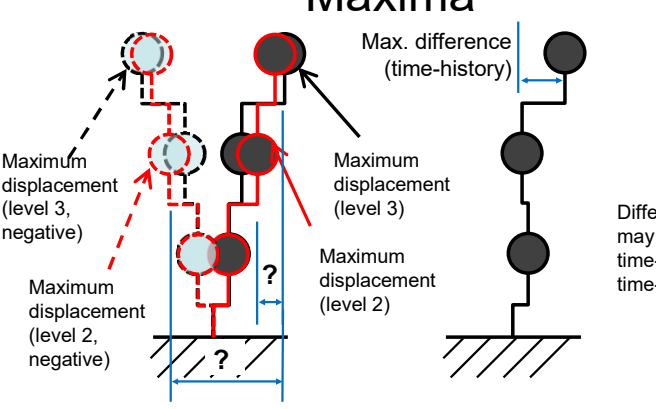
$\delta_j(t)$: story drift at level j
 $u_j(t)$: displacement at level j
- Maximum drifts must be obtained from time history

$$\delta_j(t) = u_j(t) - u_{j-1}(t)$$


41

Maxima



Differences may be tracked time-step-by-time-step


Differences of maxima Time-step-by-time-step difference



42

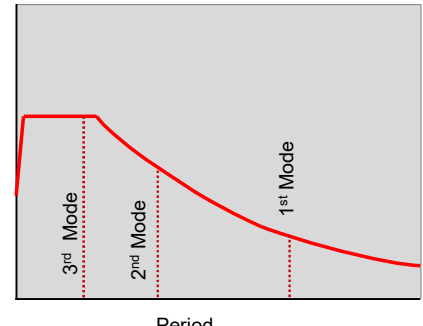
Maxima

- Maximum displacements can be obtained from displacement histories:
 - $u_{\max. j} = \max[u_j(t)]$
- Maxima can be approximated
 - $u_{\max. j} \sim [\max[u_{1,j}(t)]^2 + \max[u_{2,j}(t)]^2 + \max[u_{3,j}(t)]^2]^{1/2}$
 - Assumes linearly independent, orthogonal modes




43

Response spectrum



Each linearly independent mode can be analyzed separately (for elastic systems).

Codes use the reduced elastic (SDOF) response spectrum for modal analysis



44

Combination of modal response

- Direct superposition of modal responses not possible (as it is for time history)
- For linear, orthogonal modes:
 - $u_j = ([u_{1,j}]^2 + [u_{2,j}]^2 + [u_{3,j}]^2)^{1/2}$
 - Square root of the sum of the squares
 - “SRSS”



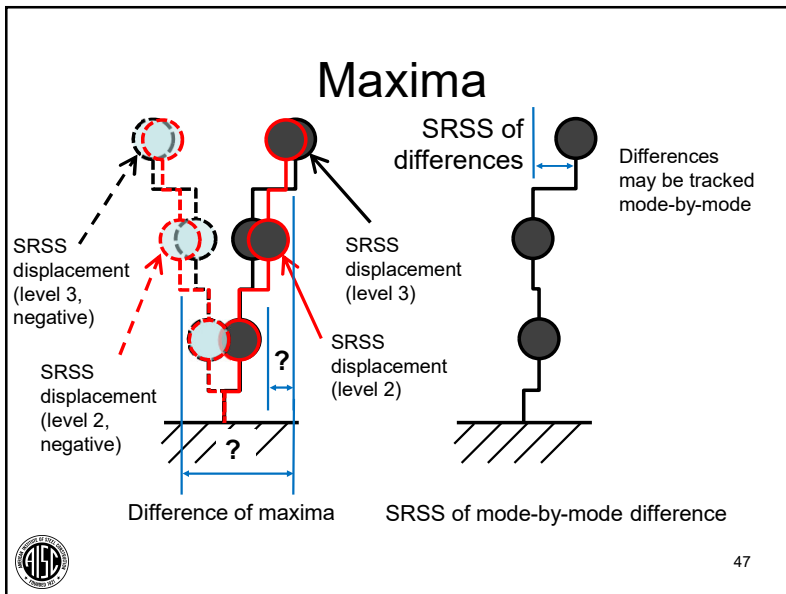
Codes specify SRSS or similar methods for modal combination 45

Combination of modal response

- Drifts cannot be obtained from SRSS displacements
 - $\delta_j > u_j - u_{j-1}$ *Common mistake!*
- Drifts must be tracked mode by mode and combined
 - $\delta_{n,j} = u_{n,j} - u_{n,j-1}$
 - $\delta_j = ([\delta_{1,j}]^2 + [\delta_{2,j}]^2 + [\delta_{3,j}]^2)^{1/2}$
- Similar for all response quantities



46



47

SRSS of modal responses

- Signs are lost
 - SRSS of results is always positive
 - Earthquake forces are reversible
- Differences meaningless
 - Drifts
 - Collector forces (more on this later)
 - etc.
- Results are approximate



48

Modal cross-coupling

- Closely spaced modes can interact
- Damping can contribute to coupling
- Complete Quadratic Combination (CQC) addresses coupling
 - Where there is negligible coupling
 - CQC=SRSS
- CQC and SRSS
 - Building codes
 - Software programs



49

CQC

$$u_j = \sqrt{\sum_{i=1}^m \sum_{n=1}^m \rho_{in} u_{n,j} u_{i,j}}$$

$$\rho_{in} = \frac{8\xi^2 (1 + \beta_{in}) \beta_{in}^{3/2}}{(1 - \beta_{in}^2) + 4\xi^2 \beta_{in} (1 + \beta_{in})^2}$$

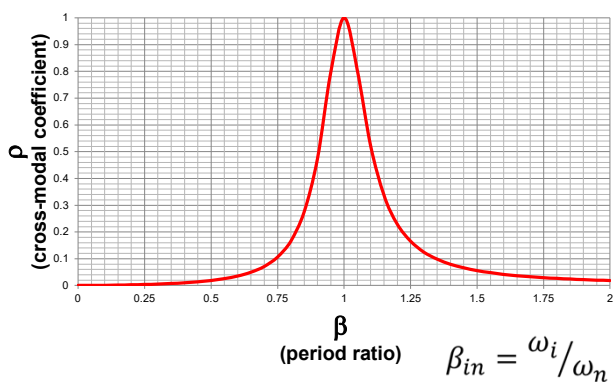
(simplified form) $\beta_{in} = \omega_i / \omega_n$



Codes allow CQC for modal combination

50

CQC (for a given damping ratio)



$$\rho_{in} = \frac{8\xi^2 (1 + \beta_{in}) \beta_{in}^{3/2}}{(1 - \beta_{in}^2) + 4\xi^2 \beta_{in} (1 + \beta_{in})^2}$$



51

CQC

- Assumes smooth spectrum
 - Spikes may create different responses for closely spaced modes
 - Applicable to smoothed response spectra
- Simplified form assumes same damping for all modes
 - Even more complicated form exists for different modal damping values



52

Modal response

- SRSS commonly used
 - Problematic when modes are closely spaced
- CQC may be used to capture cross-modal influence
 - Somewhat more complicated
 - Easily coded into programs
 - Similar results for well-spaced modes



53



Inelastic response

- Coupling of modes
- Inelasticity and modes of deformation
- Problematic inelastic modes
- Ductility demands



55

Coupling of modes


- Some coupling of modes is observed in nonlinear systems
- Modes no longer orthogonal
- Modal combination no longer completely valid
 - Provides reasonable approximation



56

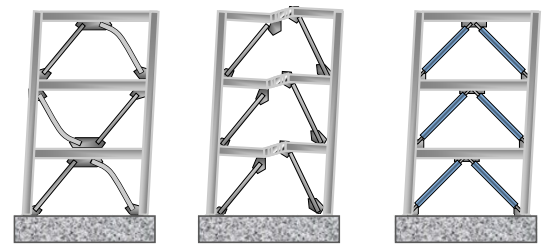
Inelasticity and modes of deformation

- “Shear” modes
 - Affect story shear stiffness
 - Affect all modes
- “Flexural” modes
 - Affect system overturning resistance
 - Primarily affect first modes
 - May not reduce response of other modes




57

“Shear” modes




SCBF EBF BRBF



58


“Shear” modes

Eccentrically braced frame link yielding affects all modes.




1st mode


Higher-mode inelastic deformation is possible.



2nd mode

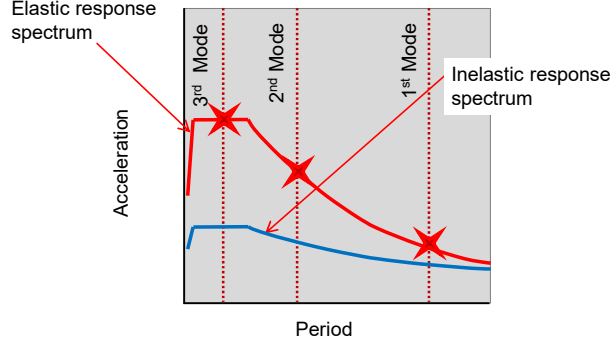


3rd mode




59

“Shear” modes



Period

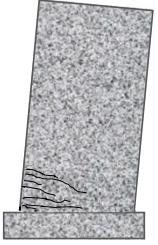


60


“Flexural” modes

Inelastic displacement is in pattern similar to first mode


Higher modes remain elastic (or nearly so)



Concrete shear wall

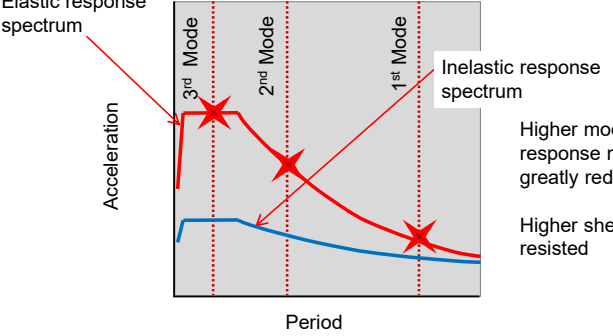


Braced frame with constrained story drifts



61

“Flexural” modes



Elastic response spectrum


Acceleration

Period

Inelastic response spectrum

Higher mode response may not be greatly reduced


Higher shears to be resisted



62

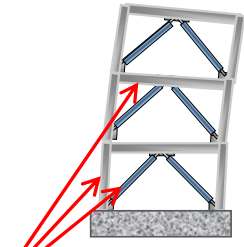
Ductility demands

- Element ductility demand >> system ductility demand
 - Element ductility demands may not be uniformly distributed
 - Mode of deformation may change
 - Post-elastic deformation may be concentrated



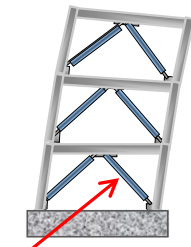
63

Ductility demands




Elastic

Elastic drift results from column, beam, and brace deformation



Post-elastic

Post-elastic drift results from brace deformation



64



Seismic Analysis

- Application of physical laws and mathematics to compute the deformations, internal forces, and stresses of structures resulting from the application of loads.
- Derivation of forces to permit the design of members and connections resulting in a structure adequate for the anticipated loads.

66

Seismic Analysis

- Equivalent lateral force (ELF)
 - Simplified procedure
 - Elastic
 - One mode
- Modal response spectrum analysis (MRSA)
 - Simplified procedure
 - Elastic
 - Several modes
- Nonlinear response-history analysis

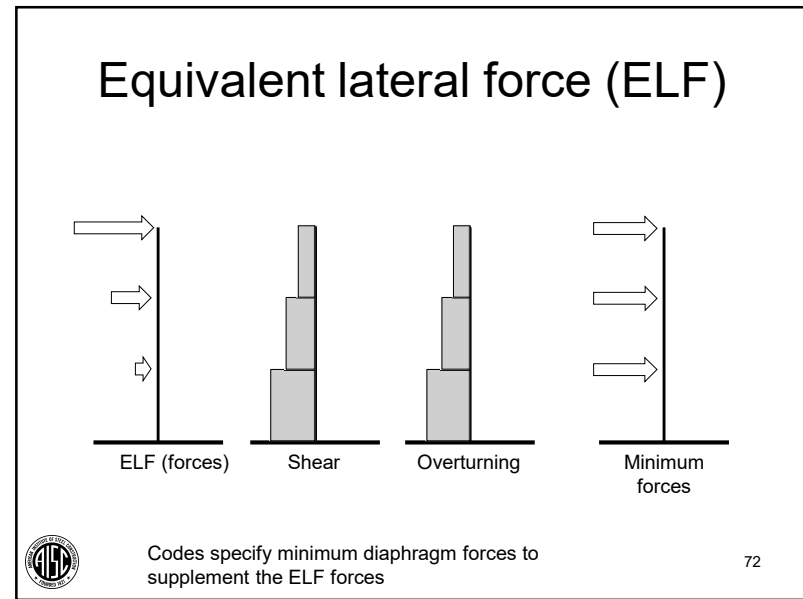
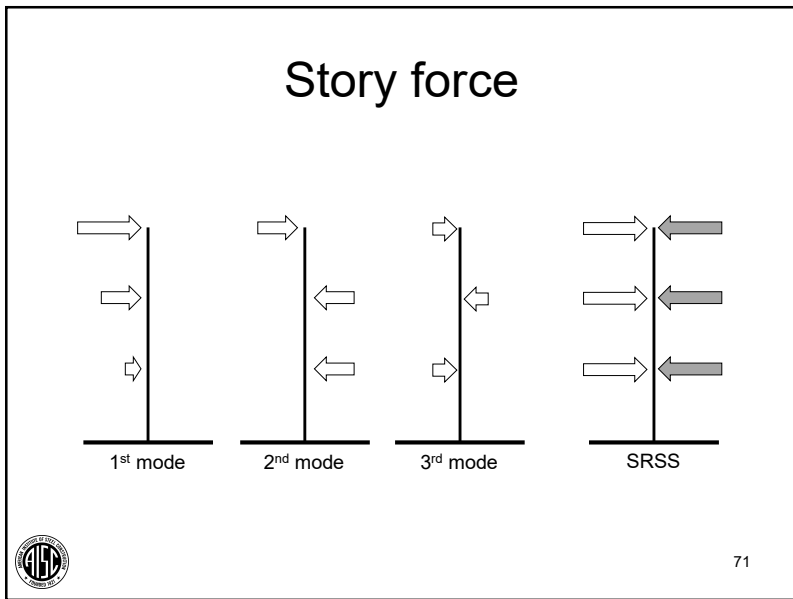
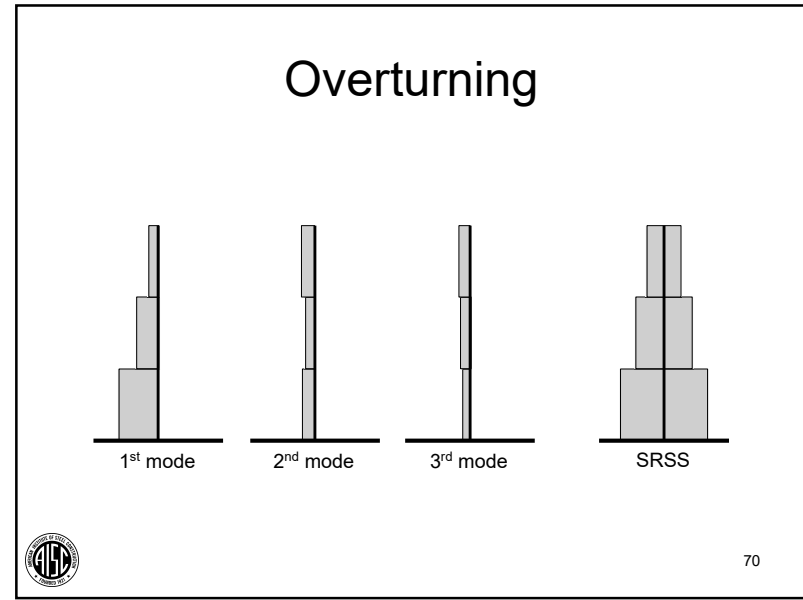
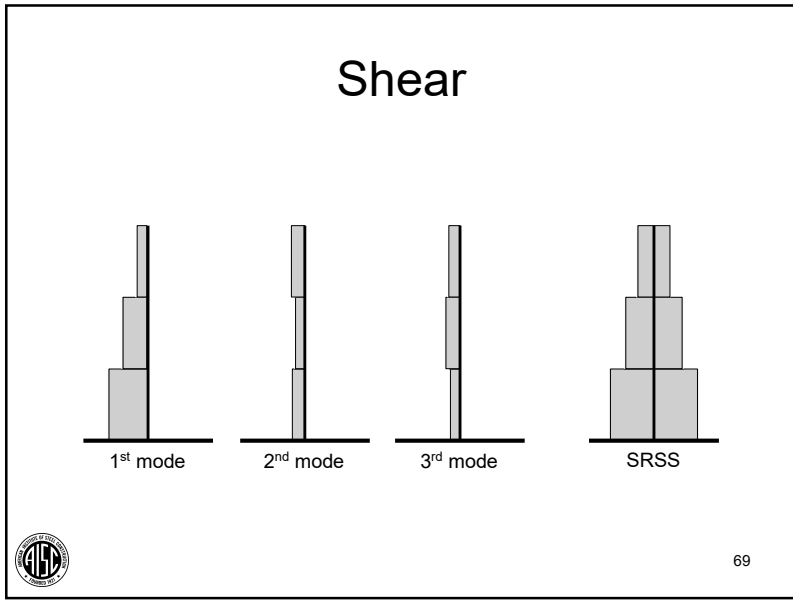
Codes allow ELF, MRSA, and nonlinear response-history analysis methods

67

Equivalent lateral force

- Goal
 - Single lateral load case
 - Capture required shear strength at each level
 - Required overturning strength at each level
 - Not possible to capture maximum story force

68



Modal response spectrum analysis

- Considered “dynamic” analysis
 - Considers modes of vibration
 - Building dynamics
 - Results are often not statically consistent
 - Equilibrium methods require judgment



73

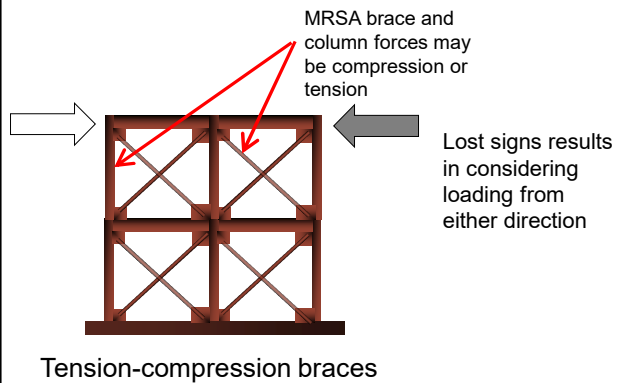
Combining modes

- SRSS often used for modal responses
- CQC should be used
 - If modes are not well spaced
 - If modes are subject to change during design
- “Lost signs” of responses require engineering judgment for realistic design



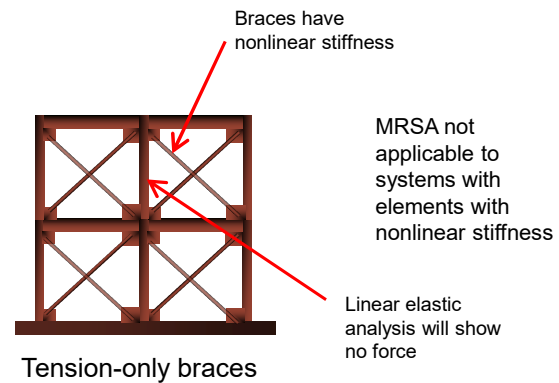
74

Lost signs



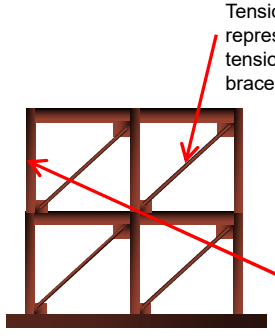
75

Lost signs



76

Lost signs




Tension-only braces represented by tension-compression braces

Tension-only braces

MRSA may be adjusted to permit analysis

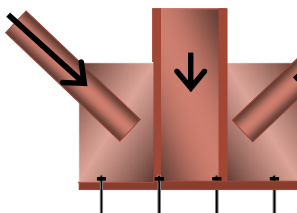
Results require adjustment

Linear elastic analysis will show no force

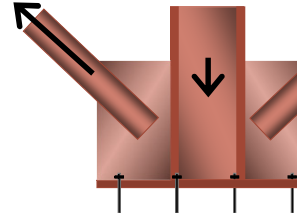


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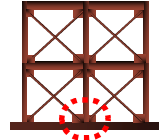
Lost signs




Realistic combination



Unrealistic combination

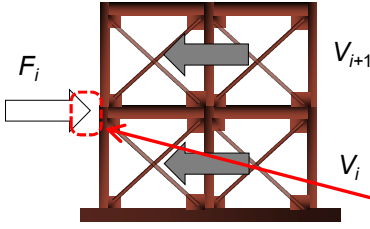




78

Tracking responses


- Track responses mode by mode
 - Difference between maxima is meaningless



$$F_i > V_{i+1} - V_i$$

Collector force


Insert beam element to track force mode by mode



79

Mass participation

- 90% typically used as minimum
- 20 Hz (0.05 sec) can be used as a cut-off
- Captures important modes of response
 - Often many modes required to reach 90%
- Remaining mass must be included
 - Can be assigned acceleration corresponding to highest analyzed mode
 - Base shear can be scaled to a minimum
 - Building codes follow this approach



Codes specify minimum percentage of total mass to be captured for MRSA

80

3-dimensional modal analysis

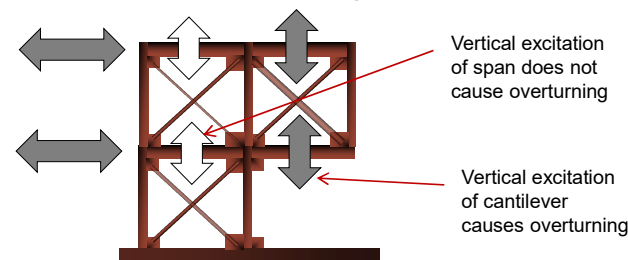
- Ground motions occur in 3 dimensions
- Horizontal
 - Orthogonal spectra should be considered
 - Combining bi-directional response
 - SRSS
 - CQC
- Vertical spectra
 - Often neglected



81

Vertical response

- Potential overturning effect couples vertical and horizontal response



82

Seismic Analysis

- Equivalent lateral force (ELF) procedure
 - Permitted for most structures
 - Not permitted in certain cases due to a combination of
 - Building height
 - Irregularity
 - Building period
 - Occupancy
 - Site seismicity



Codes provide tables of permitted analysis types for these conditions

83

Seismic Analysis

- Modal response spectrum analysis (MRSA) procedure
 - Permitted for all structures
 - Subject to system height limits
- Nonlinear response history analysis (RHA) procedure
 - Same limitations as MRSA
 - Often used when height limits exceed (with peer review)



Codes provide tables of permitted analysis types for these conditions

84




Summary



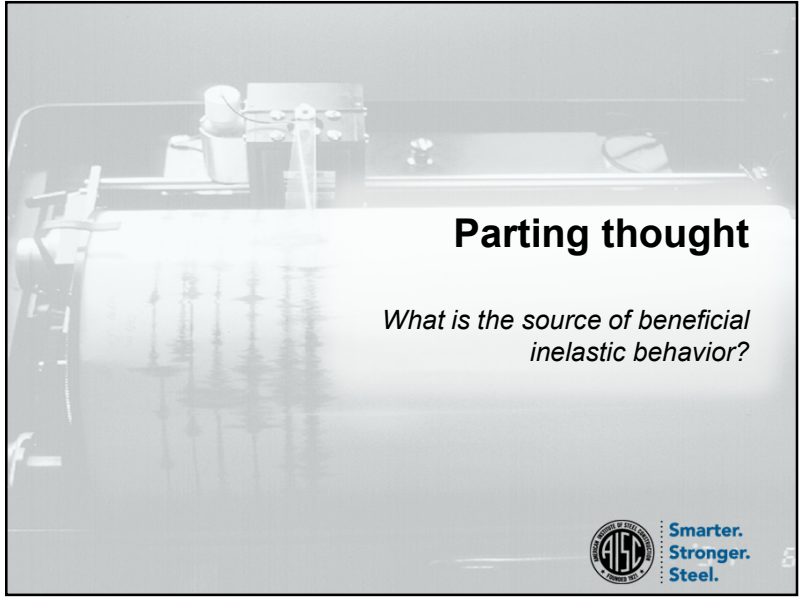
Smarter.
Stronger.
Steel.

Summary

- Buildings have multiple modes of response
- Modes can be analyzed individually and results combined
- Equivalent lateral forces can approximate modal response
- Response quantities of interest should be tracked mode by mode in modal analysis
- Inelastic behavior affects modal response




86



Parting thought

What is the source of beneficial inelastic behavior?




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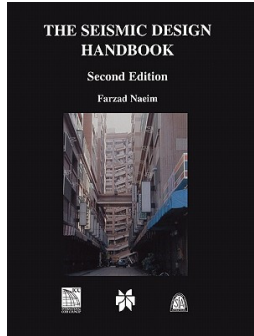
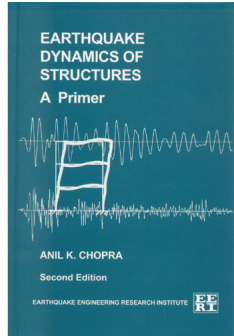
End of session 3

Next:
**Session 4:
Steel behavior**

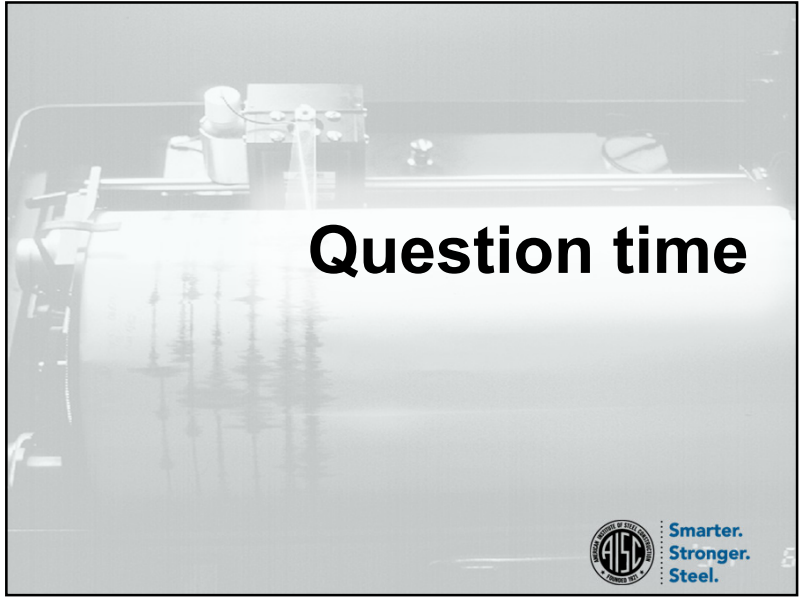


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Additional resources



89



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.



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CEU / PDH Certificates

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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



AISC > MY ACCOUNT > COURSE RESOURCES

Course Resources

Event	Start Date
Seismic Design in Steel	1/11/1990 12:00:00 AM
8-Session Package-Design of Facade Attachments	5/9/2018 1:00:00 PM
NS 28 8-Session Package-Night School 14 - Fundamentals of Connection Design	10/9/2017 7:00:00 PM
NS 26 8-Session Package-Night School 16 - Seismic Design in Steel	2/26/2018 7:00:00 PM
NS 27 8-Session Package-Night School 17 - Design of Facade Attachments	7/26/2018 7:00:00 PM
NS 28 8-Session Package-Night School 18 - Steel Construction: Mill To Topping Out	10/15/2018 7:00:00 PM
NS 29 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	6/13/2019 7:00:00 PM
8-Session Package-Seismic Design in Steel - Courses & Exams	7/26/2018 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 10/06/2020 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 10/13/2020 5:00PM EDT	Available 10/13/2020 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 10/29/2020 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 11/10/2020 5:00PM EST	No longer available	Pending
NS24.6 - Stability of Beam-Columns - Practical Considerations	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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