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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.

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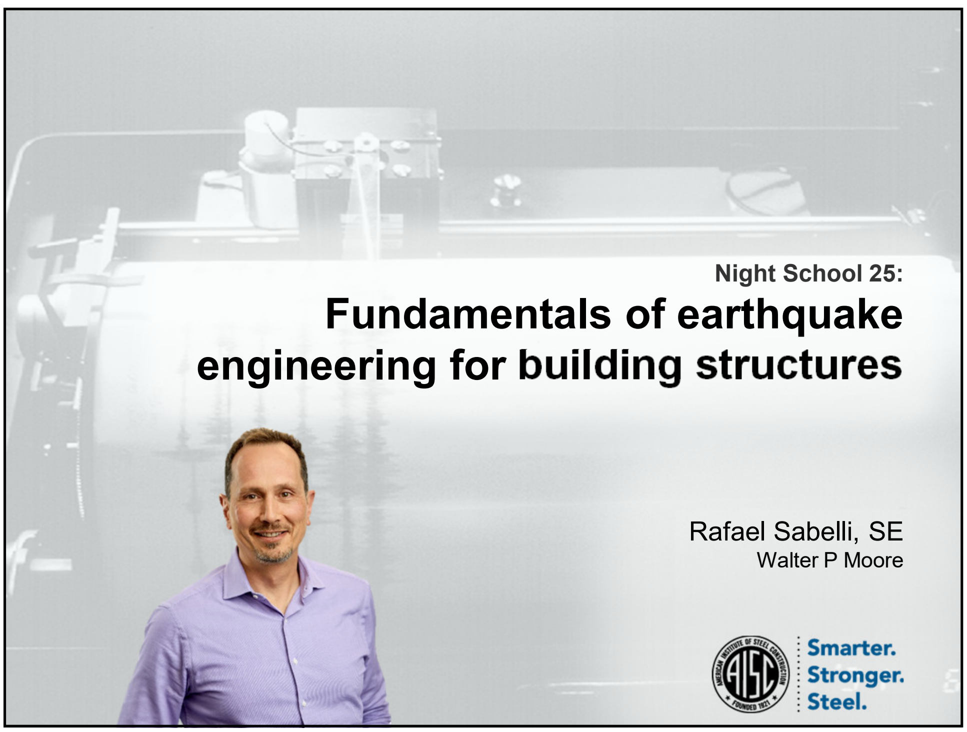
Learning Objectives

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



Course outline

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

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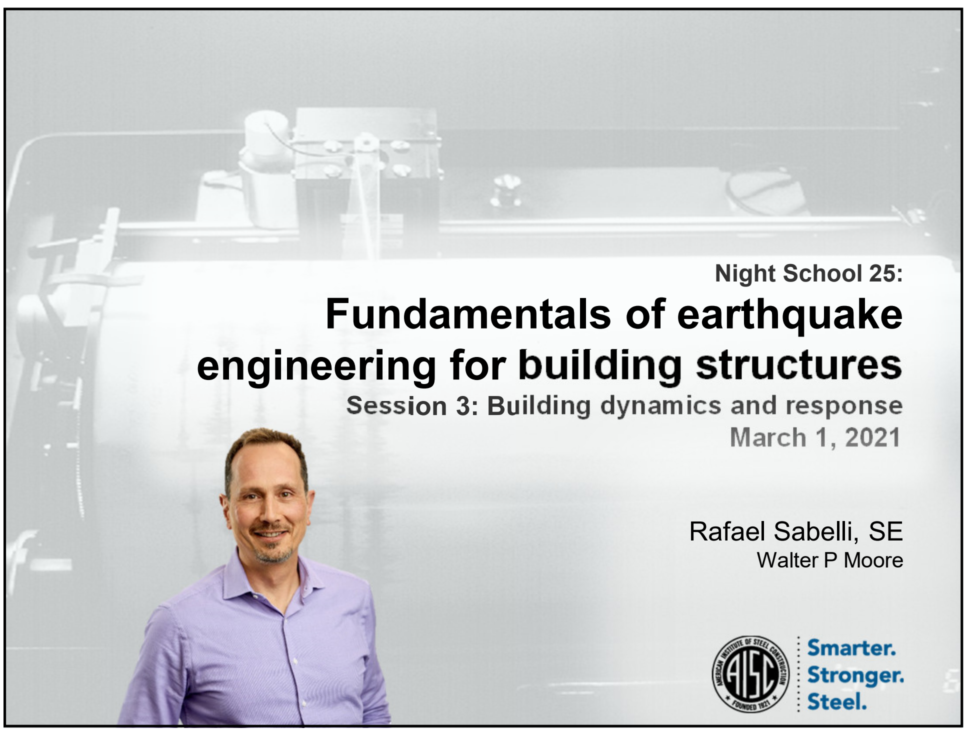

Session topics

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

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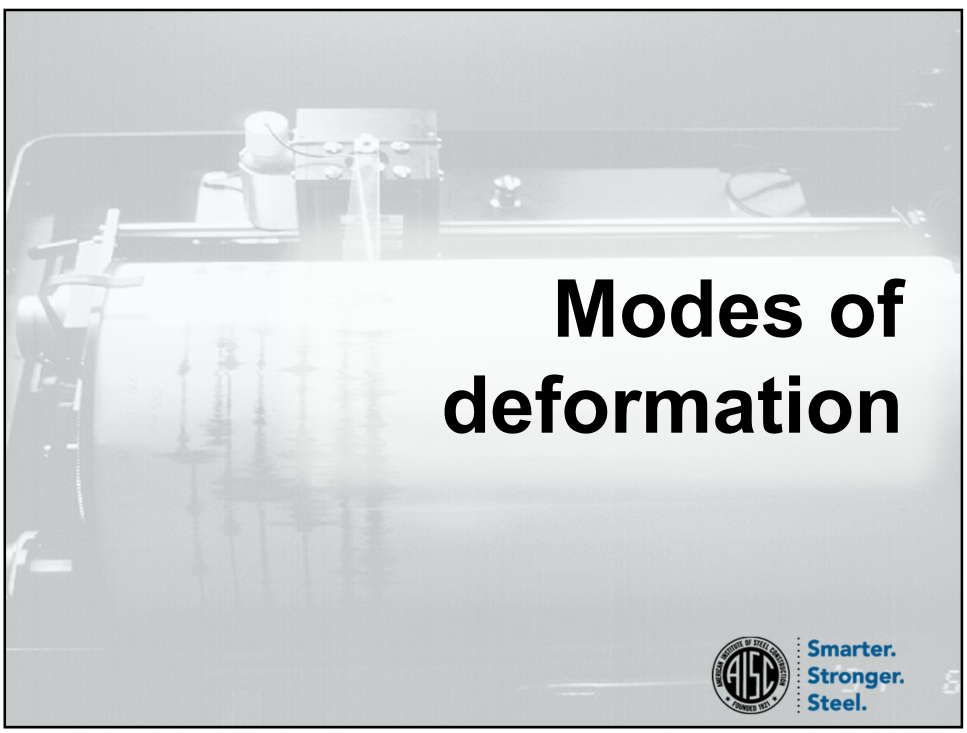

Modes of deformation

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

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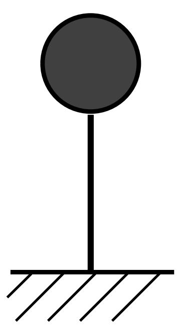
Buildings



Identify 3 differences:

Mass is distributed vertically.

Mass is distributed horizontally.

Degrees of freedom at every floor.

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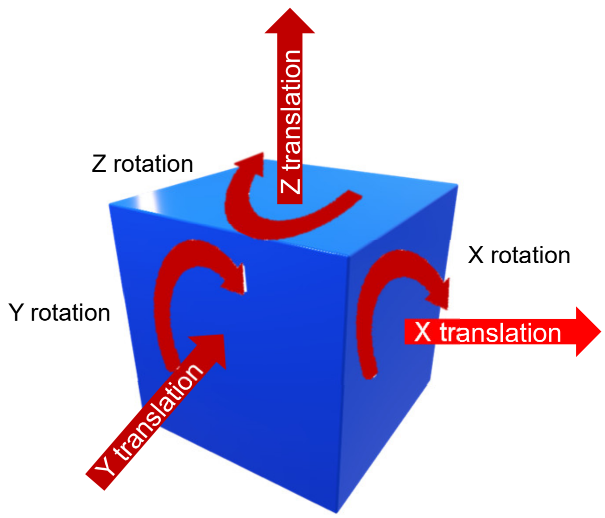
Degrees of freedom (DOF)



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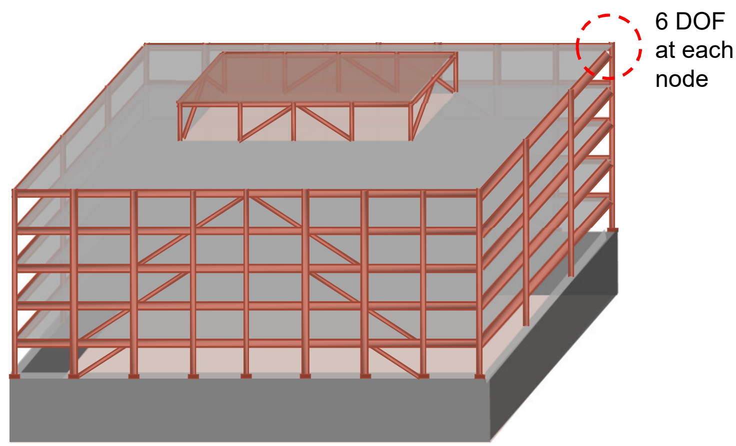
Degrees of freedom (DOF)



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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

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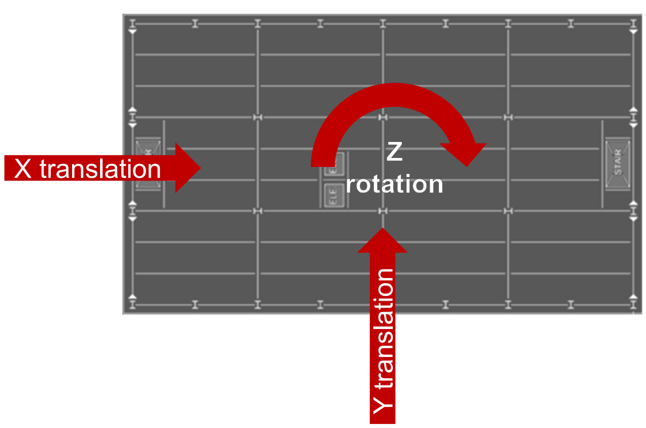
Plan degrees of freedom



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

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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

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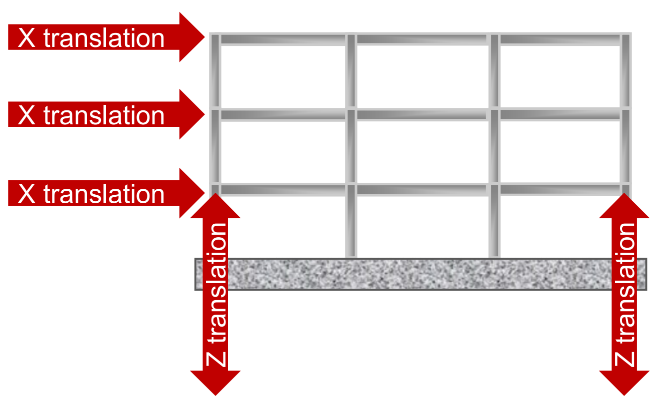
Degrees of freedom



Z translation important in that overturning flexibility contributes to lateral displacement

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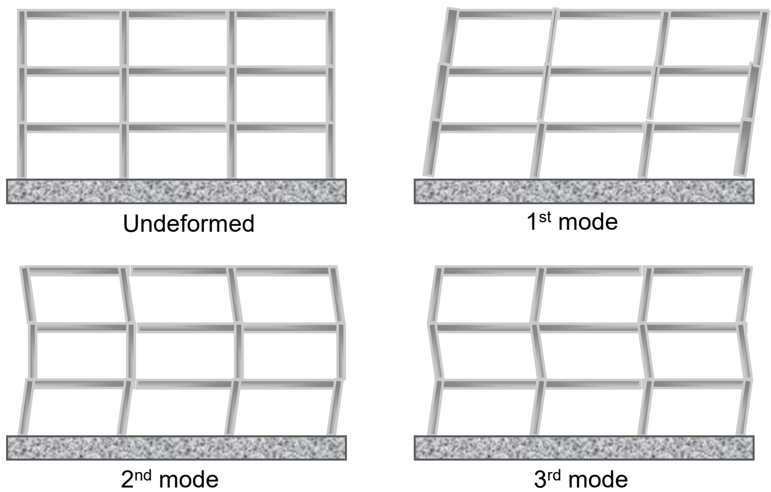
2-dimensional modes



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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

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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
- <u>Structures can be analyzed as a group of modes</u>

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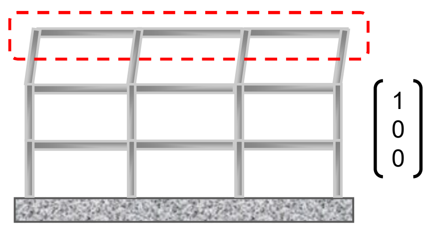
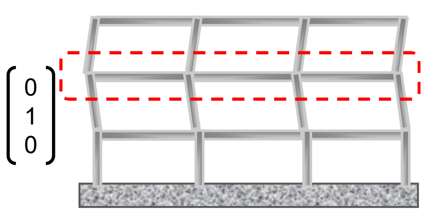
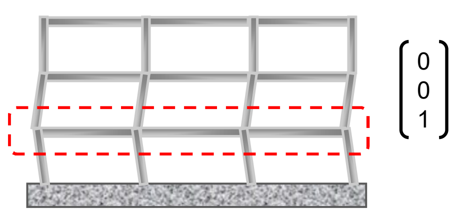
These are not modes

Only one level moves:
Linearly independent
Not a natural mode



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





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Modal analysis

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

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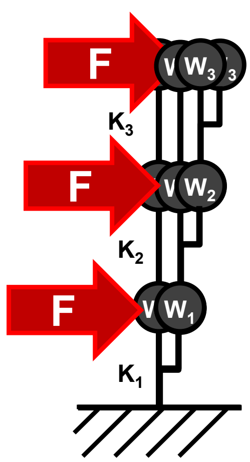
Lumped-mass and stiffness model



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

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

$\Delta_1 = F/K_1$

Overturning projection missing
from this simplified model

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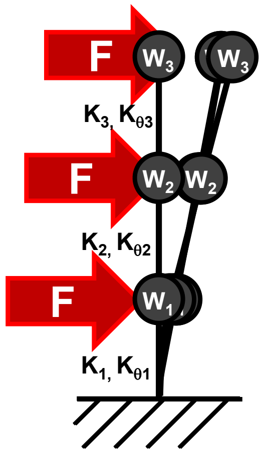
Lumped-mass and stiffness model



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

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

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

Complete stiffness matrix required for overturning

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

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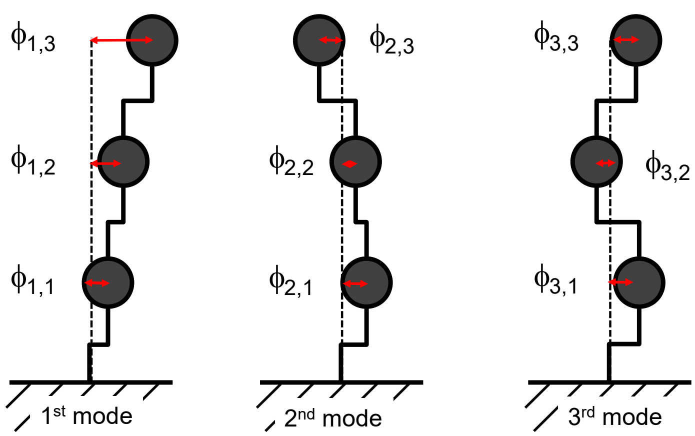
Modal vectors



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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

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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

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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*

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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

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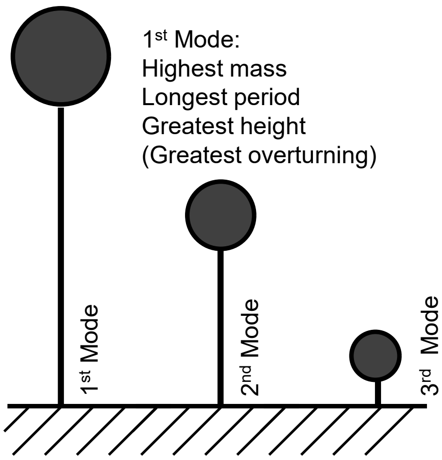
Independent modes



1st Mode:
Highest mass
Longest period
Greatest height
(Greatest overturning)

Each mode has:

- Modal mass
- Modal stiffness
- Modal period
- Modal shape (not represented)

Each mode can be represented by single degree-of-freedom [SDOF] model

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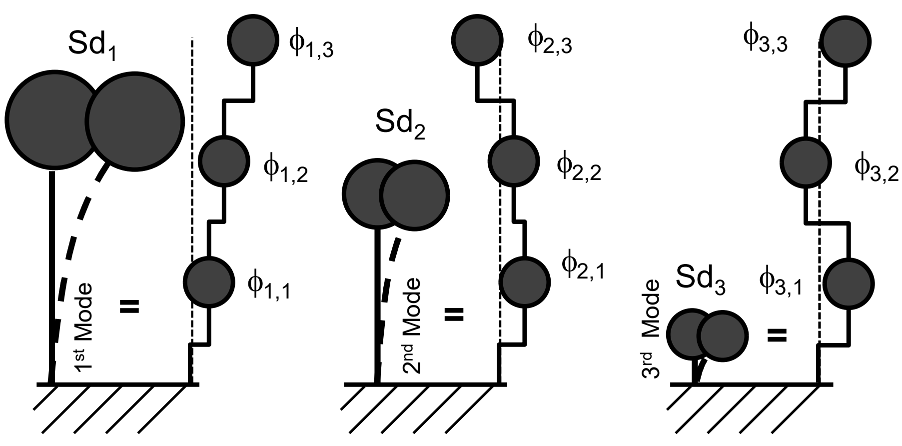
Modal model



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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

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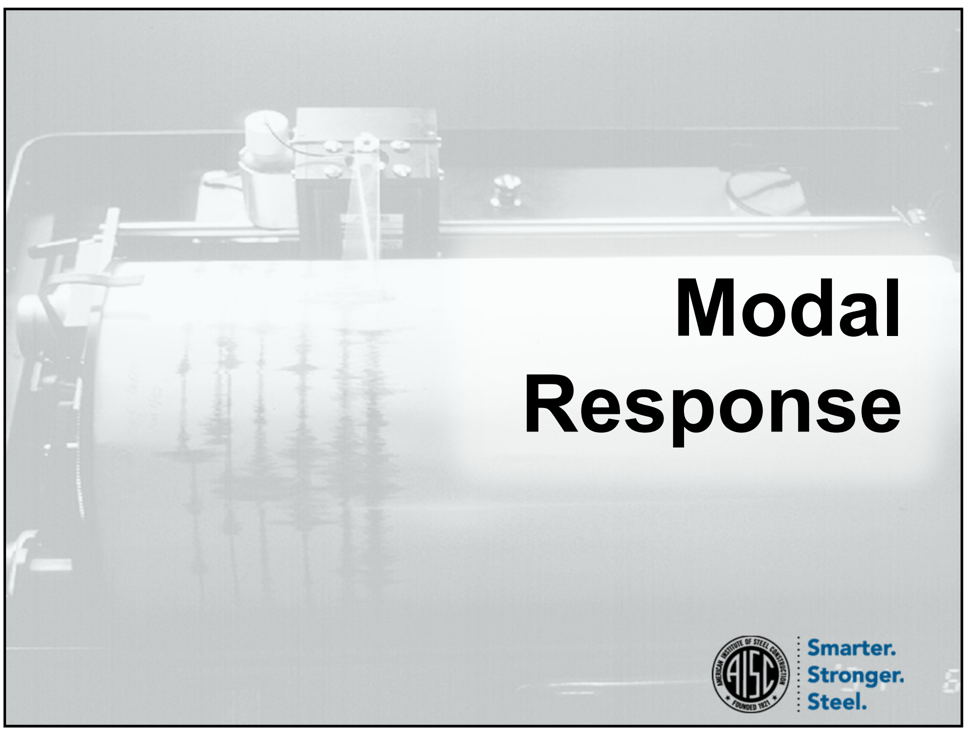

Modal response

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

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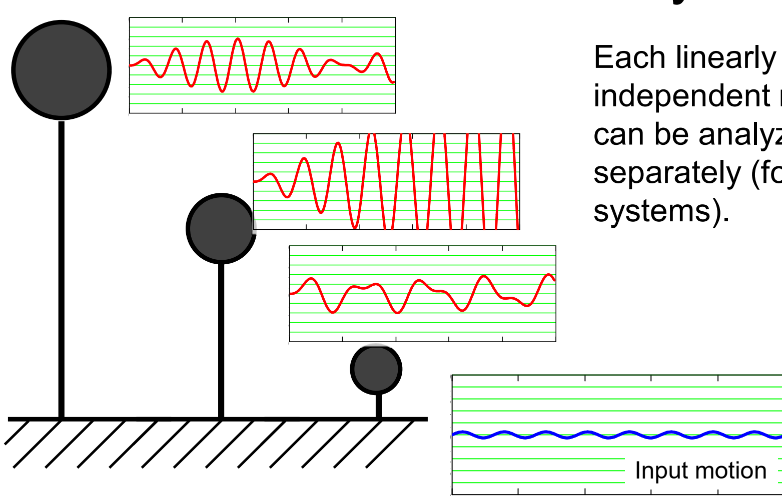
Modal time-history



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

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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:

    $u_J(t) = \Sigma u_{i,J}(t) = u_{1,J}(t) + u_{2,J}(t) + u_{3,J}(t)$

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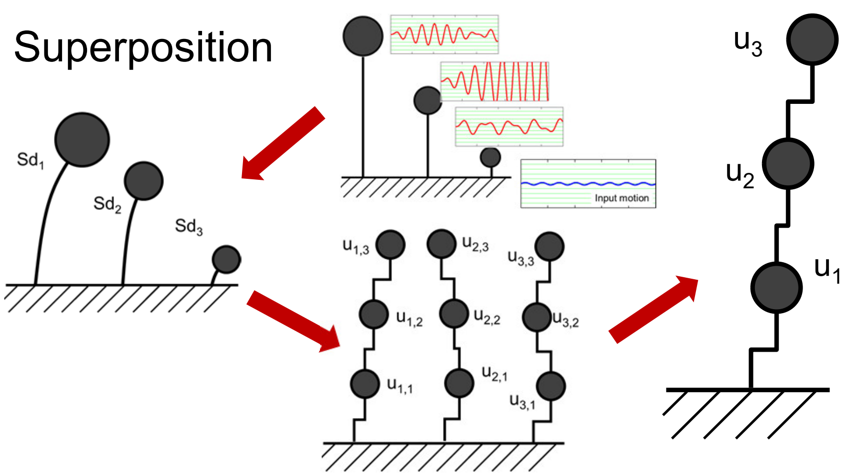
Modal time-history

- Superposition



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Maxima

- Maximum story drifts cannot be obtained from maximum displacements

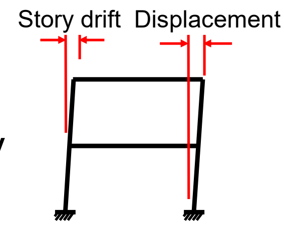
  $\delta_j(t) > \max[u_j(t)] - \max[u_{j-1}(t)]$

  $\delta_j(t)$: story drift at level j

  $u_j(t)$: displacement at level j

- Maximum drifts must be obtained from time history

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



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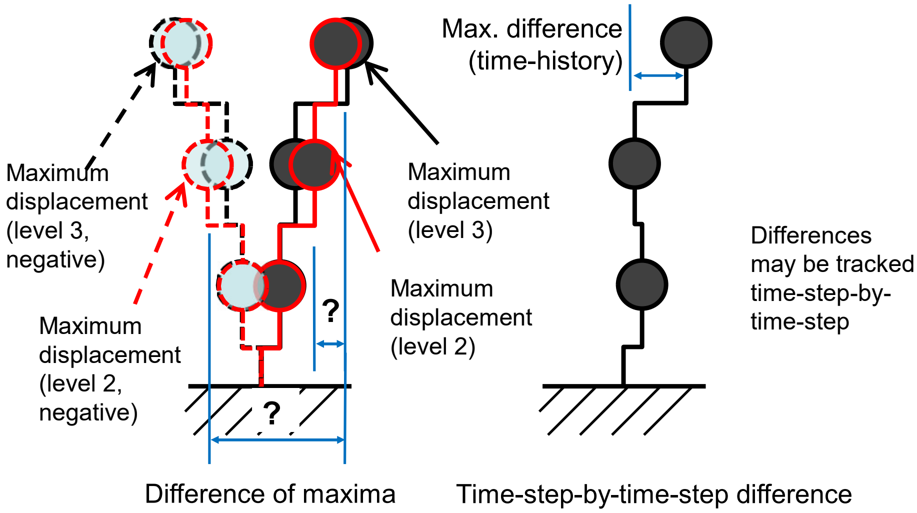
Maxima



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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

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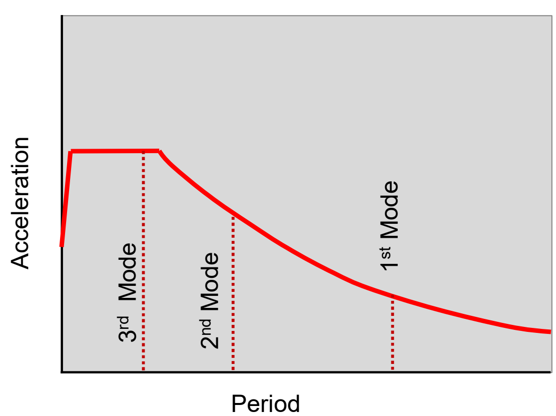
Response spectrum



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

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

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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

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Combination of modal response

- Drifts cannot be obtained from SRSS displacements

  $\delta_j > u_j - u_{j-1}$ Common mistake!
- Drifts must be tracked <u>mode by mode</u> 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

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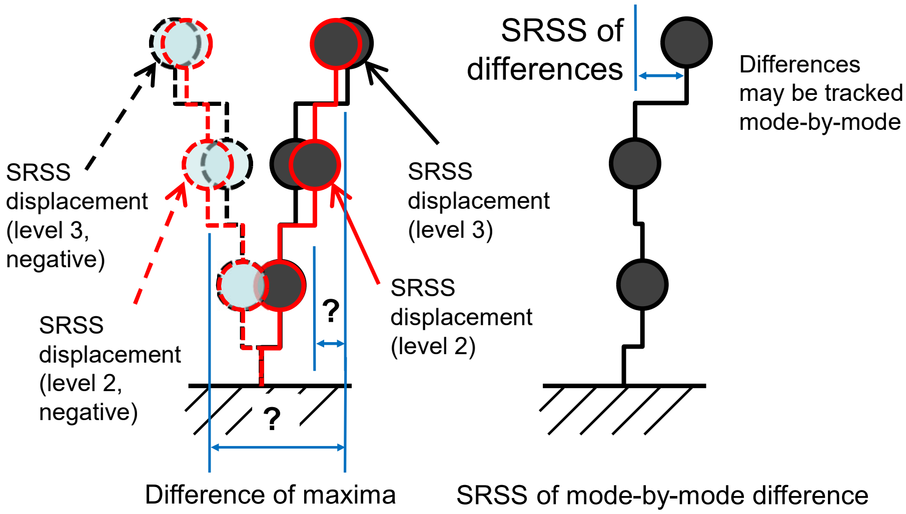
Maxima



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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

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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

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CQC

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

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

(simplified form)

$$\beta_{in} = {}^{\omega_i}/_{\omega_n}$$

Codes allow CQC for modal combination

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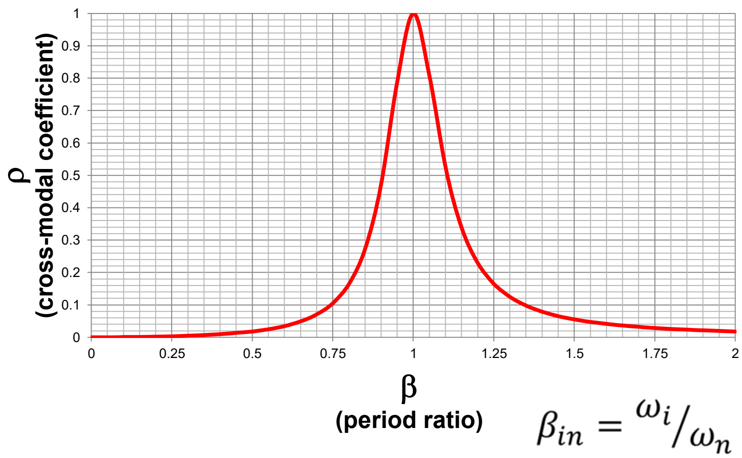
CQC (for a given damping ratio)



$$\beta_{in} = {\omega_i}/{\omega_n}$$

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

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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

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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

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Inelastic response

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

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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

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Inelasticity and modes of deformation

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

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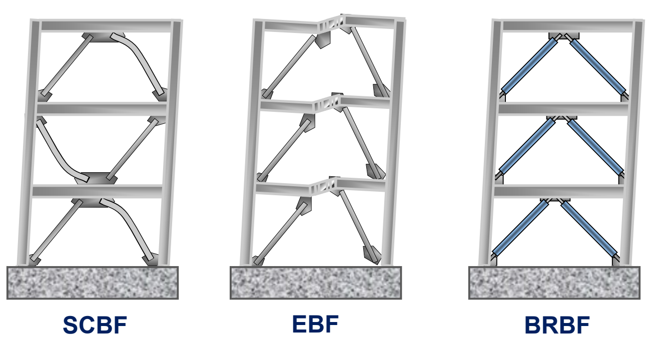
"Shear" modes



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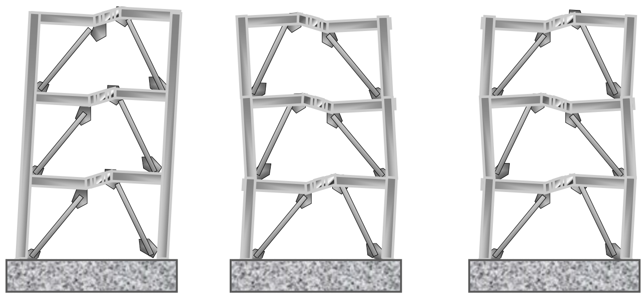
"Shear" modes

Eccentrically braced frame link yielding affects all modes.

Higher-mode inelastic deformation is possible.



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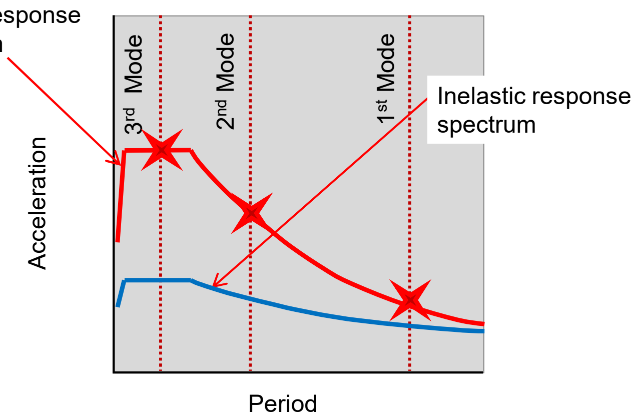
"Shear" modes



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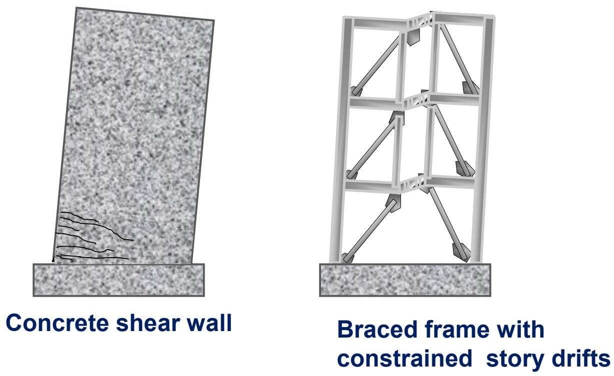
"Flexural" modes

Inelastic displacement is in pattern similar to first mode

Higher modes remain elastic (or nearly so)



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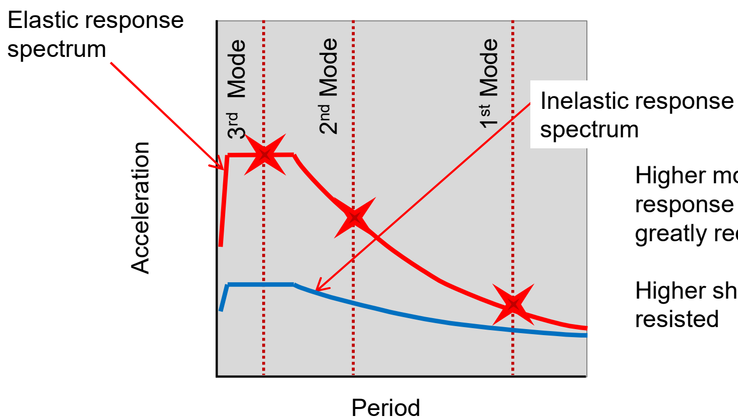
"Flexural" modes



Higher mode response may not be greatly reduced

Higher shears to be resisted

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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

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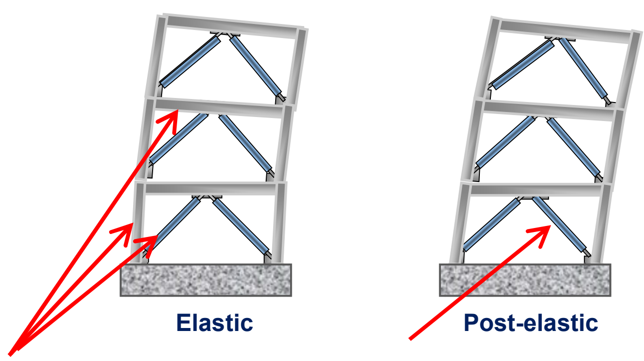
Ductility demands



Elastic drift results from column, beam, and brace deformation

Post-elastic drift results from brace deformation

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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.

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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

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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

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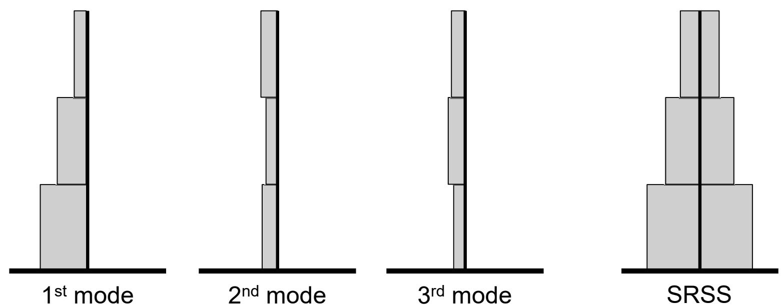
Shear



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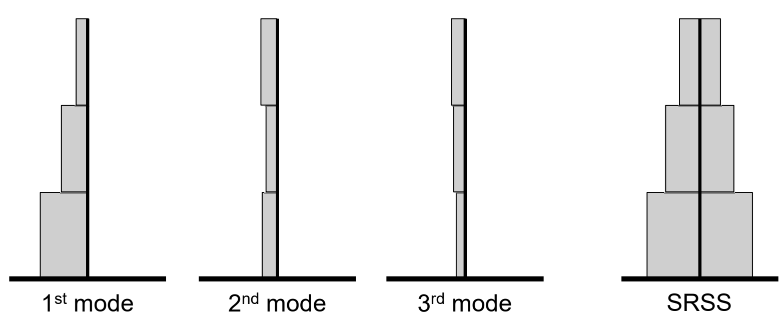
Overturning



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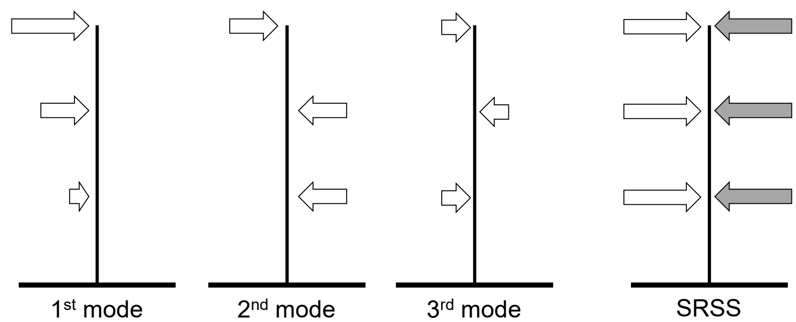
Story force



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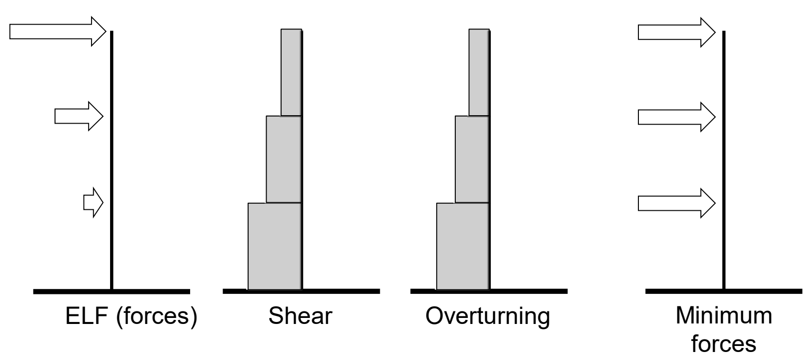
Equivalent lateral force (ELF)



Codes specify minimum diaphragm forces to supplement the ELF forces

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Modal response spectrum analysis

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

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Combining modes

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

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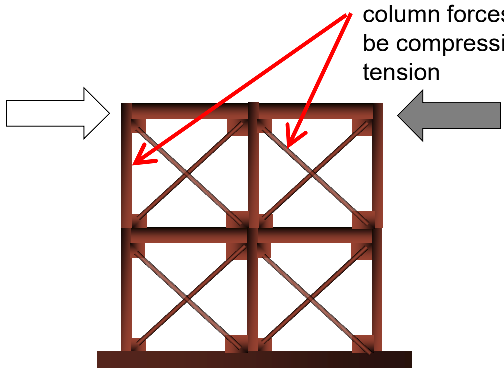
Lost signs

MRSA brace and column forces may be compression or tension



Lost signs results in considering loading from either direction

Tension-compression braces

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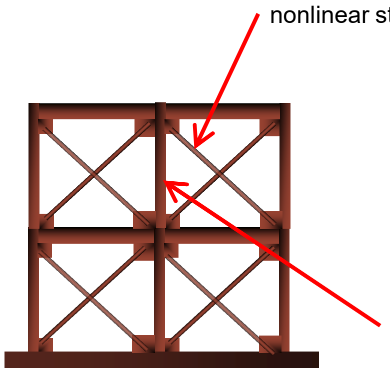
Lost signs

Braces have nonlinear stiffness



MRSA not applicable to systems with elements with nonlinear stiffness

Linear elastic analysis will show no force

Tension-only braces

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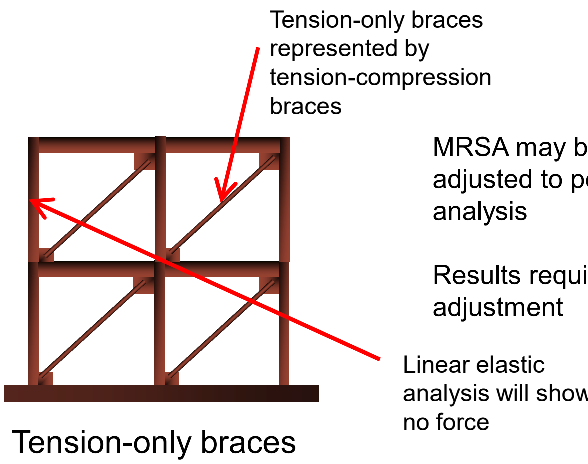
Lost signs



MRSA may be adjusted to permit analysis

Results require adjustment

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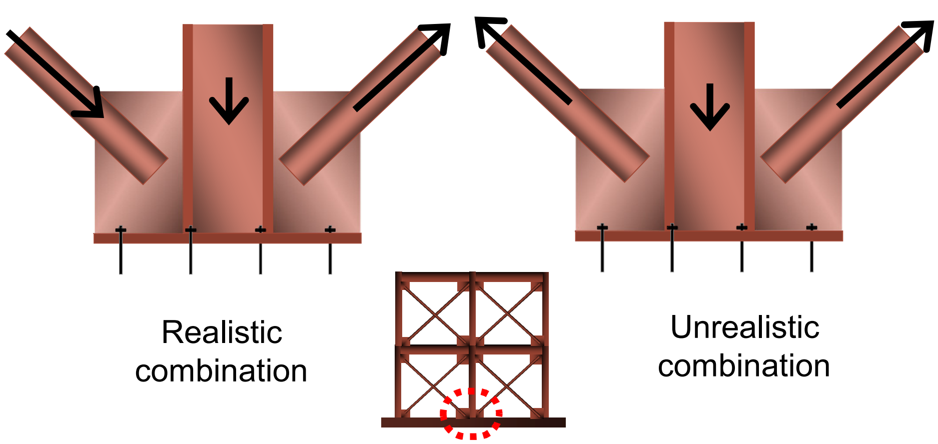
Lost signs



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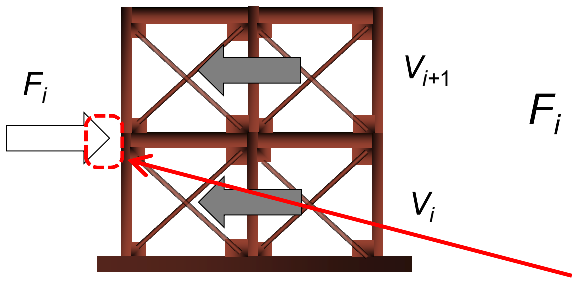
Tracking responses

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



Collector force

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

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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

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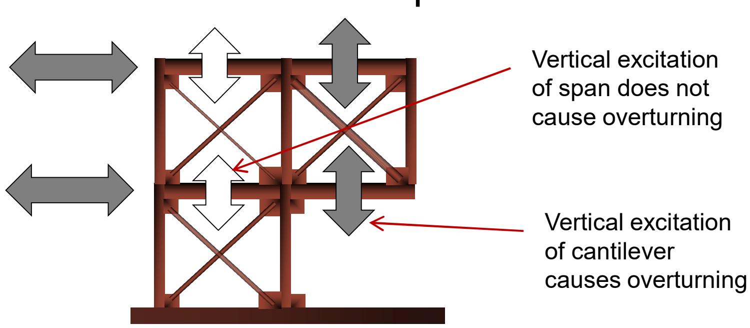
Vertical response

- Potential overturning effect couples vertical and horizontal response



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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

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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

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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

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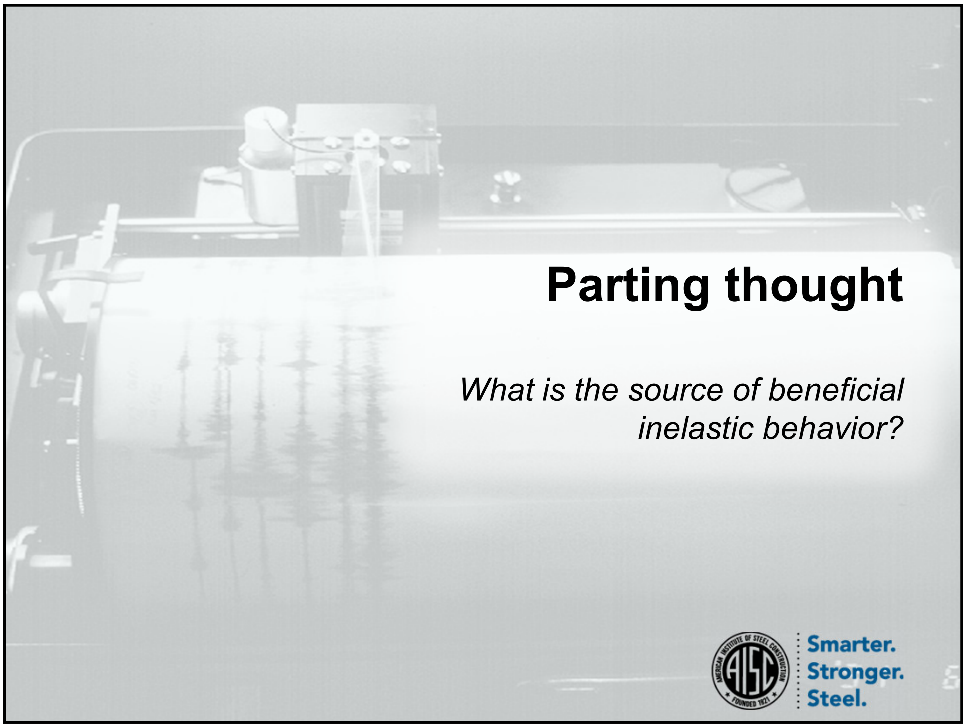
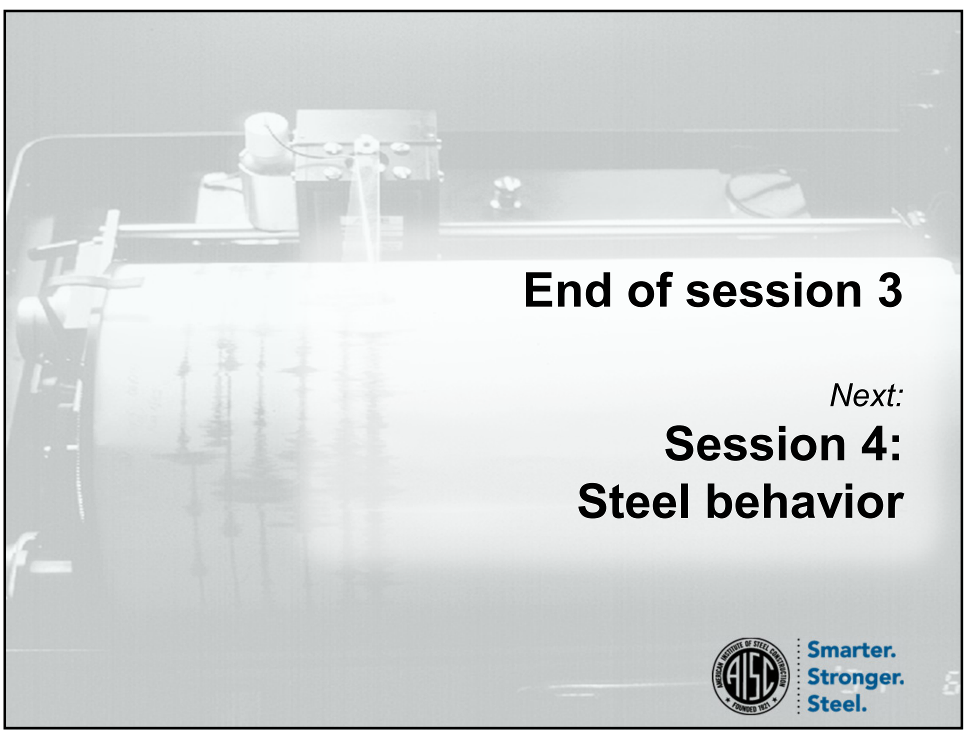
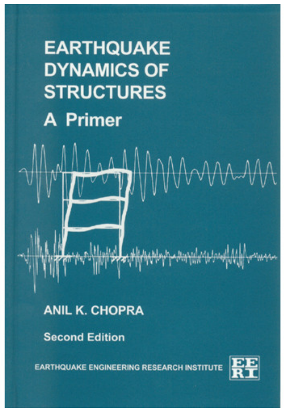
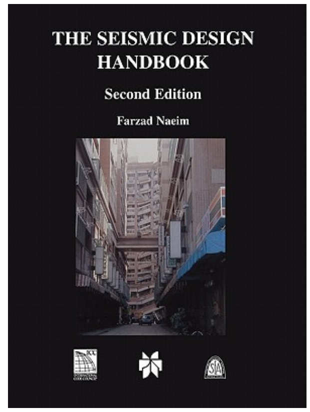

Parting thought
What is the source of beneficial inelastic behavior?
Smarter.
Stronger.
Steel.


End of session 3
Next:
Session 4:
Steel behavior
Smarter.
Stronger.
Steel.

Additional resources





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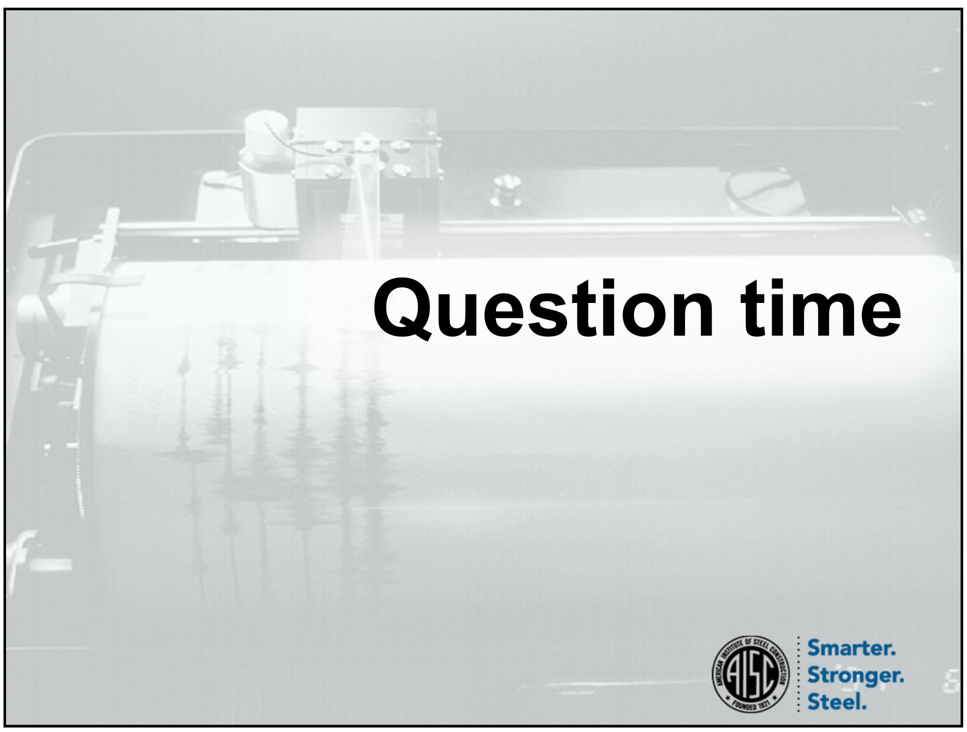

Single-Session Registrants

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.

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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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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.

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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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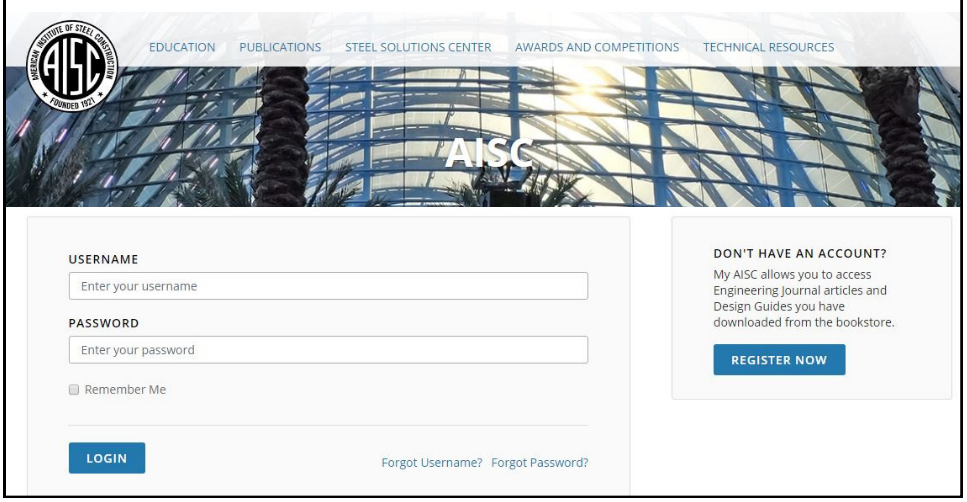
8-Session Registrants

Course Resources

Go to www.aisc.org and sign in.



8-Session Registrants

Course Resources

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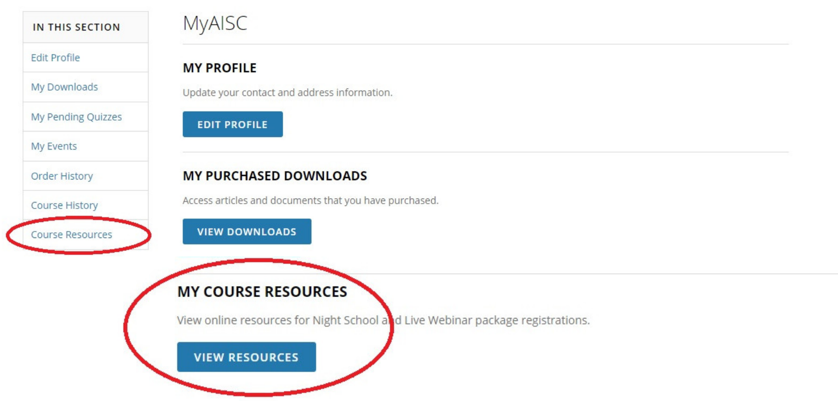
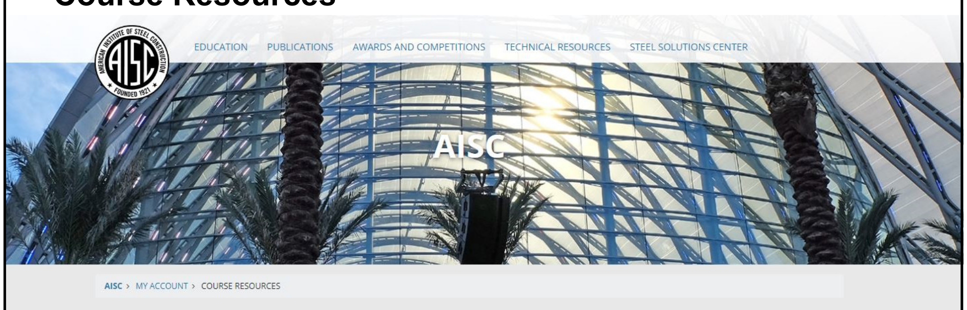


8-Session Registrants

Course Resources

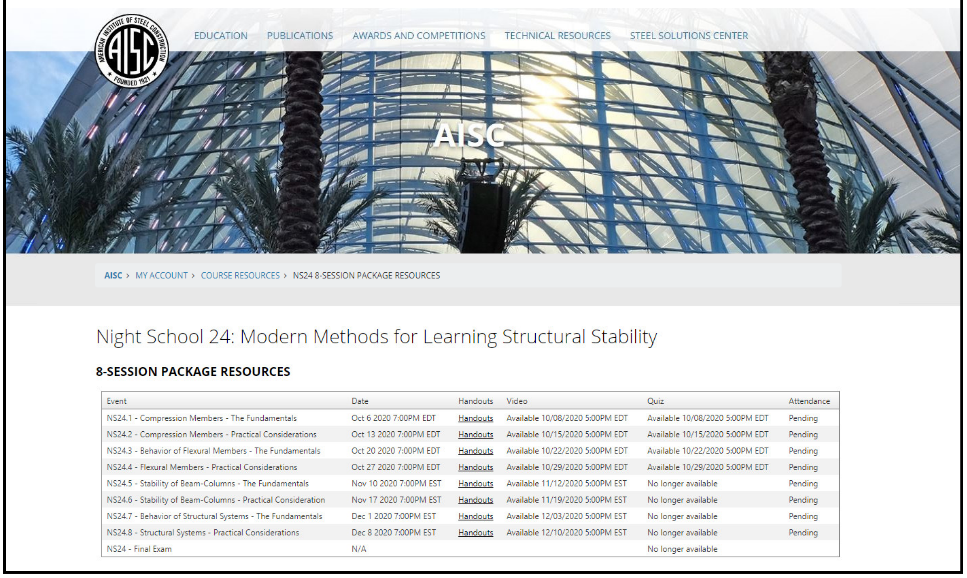


Course Resources

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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