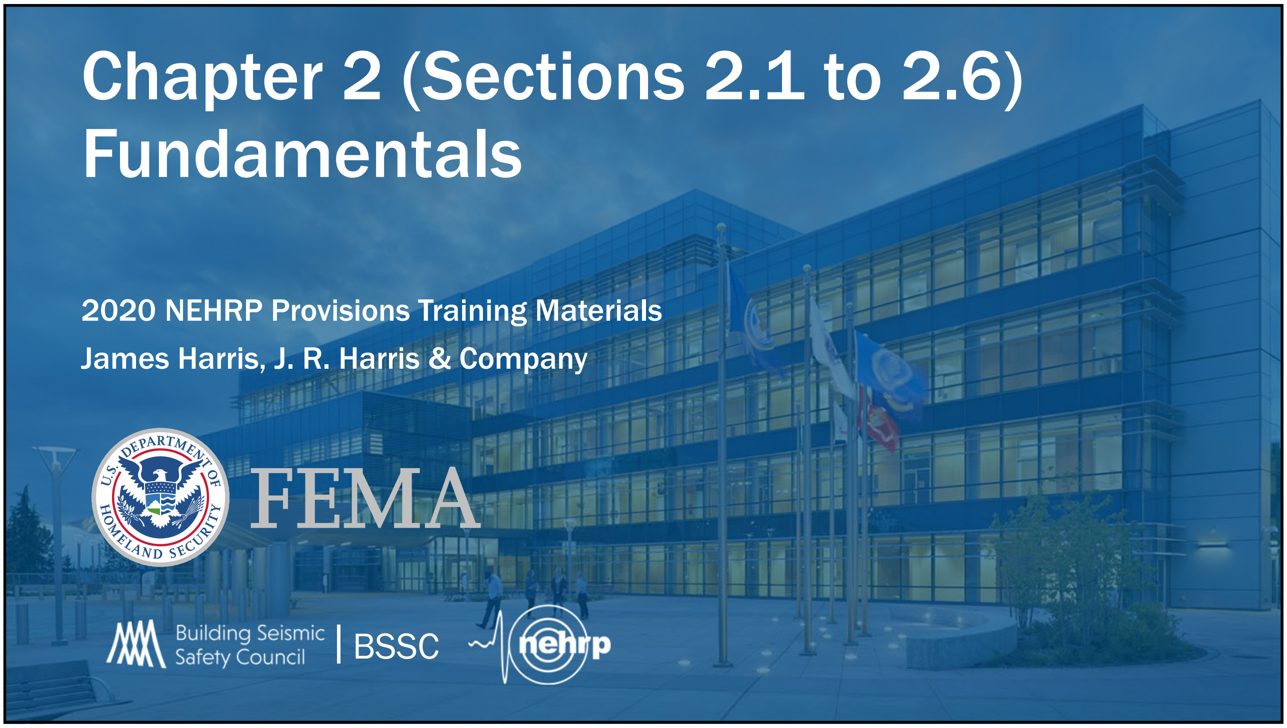

Chapter 2 (Sections 2.1 to 2.6) Fundamentals

2020 NEHRP Provisions Training Materials

James Harris, J. R. Harris & Company

Overview

- Fundamental Concepts
- Ground Motions and Their Effects
- Structural Dynamics of Linear SDOF Systems
- Response Spectra
- Structural Dynamics of Simple MDOF Systems
- Inelastic Behavior
- Structural Design

Fundamental Concepts (1)

- Ordinarily, a large earthquake produces the most severe loading that a building is expected to survive. The probability that failure will occur is very real and is greater than for other loading phenomena. Also, in the case of earthquakes, the definition of failure is altered to permit certain types of behavior and damage that are considered unacceptable in relation to the effects of other phenomena.
- The levels of uncertainty are much greater than those encountered in the design of structures to resist other phenomena. The high uncertainty applies both to knowledge of the loading function and to the resistance properties of the materials, members, and systems.
- The details of construction are very important because flaws of no apparent consequence often will cause systematic and unacceptable damage simply because the earthquake loading is so severe and an extended range of behavior is permitted.

Fundamental Concepts (2)

- During an earthquake the ground shakes violently in all directions. Buildings respond to the shaking by vibration, and the movements caused by the vibration and the ground motion induce inertial forces throughout the structure.
- In most parts of the country the inertial forces are so large that it is not economical to design a building to resist the forces elastically. Thus inelastic behavior is necessary, and structures must be detailed to survive several cycles of inelastic behavior during an earthquake.
- The structural analysis that is required to exactly account for the dynamic loading and the inelastic response is quite complex and is too cumbersome for most projects. The NEHRP Provisions and ASCE 7 provide simplified approximate analysis approaches that overcome these difficulties.
- Rules for detailing structures for seismic resistance are provided by standards such as ACI 318 and the AISC Specification and the AISC Seismic Provisions

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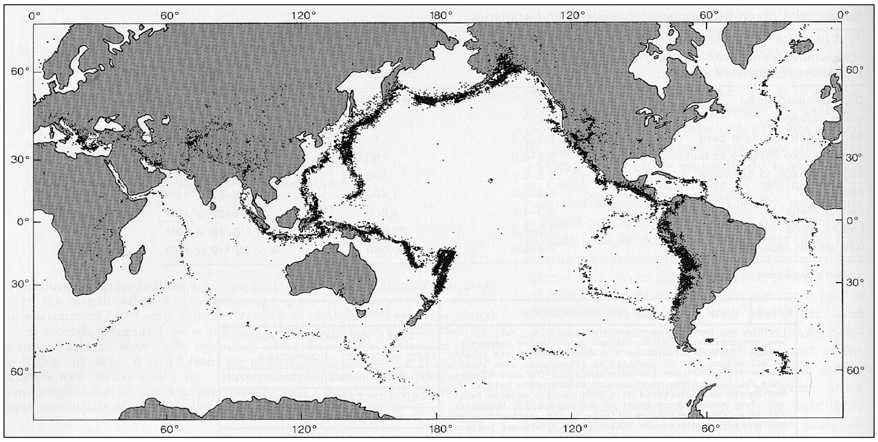
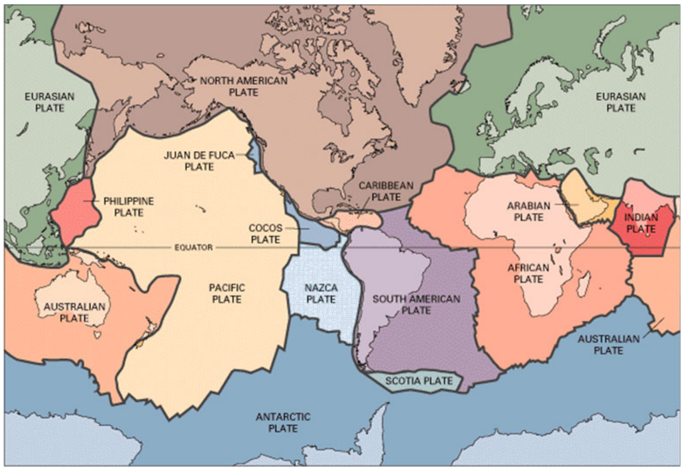
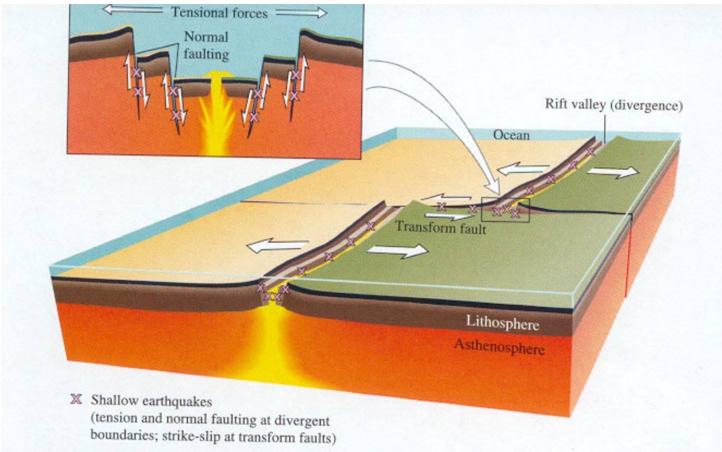
Seismic Activity on Earth



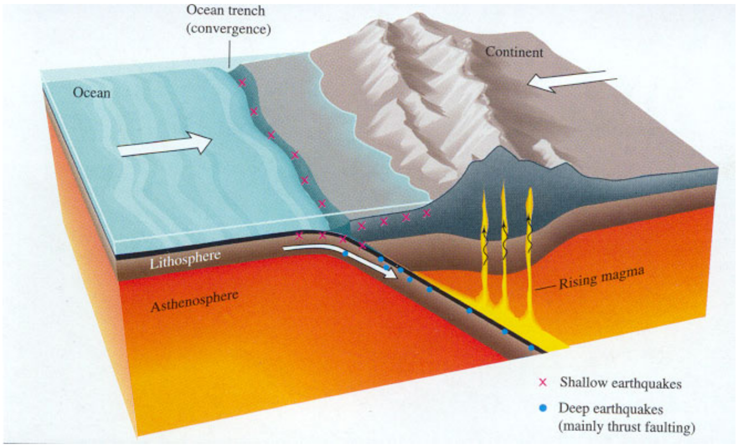
Tectonic Plates



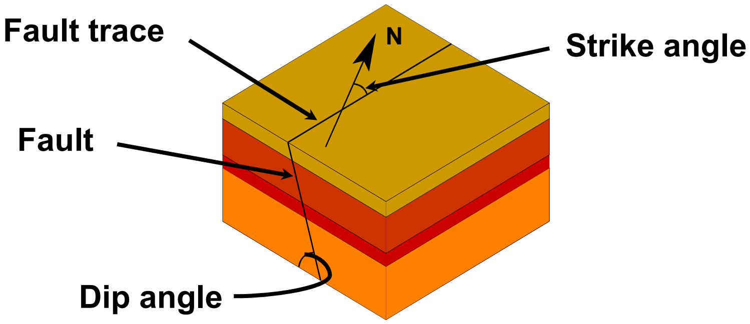
Section of Earth Crust at Ocean Rift Valley



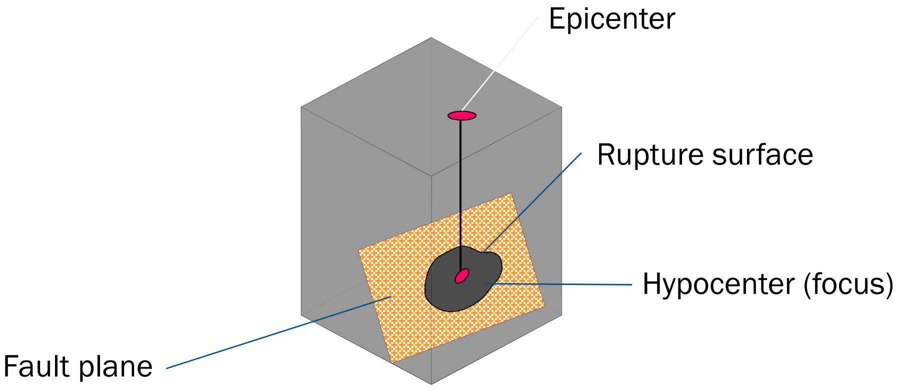
Section of Earth Crust at Plate Boundary (Subduction Zone)



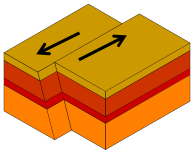
Fault Features



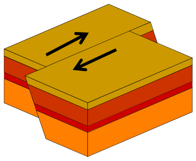
Faults and Fault Rupture



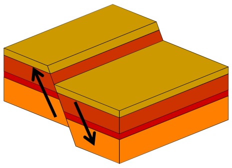
Types of Faults



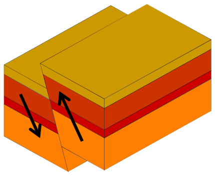
Strike Slip
(Left Lateral)



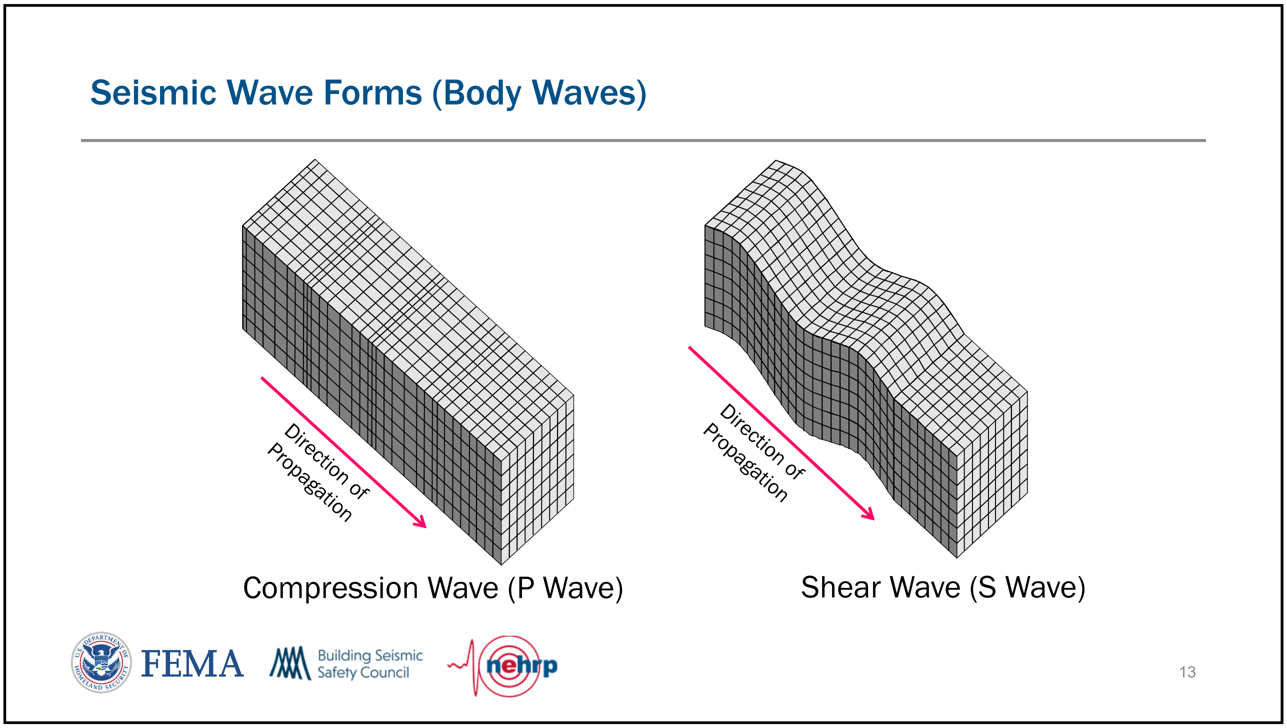
Strike Slip
(Right Lateral)



Normal



Reverse (Thrust)

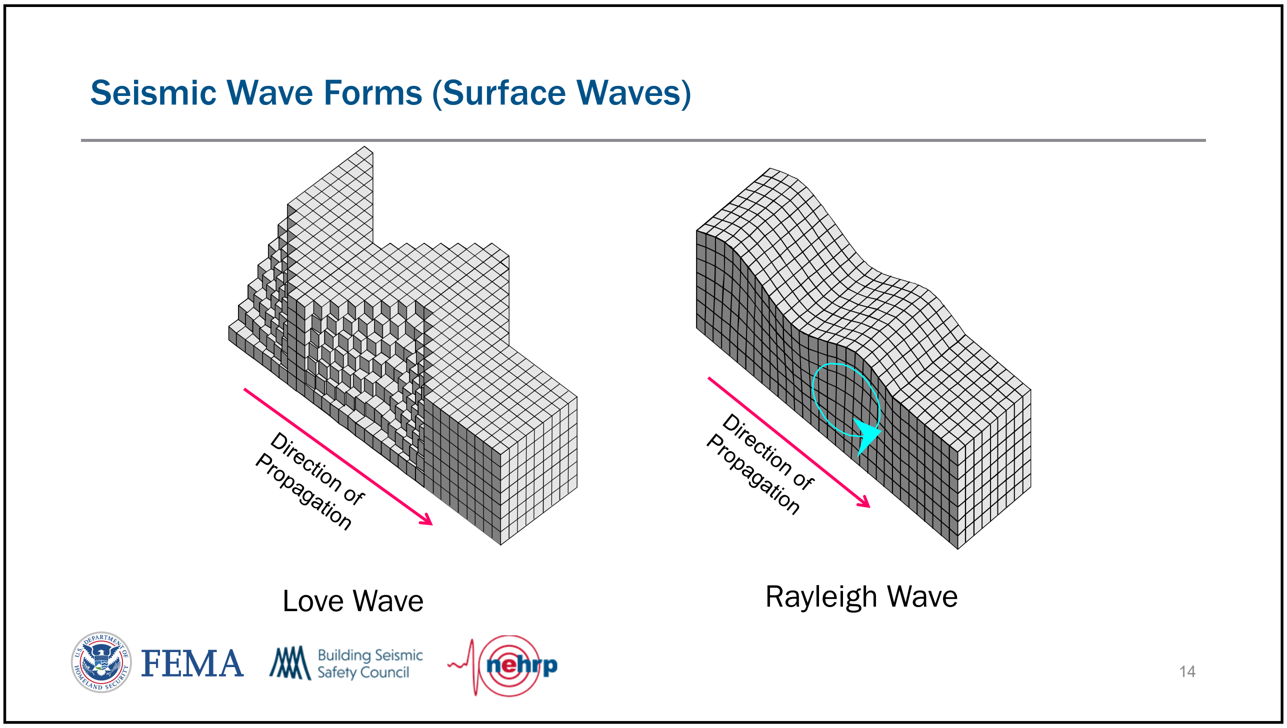


Seismic Wave Forms (Body Waves)

Compression Wave (P Wave)

Shear Wave (S Wave)

FEMA Building Seismic Safety Council nehrp



Seismic Wave Forms (Surface Waves)

Love Wave

Rayleigh Wave

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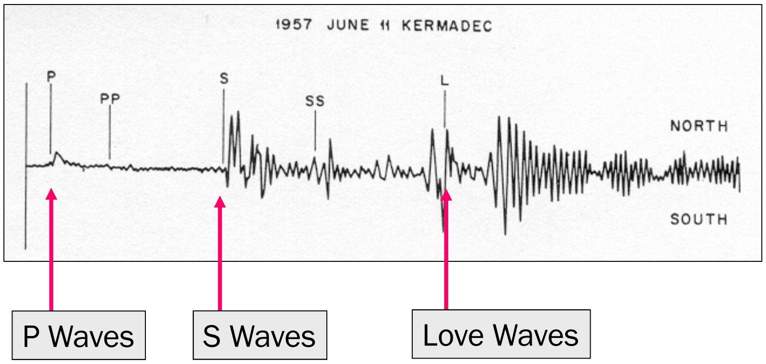
Arrival of Seismic Waves



P Waves

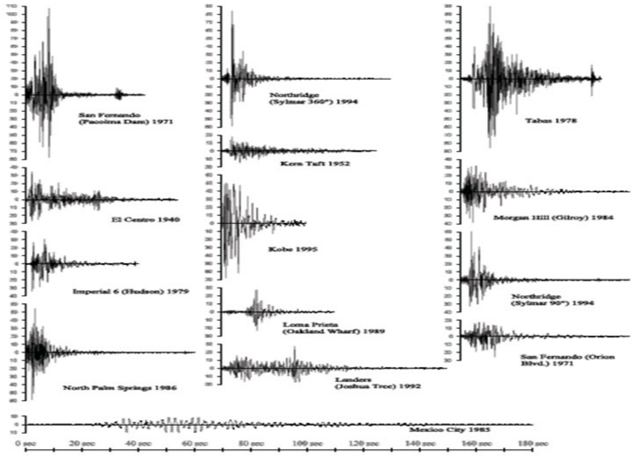
S Waves

Love Waves

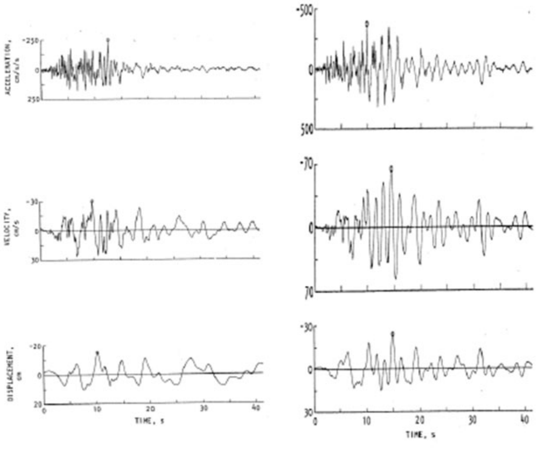
Effects of Earthquakes

- Ground Failure
  - Rupture
  - Landslide
  - Liquefaction
  - Lateral Spreading
- Tsunami
- Seiche
- Ground Shaking

Recorded Ground Motions



Shaking at the Holiday Inn During the 1971 San Fernando Valley EQ



(a) Motion at ground level

(b) Motion at roof

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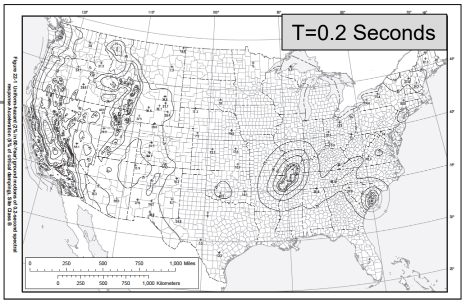
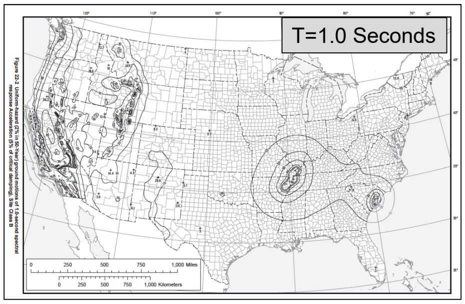
NEHRP (2009) Seismic Hazard Maps

- Probabilistic / Deterministic (Separate Maps)
- Uniform Risk (Separate Maps)
- Spectral Contours (PGA, 0.1, 0.2 sec)
- 5 % Damping
- Site Class B/C Boundary
- Maximum Direction Values


T=0.2 Seconds


T=1.0 Seconds

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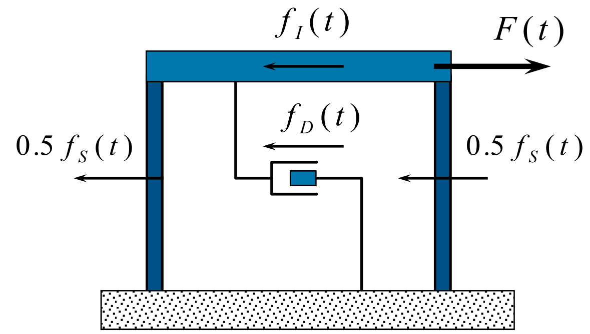
Structural Dynamics of SDOF Systems

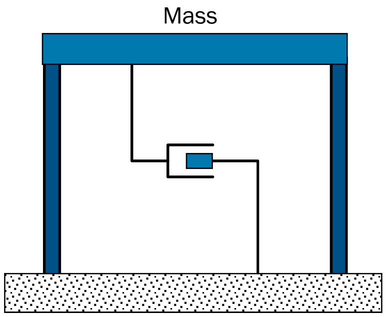


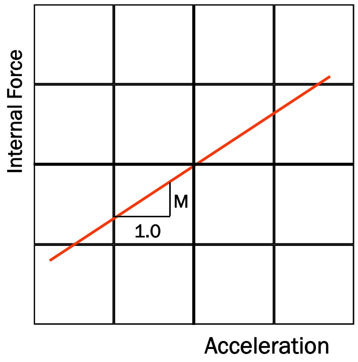
$$f_I(t) + f_D(t) + f_S(t) = F(t)$$

$$\boxed{m\,\ddot{u}(t) + c\,\dot{u}(t) + k\,u(t) = F(t)}$$

Mass

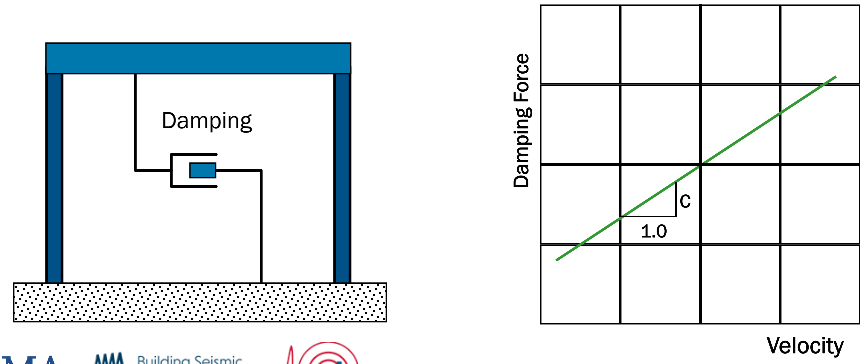
- Includes all dead weight of structure
- May include some live load
- Has units of force/acceleration



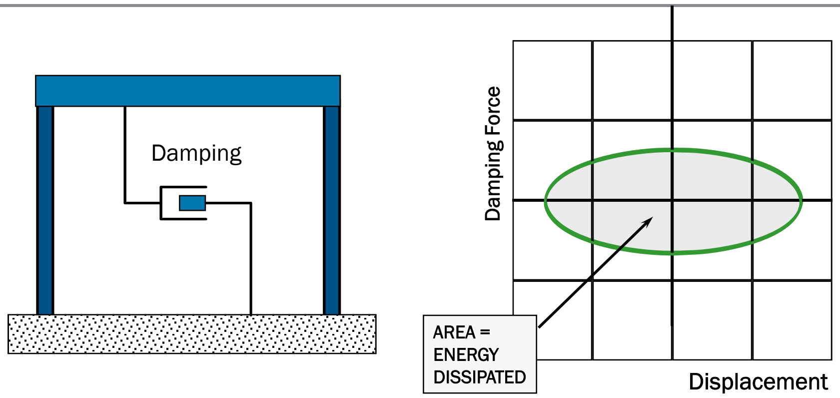


Linear Viscous Damping

- In absence of dampers, is called inherent damping
- Usually represented by linear viscous dashpot
- Has units of force/velocity



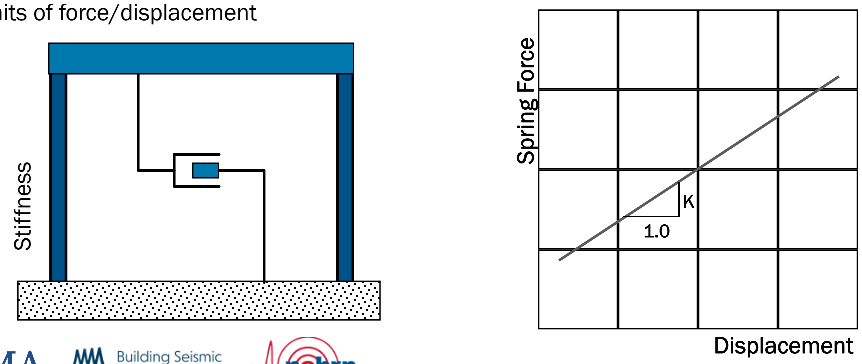
Damping and Energy Dissipation



Damping vs displacement response is elliptical for linear viscous damper.

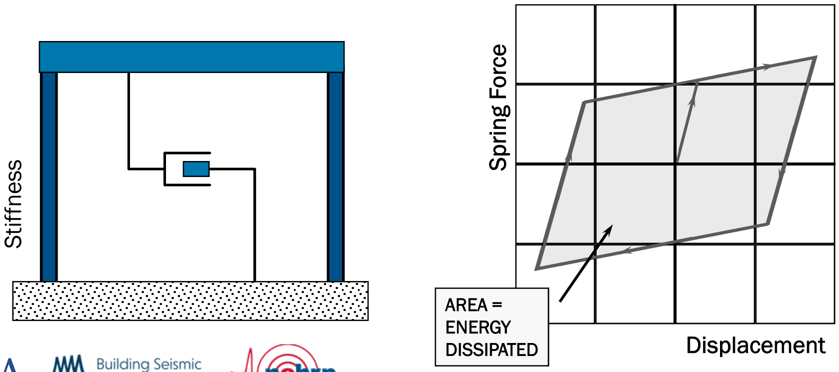
Elastic Stiffness

- Includes all structural members
- May include some “seismically nonstructural” members
- Requires careful mathematical modelling
- Has units of force/displacement



Inelastic Behavior

- Is almost always nonlinear in real seismic response
- Nonlinearity is implicitly handled by codes
- Explicit modelling of nonlinear effects is possible (but very difficult)



Undamped Free Vibration

Equation of motion: $m\ddot{u}(t) + k\,u(t) = 0$

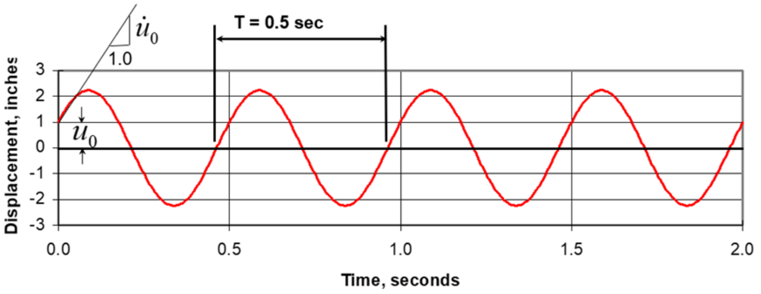
Initial conditions: $\dot{u}_0 \qquad u_0$

Assume: $u(t) = A\sin(\omega t) + B\cos(\omega t)$

Solution: $A = \dfrac{\dot{u}_0}{\omega} \qquad B = u_0 \qquad \omega = \sqrt{\dfrac{k}{m}}$

$$\boxed{u(t) = \frac{\dot{u}_0}{\omega}\sin(\omega t) + u_0\cos(\omega t)}$$

Undamped Free Vibration (2)



Circular Frequency
(radians/sec)

$$\boxed{\omega = \sqrt{\frac{k}{m}}}$$

Cyclic Frequency
(cycles/sec, Hertz)

$$\boxed{f = \frac{\omega}{2\pi}}$$

Period of Vibration
(sec/cycle)

$$\boxed{T = \frac{1}{f} = \frac{2\pi}{\omega}}$$

Periods of Vibration of Common Structures

20-story moment resisting frame	T = 2.4 sec
10-story moment resisting frame	T = 1.3 sec
1-story moment resisting frame	T = 0.2 sec
20-story steel braced frame	T = 1.6 sec
10-story steel braced frame	T = 0.9 sec
1-story steel braced frame	T = 0.1 sec
Gravity dam	T = 0.2 sec
Suspension bridge	T = 20 sec

Damped Free Vibration

Equation of motion: $$m\,\ddot{u}(t) + \boxed{c\,\dot{u}(t)} + k\,u(t) = 0$$

Initial conditions: $u_0 \quad \dot{u}_0$

Assume: $u(t) = e^{st}$

Solution:

$$u(t) = e^{-\xi\omega t}\left[u_0\cos(\omega_D t) + \frac{\dot{u}_0 + \xi\omega u_0}{\omega_D}\sin(\omega_D t)\right]$$

$$\boxed{\xi = \frac{c}{2m\omega} = \frac{c}{c_c}} \qquad \boxed{\omega_D = \omega\sqrt{1-\xi^2}}$$

Damped Free Vibration (2)

$$\xi = \frac{c}{2m\omega} = \frac{c}{c_c}$$

c_c is the *critical damping constant.*

ξ is expressed as a ratio ($0.0 < \xi < 1.0$) in computations.

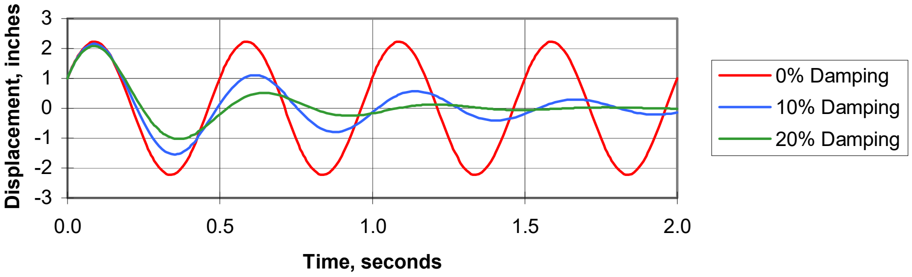
Sometimes ξ is expressed as a% ($0 < \xi < 100\%$).

Response of Critically Damped System, $\xi=1.0$ or 100% critical

---

Damped Free Vibration (3)

True damping in structures is NOT viscous. However, for low damping values, viscous damping allows for linear equations and vastly simplifies the solution.

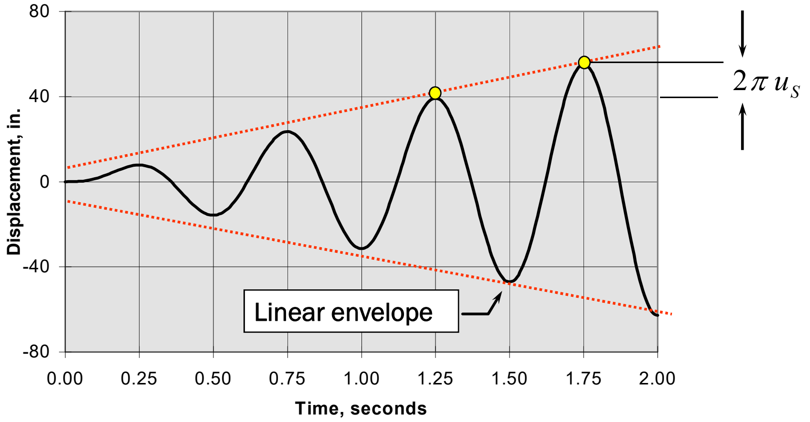


Damping in Structures

Welded steel frame	ξ = 0.010
Bolted steel frame	ξ = 0.020
Uncracked prestressed concrete	ξ = 0.015
Uncracked reinforced concrete	ξ = 0.020
Cracked reinforced concrete	ξ = 0.035
Glued plywood shear wall	ξ = 0.100
Nailed plywood shear wall	ξ = 0.150
Damaged steel structure	ξ = 0.050
Damaged concrete structure	ξ = 0.075
Structure with added damping	ξ = 0.250

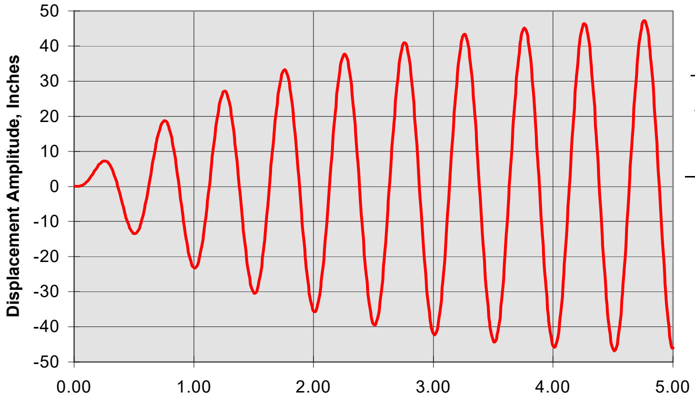
Undamped Harmonic Loading and Resonance

$$m\ddot{u}(t) + ku(t) = p_0 \sin(\overline{\omega} t)$$



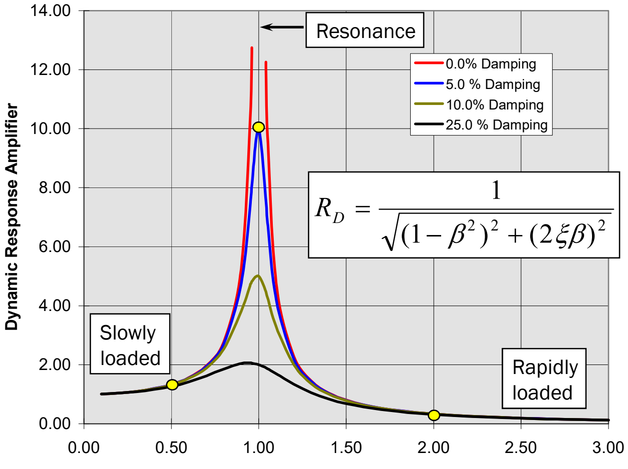
Damped Harmonic Loading and Resonance

$$m\,\ddot{u}(t) + \boxed{c\dot{u}(t)} + k\,u(t) = p_0 \sin(\overline{\omega} t)$$



$$\frac{1}{2\xi}\delta_{Static}$$

Resonant Response Curve



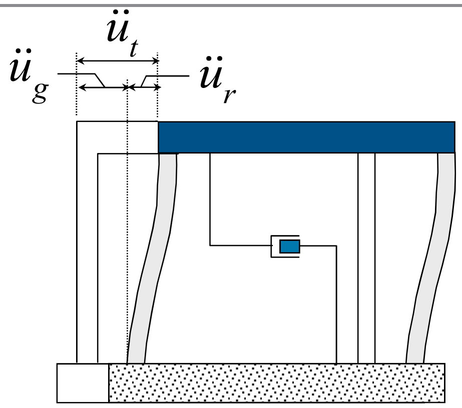
$$R_D = \frac{1}{\sqrt{(1-\beta^2)^2 + (2\xi\beta)^2}}$$

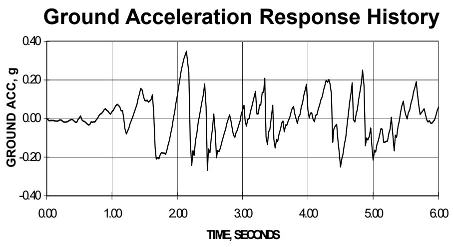
General Dynamic Loading

- Fourier transform
- Duhamel integration
- Piecewise exact
- Newmark techniques

All techniques are carried out numerically.

Effective Earthquake Force





$$m[\ddot{u}_g(t)+\ddot{u}_r(t)]+c\,\dot{u}_r(t)+k\,u_r(t)=0$$

$$\boxed{m\ddot{u}_r(t)+c\,\dot{u}_r(t)+k\,u_r(t)=-m\ddot{u}_g(t)}$$

Simplified SDOF Equation of Motion

$$m\ddot{u}_r(t) + c\dot{u}_r(t) + ku_r(t) = -m\ddot{u}_g(t)$$

Divide through by m:

$$\ddot{u}_r(t) + \frac{c}{m}\dot{u}_r(t) + \frac{k}{m}u_r(t) = -\ddot{u}_g(t)$$

Make substitutions:

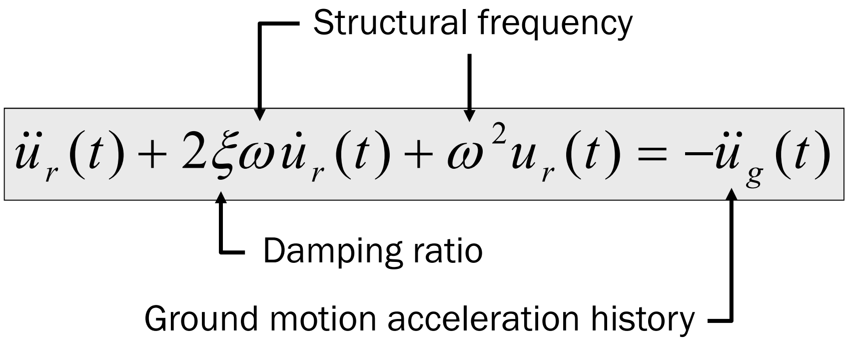
$$\frac{c}{m} = 2\xi\omega \qquad \frac{k}{m} = \omega^2$$

Simplified form:

$$\boxed{\ddot{u}_r(t) + 2\xi\omega\dot{u}_r(t) + \omega^2 u_r(t) = -\ddot{u}_g(t)}$$

Use of Simplified Equation of Motion

For a given ground motion, the response history $u_r(t)$ is function of the structure's frequency ω and damping ratio ξ.



Structural frequency

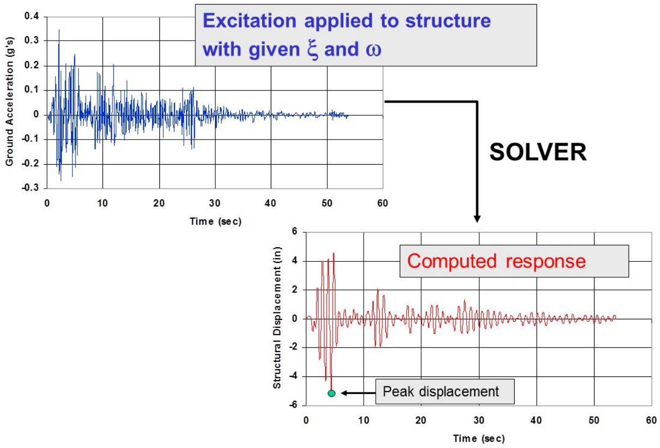
$$\boxed{\ddot{u}_r(t) + 2\xi\omega\dot{u}_r(t) + \omega^2 u_r(t) = -\ddot{u}_g(t)}$$

Damping ratio

Ground motion acceleration history

Use of Simplified Equation

Change in ground motion or structural parameters ξ and ω requires re-calculation of structural response



Excitation applied to structure with given ξ and ω

SOLVER

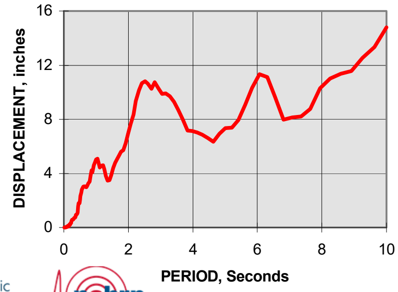
Computed response

Peak displacement

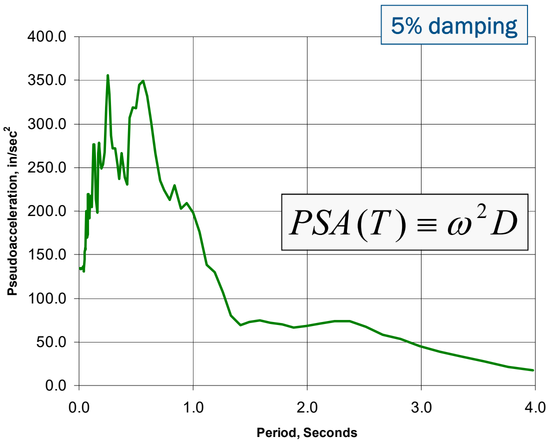
Creating an Elastic Response Spectrum

An *elastic displacement response spectrum* is a plot of the peak computed relative displacement, u_r, for an elastic structure with a constant damping ξ, a varying fundamental frequency ω (or period $T = 2\pi/\omega$), responding to a given ground motion.

5% damped response spectrum for structure responding to 1940 El Centro ground motion



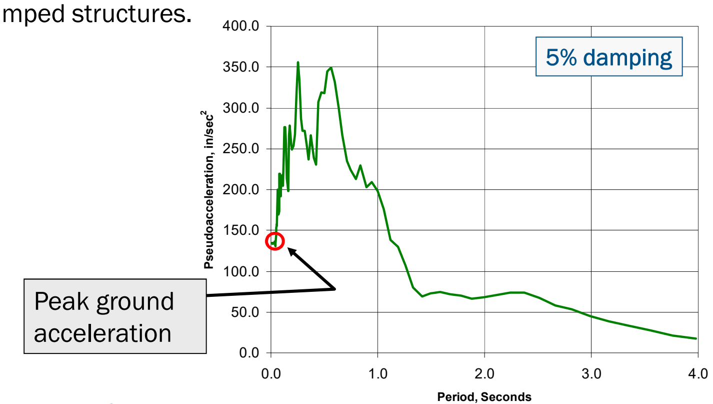
Pseudoacceleration Spectrum



$$PSA(T) \equiv \omega^2 D$$

Pseudoacceleration is Total Acceleration

The pseudoacceleration response spectrum represents the **total acceleration** of the system, not the relative acceleration. It is nearly identical to the true total acceleration response spectrum for lightly damped structures.



Peak ground acceleration

Using Pseudoacceleration to Compute Seismic Force

<u>Example Structure</u>

K = 500 k/in

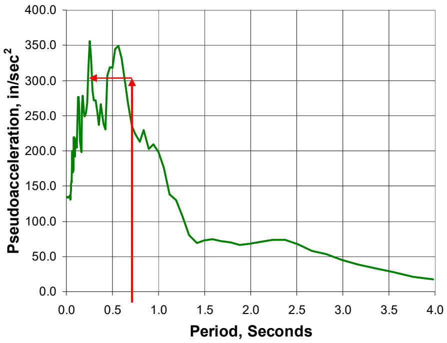
W = 2,000 k

M = 2000/386.4 = 5.18 k-sec^2/in

$\omega = (K/M)^{0.5}$ =9.82 rad/sec

$T = 2\pi/\omega$ = 0.64 sec

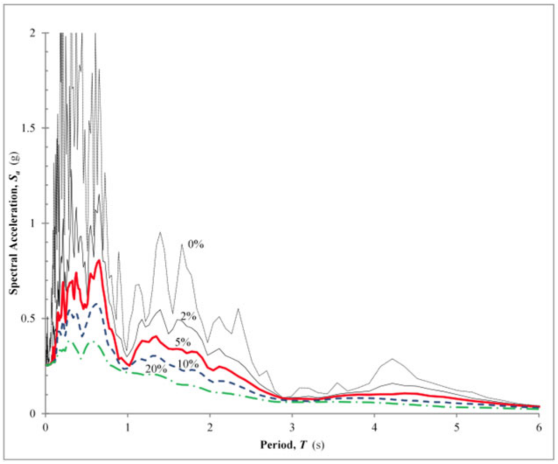
5% critical damping



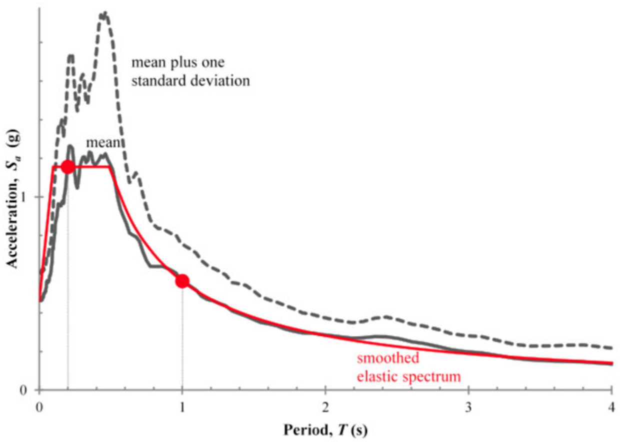
At T = 0.64 sec, pseudoacceleration = 301 in./sec^2

Base shear = M x PSA = 5.18(301) = 1559 kips

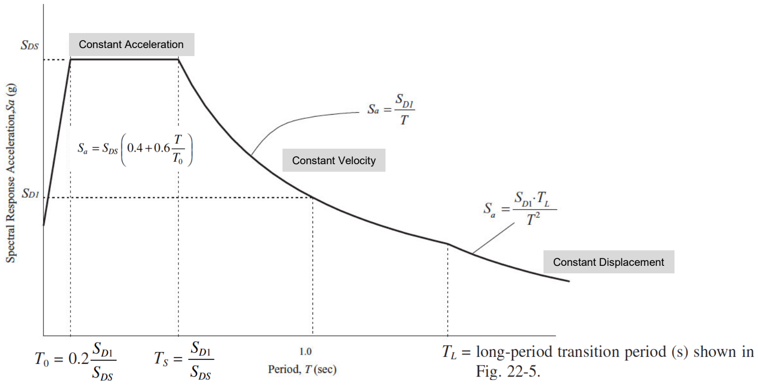
Response Spectra for 1971 San Fernando Valley EQ (Holiday Inn)



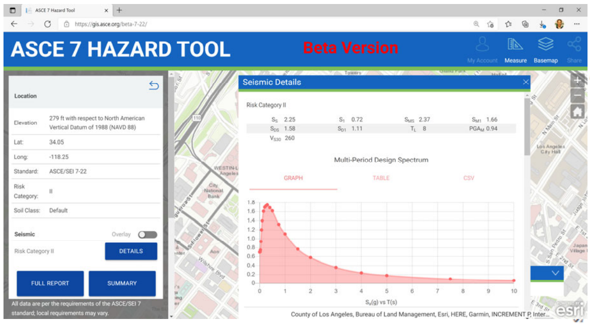
Averaged Spectrum and Code Spectrum



NEHRP/ASCE 7 Design Spectrum



NEHRP 2020 Multi-Period Spectrum and “Two” Period Spectrum


ASCE 7 Hazard Tool
https://gis.asce.org/beta-7-22/

ASCE 7 HAZARD TOOL Beta Version

Location

Elevation: 279 ft with respect to North American Vertical Datum of 1988 (NAVD 88)
Lat: 34.05
Long: -118.25
Standard: ASCE/SEI 7-22
Risk Category: II
Soil Class: Default

Seismic
Risk Category II

All data are per the requirements of the ASCE/SEI 7 standard; local requirements may vary.

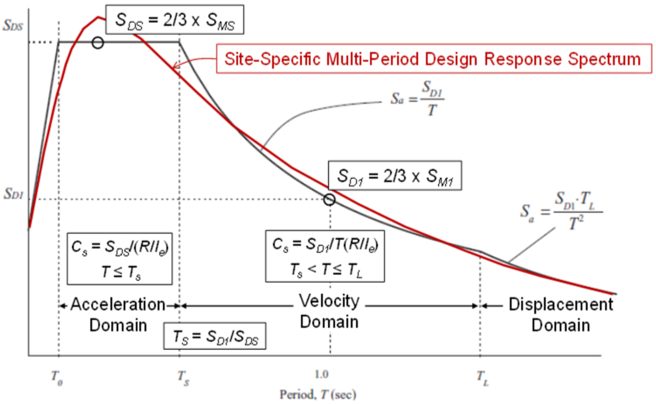
Seismic Details

Risk Category II

S_S	2.25	S_1	0.72	S_{MS}	2.37	S_{M1}	1.66
S_{DS}	1.58	S_{D1}	1.11	T_L	8	PGA_M	0.94
V_{S30}	260						

Multi-Period Design Spectrum

County of Los Angeles, Bureau of Land Management, Esri, HERE, Garmin, INCREMENT P, Inter...



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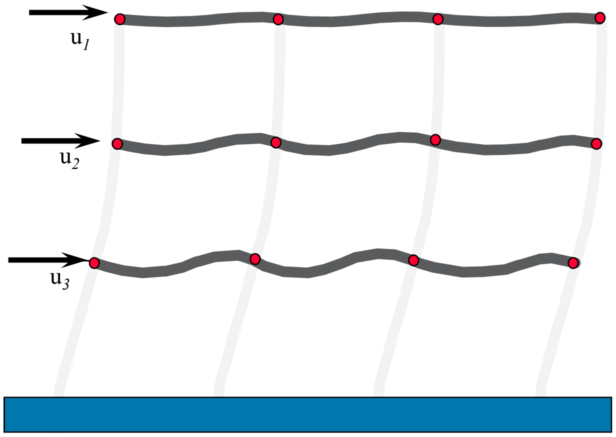
MDOF Systems



Analysis of Linear MDOF Systems

- MDOF Systems may either be solved step by step through time by using the full set of equations in the original coordinate system, or by transforming to the “Modal” coordinate system, analyzing all modes as SDOF systems, and then converting back to the original system. In such a case the solutions obtained are mathematically exact, and identical. This analysis is referred to as either Direct (no transformation) or Modal (with transformation) Linear Response History Analysis. This procedure is covered in Chapter 16 of ASCE 7.
- Alternately, the system may be transformed to modal coordinates, and only a subset (first several modes) of equations be solved step by step through time before transforming back to the original coordinates. Such a solution is approximate. This analysis is referred to as Modal Linear Response History Analysis. This procedure is not directly addressed in ASCE 7 (although in principle, Ch. 16 could be used)

Analysis of Linear MDOF Systems

- Another alternate is to convert to the modal coordinates, and instead of solving step-by-step, solve a subset (the first several modes) of SDOF systems system using a response spectrum. Such a solution is an approximation of an approximation. This analysis is referred to as Modal Response Spectrum Analysis. This procedure is described in Chapter 12 of ASCE 7.
- Finally, the equivalent lateral force method may be used, which in essence, is a one-mode (with higher mode correction) Modal Response Spectrum Analysis. This is an approximation of an approximation of an approximation (but is generally considered to be “good enough for design”.) The Provisions and ASCE 7 do place some restrictions on the use of this method.

Overview

- Fundamental Concepts
- Ground Motions and Their Effects
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Basic Base Shear Equations in NEHRP and ASCE 7

$$V = C_s W$$

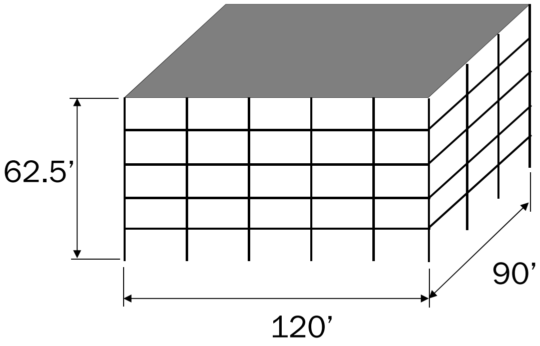
$$C_s = \frac{S_{DS}}{(R/I_e)} \qquad C_s = \frac{S_{D1}}{T(R/I_e)}$$

S_{DS} and S_{D1} are short and one second (T=0.2 s and 1.0 s)Design Basis Spectral Accelerations, including Site Effects

I_e is the Importance Factor

R is a Response Modification Factor, representing Inelastic Behavior (Ductility, Over-strength, and a few other minor ingredients).

Building Designed for Wind or Seismic Load



Building properties:
Moment resisting frames
Density ρ = 8 pcf
Period T = 1.0 sec
Damping ξ = 5%
Soil Site Class “B”

Total wind force on 120’ face = 406 kips

Total wind force on 90’ face = 304 kips

Total *ELASTIC* earthquake force (in each direction) = 2592 kips

Comparison of EQ vs Wind

- ELASTIC earthquake forces 6 to 9 times wind!
- Virtually impossible to obtain economical design

$$\frac{V_{EQ}}{V_{W120}} = \frac{2592}{406} = 6.4$$

$$\frac{V_{EQ}}{V_{W90}} = \frac{2592}{304} = 8.5$$

How to Deal with Huge EQ Force?

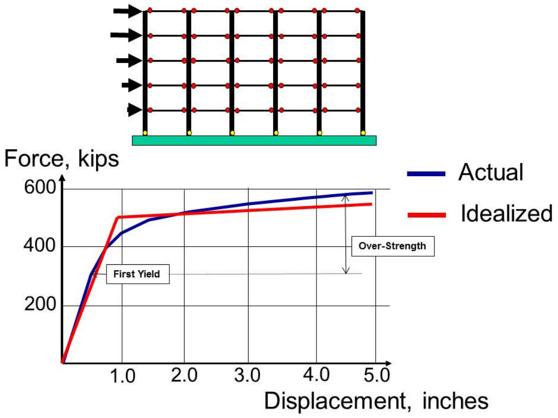
- Pay the premium for remaining elastic
- Isolate structure from ground (seismic isolation)
- Increase damping (passive energy dissipation)
- Allow controlled inelastic response

Historically, building codes use inelastic response procedure.

Inelastic response occurs through structural damage (yielding).

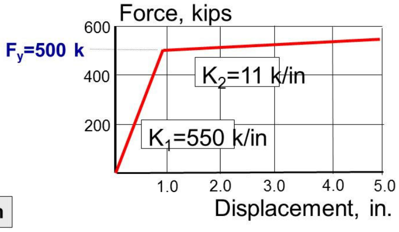
We must control the damage for the method to be successful.

Nonlinear Static Pushover Analysis

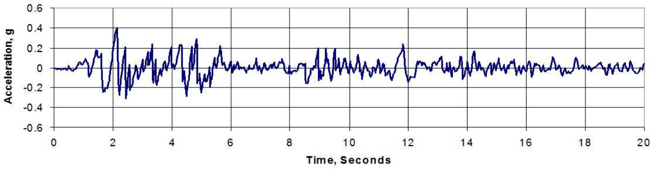


Mathematical Model and Ground Motion

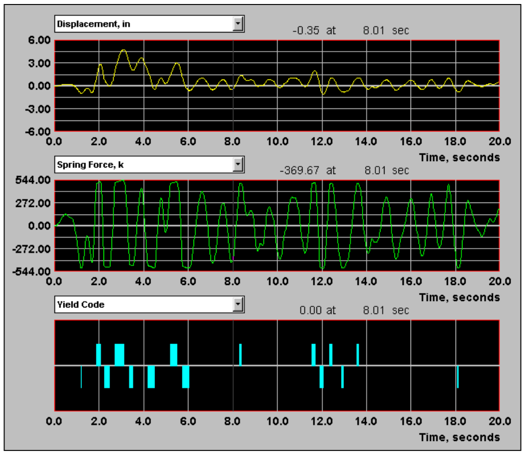
Idealized SDOF Model



El Centro Ground Motion



Results of Nonlinear Analysis



Maximum displacement:

4.79”

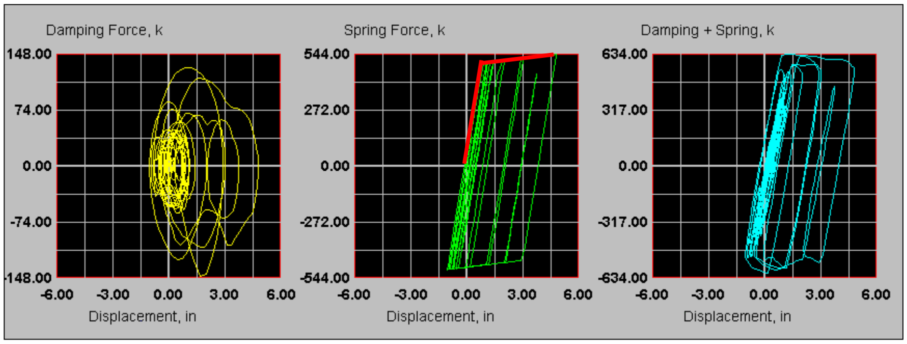
Maximum shear force:

542 k

Number of yield events:

15

Response Computed by Nonlin



Yield displacement = 500/550 = 0.91 inch

Ductility Demand $\equiv \dfrac{\text{Maximum Displacement}}{\text{Yield Displacement}} = \dfrac{4.79}{0.91} = 5.26$

Interim Conclusion (the Good News)

The frame, designed for a wind force which is 15% of the ELASTIC earthquake force, can survive the earthquake if:

- It has the capability to undergo *numerous cycles of INELASTIC deformation*
- It has the capability to *deform at least 5 to 6 times the yield deformation*
- It suffers *no appreciable loss of strength*

REQUIRES ADEQUATE DETAILING

Interim Conclusion (The Bad News)

As a result of the large displacements associated with the inelastic deformations, the structure will suffer considerable structural and nonstructural damage.

- This damage must be controlled by adequate detailing and by limiting structural deformations (drift).

Development of the Equal Displacement Concept

Concept used by:

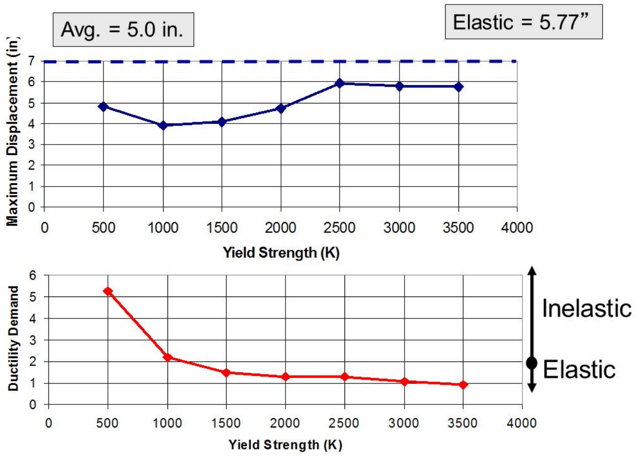
IBC NEHRP ASCE-7	In association with “force based” design concept. Used to predict design forces and displacements
ASCE 41	In association with static pushover analysis. Used to predict displacements at various performance points.

The Equal Displacement Concept

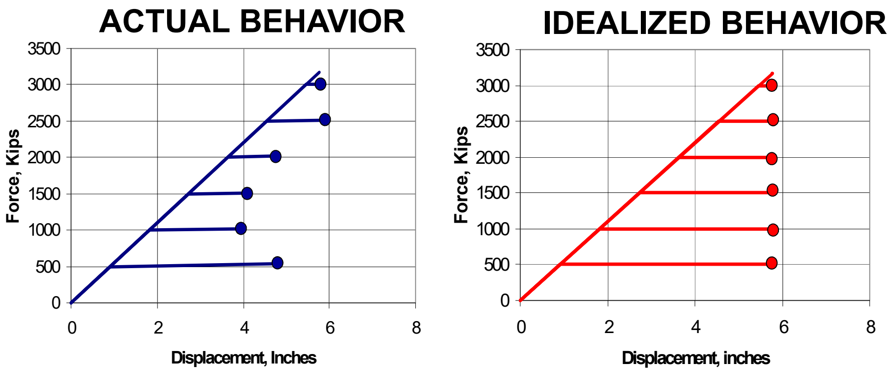
“The displacement of an inelastic system, with stiffness K and strength F_y, subjected to a particular ground motion, is approximately equal to the displacement of the same system responding elastically.”

(The displacement of a system is independent of the yield strength of the system.)

Repeated Analysis for Various Yield Strengths (and constant stiffness)



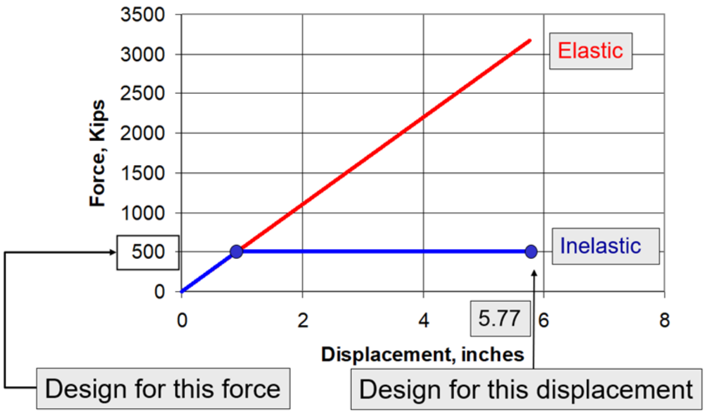
Constant Displacement Idealization of Inelastic Response



Equal Displacement Idealization of Inelastic Response

- For design purposes, it may be assumed that inelastic displacements are equal to the displacements that would occur during an elastic response.
- The required force levels under inelastic response are much less than the force levels required for elastic response.

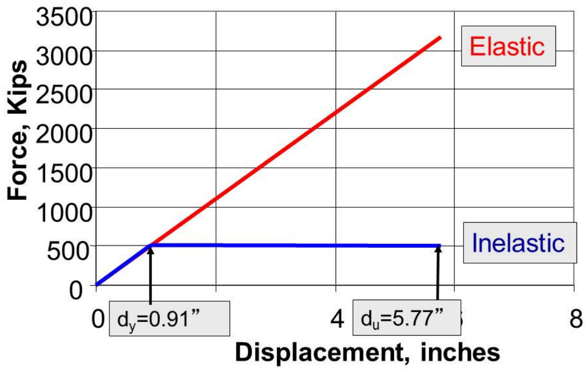
Equal Displacement Concept of Inelastic Design



Design for this force

Design for this displacement

Key Ingredient: Ductility



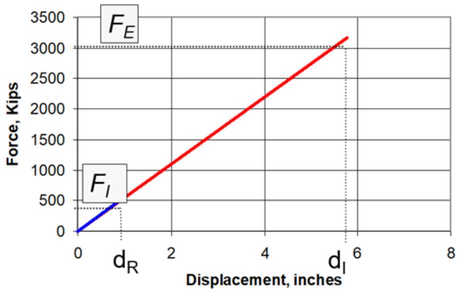
Ductility supply MUST BE > ductility demand = $\frac{5.77}{0.91} = 6.34$

Application in Principle

Using response spectra, estimate **elastic** force demand F_E

Estimate ductility supply, m, and determine **inelastic** force demand $F_I = F_E/m$**. Design structure for** F_I**.**

Compute reduced displacement. d_R, and multiply by m to obtain true inelastic displacement, d_I. **Check Drift using** d_I**.**

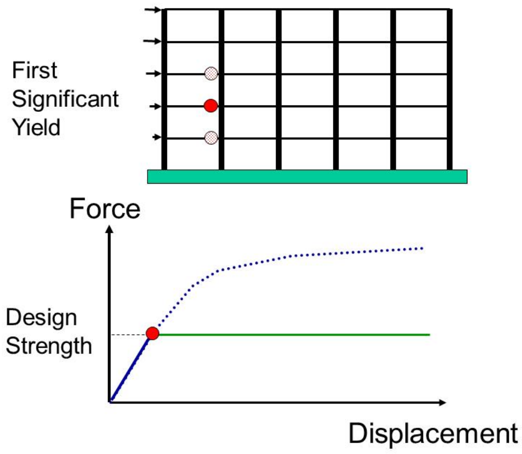


Application in Practice (NEHRP and ASCE 7)

Use basic elastic spectrum but, for strength, divide all pseudoacceleration values by *R*, a response modification factor that accounts for:

- Anticipated ductility supply
- Overstrength
- Damping (if different than 5% of critical)
- Past performance of similar systems
- Redundancy

Ductility/Overstrength First Significant Yield

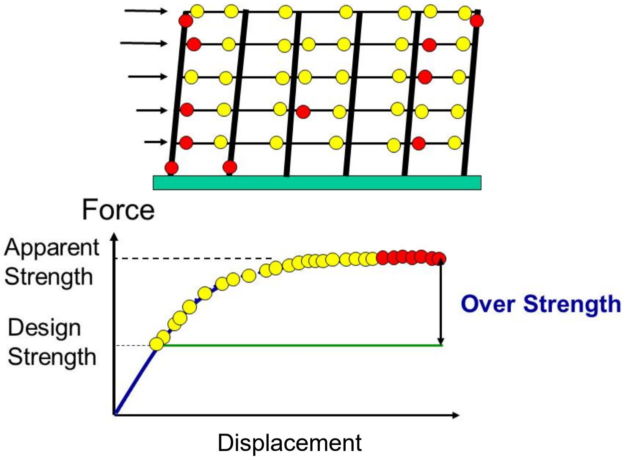


First Significant Yield and Design Strength

First Significant Yield is the level of force that causes complete plastification of at least the most critical region of the structure (e.g., formation of the first plastic hinge).

The design strength of a structure is equal to the resistance at first significant yield.

Overstrength



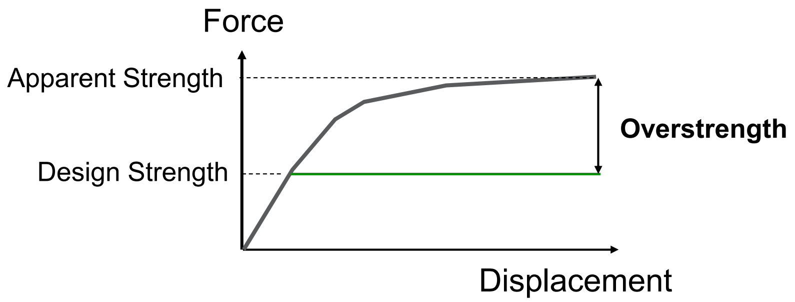
Sources of Overstrength

- Sequential yielding of critical regions
- Material overstrength (actual vs specified yield)
- Strain hardening
- Capacity reduction (ϕ) factors
- Member selection
- Structures where the proportioning is controlled by the seismic drift limits

FEMA Building Seismic Safety Council nehrp

Definition of Overstrength Factor Ω

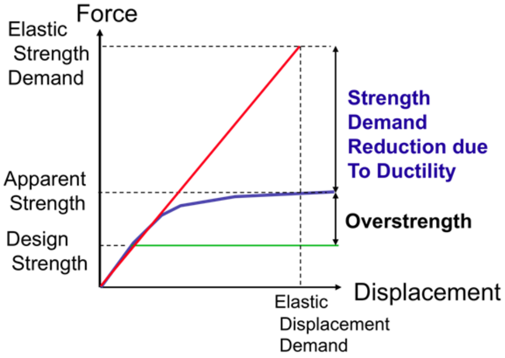
$$\text{Overstrength Factor } \Omega = \frac{\text{Apparent Strength}}{\text{Design Strength}}$$



FEMA Building Seismic Safety Council nehrp

Definition of Ductility Reduction Factor R_d

$$\text{Ductility Reduction } R_d = \frac{\text{Elastic Strength Demand}}{\text{Apparent Strength}}$$

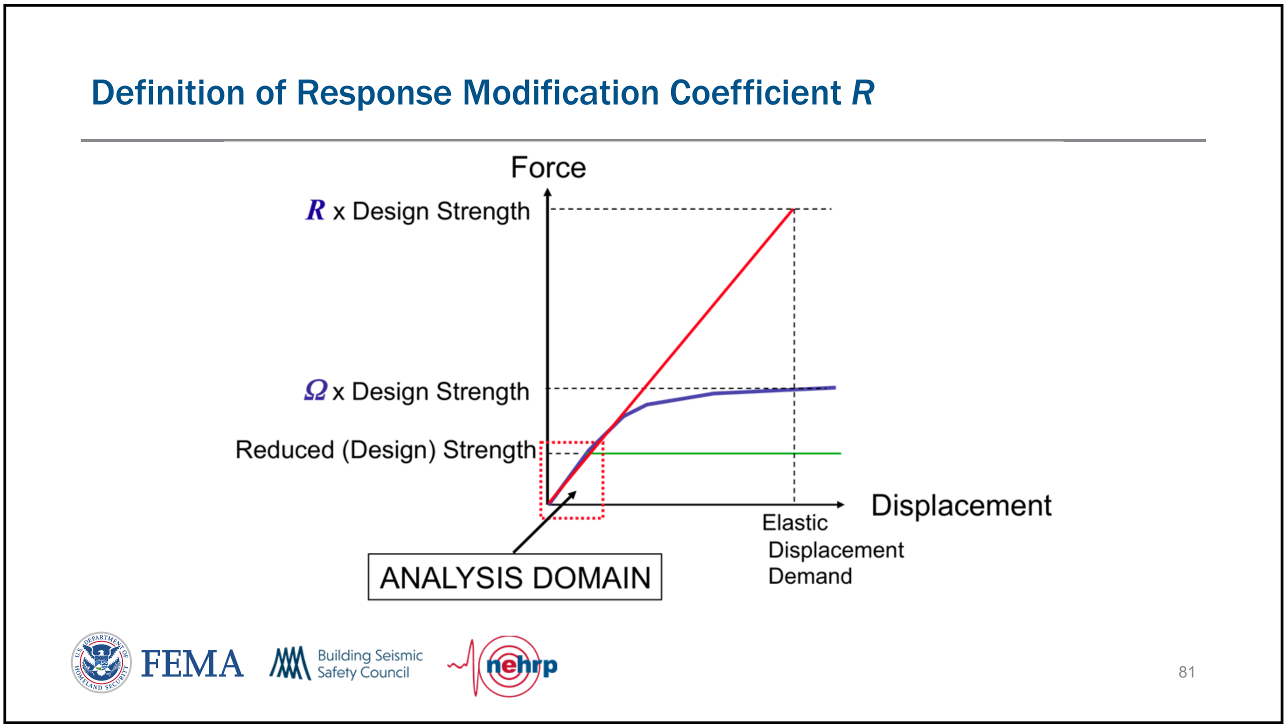


Definition of Response Modification Coefficient *R*

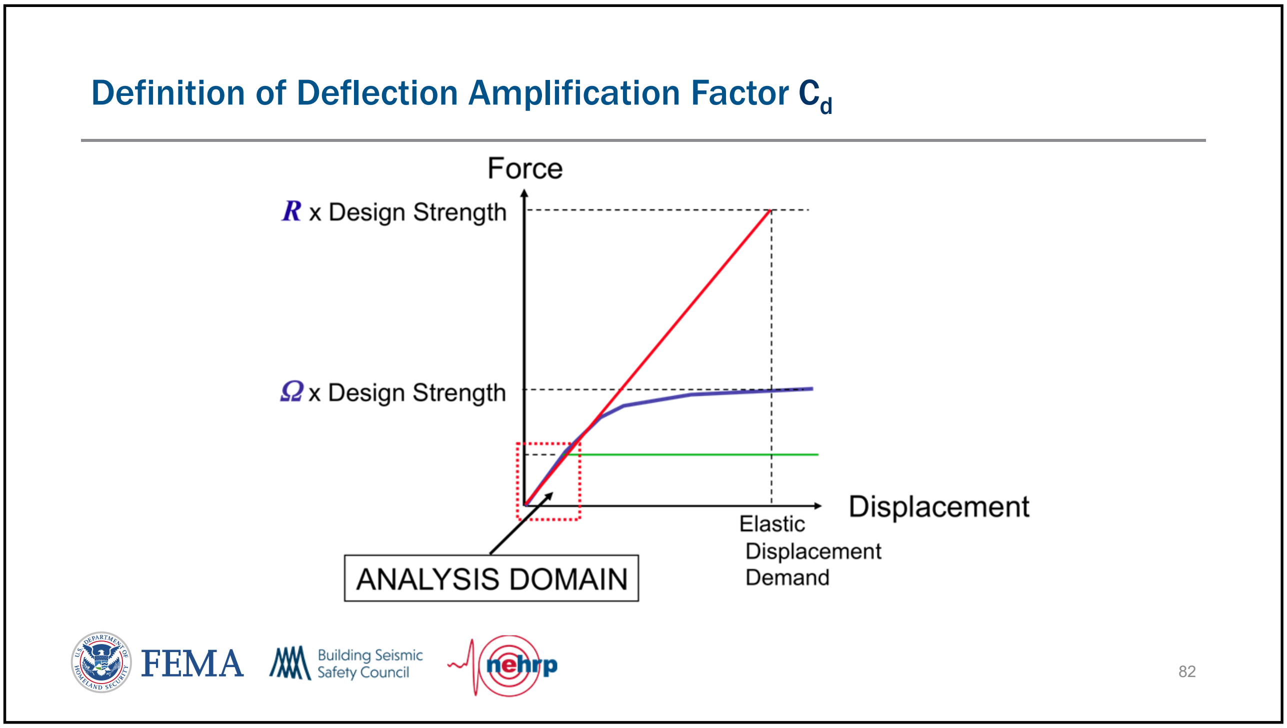
$$\text{Overstrength Factor } \Omega = \frac{\text{Apparent Strength}}{\text{Design Strength}}$$

$$\text{Ductility Reduction } R_d = \frac{\text{Elastic Strength Demand}}{\text{Apparent Strength}}$$

$$R = \frac{\text{Elastic Strength Demand}}{\text{Design Strength}} = R_d\,\Omega$$



Definition of Response Modification Coefficient *R*



Definition of Deflection Amplification Factor C_d

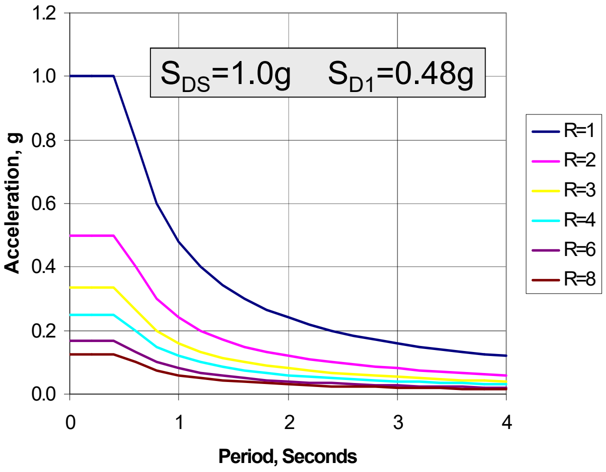
Example of Design Factors for Reinforced Concrete Structures

	R	Ω_o	C_d
Special Moment Frame	8	3	5.5
Intermediate Moment Frame	5	3	4.5
Ordinary Moment Frame	3	3	2.5
Special Reinforced Shear Wall	5	2.5	5.0
Ordinary Reinforced Shear Wall	4	2.5	4.0
Detailed Plain Concrete Wall	2	2.5	2.0
Ordinary Plain Concrete Wall	1.5	2.5	1.5

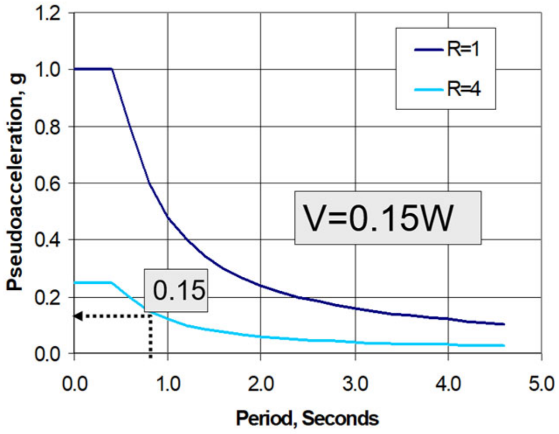
Design Spectra as Adjusted for Inelastic Behavior

$$C_S = \frac{S_{DS}}{R/I}$$

$$C_S = \frac{S_{D1}}{T(R/I)}$$

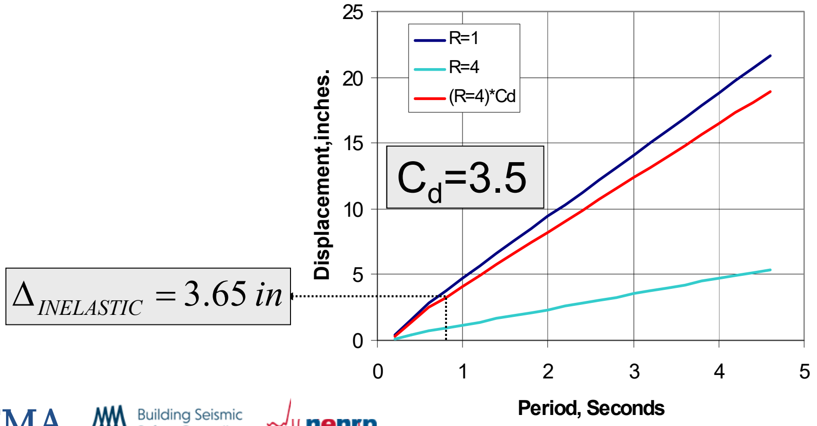


Using Inelastic Spectrum to Determine Inelastic Force Demand



Using the Inelastic Spectrum and C_d to Determine the Inelastic Displacement Demand

$$\Delta_{INELASTIC} = C_d \times \Delta_{REDUCED\ ELASTIC}$$


$$\Delta_{INELASTIC} = 3.65\ in$$

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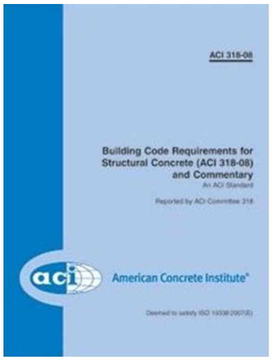
Design and Detailing Requirements



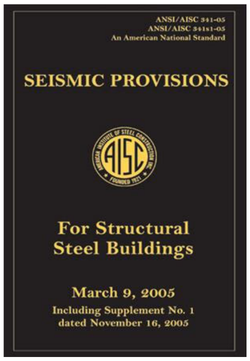
ACI 318-08

Building Code Requirements for
Structural Concrete (ACI 318-08)
and Commentary
An ACI Standard

Reported by ACI Committee 318

American Concrete Institute®

Deemed to satisfy ISO 19338:2007(E)



ANSI/AISC 341-05
ANSI/AISC 341s1-05
An American National Standard

SEISMIC PROVISIONS

For Structural
Steel Buildings

March 9, 2005
Including Supplement No. 1
dated November 16, 2005

Questions

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