Seismic Code Requirements

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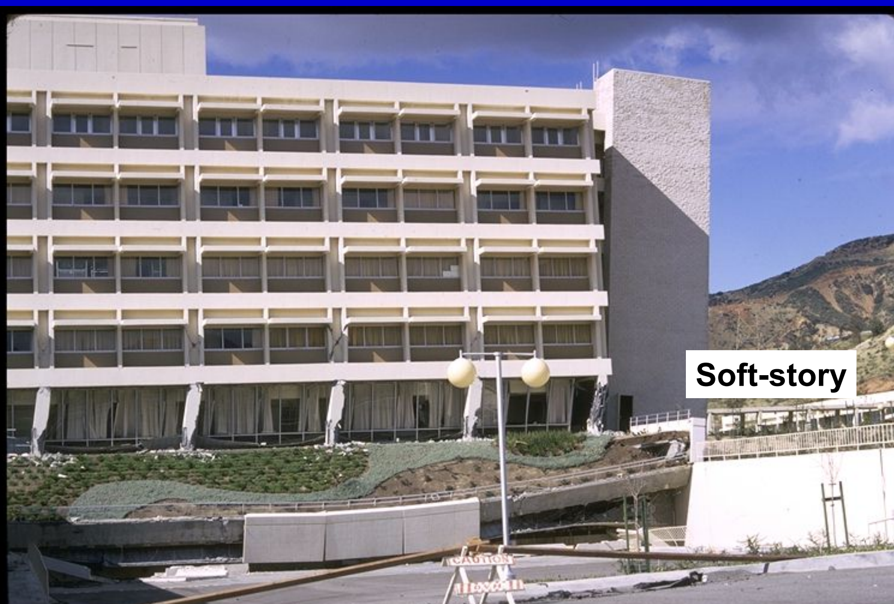
CE243A 1

1971
San Fernando, California
Earthquake

CE243A 2

1971 San Fernando Earthquake

CE243A 3



1971 San Fernando Earthquake

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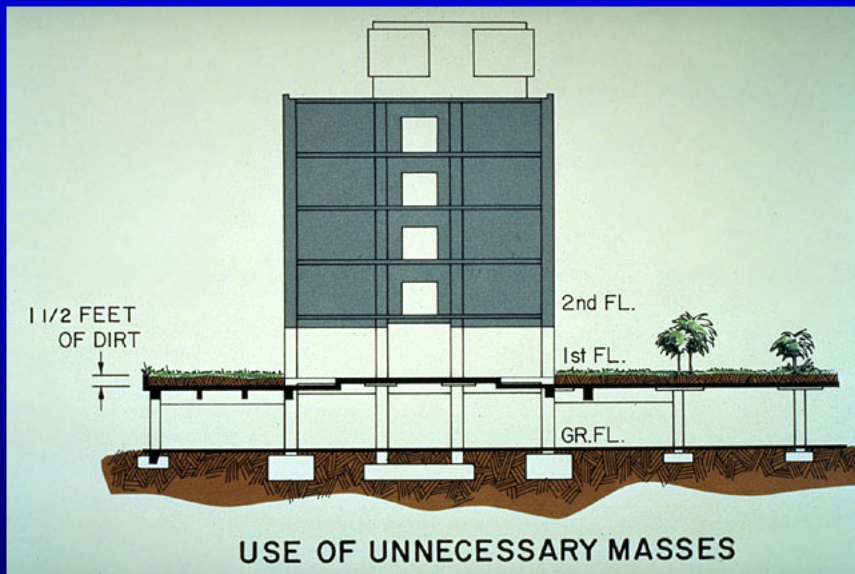

1971 San Fernando Earthquake

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1971 San Fernando Earthquake

CE243A 6

Confinement

Ties @ 18" o.c. Spiral @ 3" o.c.

1971 San Fernando Earthquake

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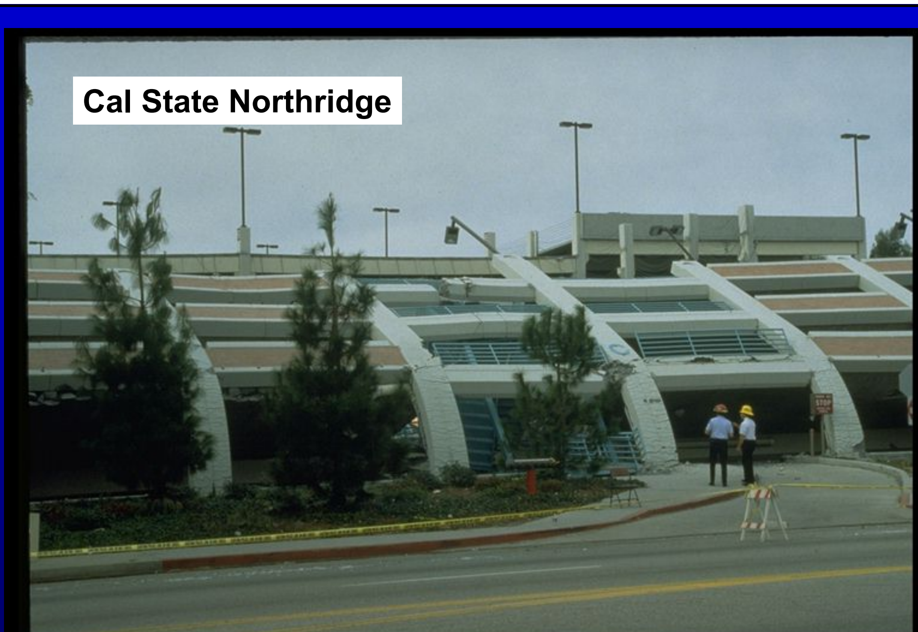

1994 Northridge Earthquake

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1994 Northridge Earthquake

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1994 Northridge Earthquake

CE243A 10

1994 Northridge Earthquake

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1994 Northridge Earthquake

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1994 Northridge Earthquake

- Major failures:
  - Steel moment-resisting frames
  - Precast concrete parking structures
  - Tiltup & masonry buildings with wood roofs
- Major successes
  - retrofitted unreinforced masonry structures
  - retrofitted bridge structures

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1994 Northridge Earthquake

- 1997 UBC & NEHRP changes:
  - removal of pre-qualified steel connection details
  - addition of near-fault factor to base shear equation
  - prohibition on highly irregular structures in near-fault regions
  - stricter detailing for non-participating elements
  - deformation compatibility requirements
  - chords & collectors designed for "real" forces
  - redundancy factor added to design forces

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Summary

- Observation of the behavior of real buildings in real earthquakes have been the single largest influence on the development of our building codes
- The lull in earthquakes in populated areas between approximately 1940 and 1970 gave a false since of security at a time when the population of California was expanding rapidly
- Performance of newer buildings and bridges has generally been good in recent earthquakes; however, older buildings pose a substantial hazard.

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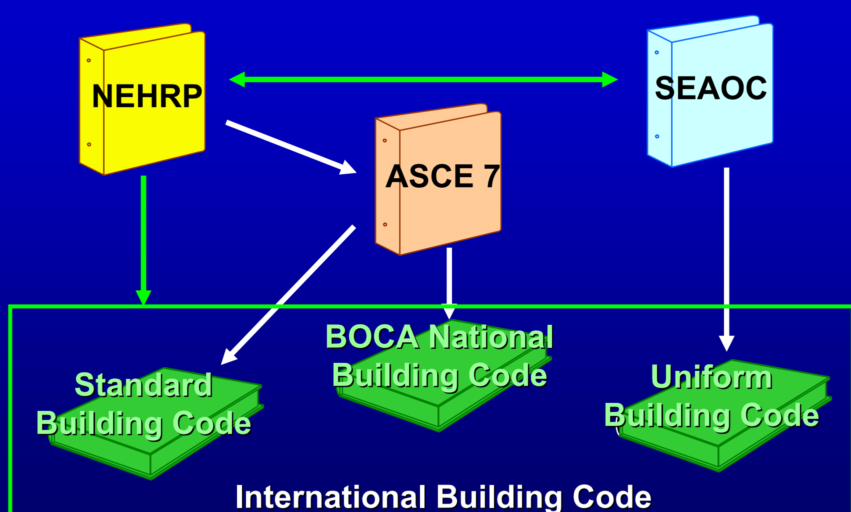
Seismic Codes and Source Documents



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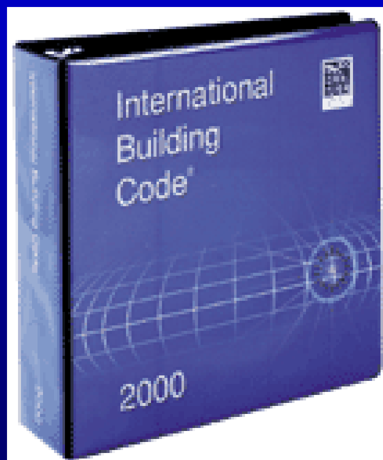
IBC 2000, 2003



- International Code Council (ICC), established in 1994
- Seismic provisions
  - ASCE 7-02
    - Modeling
    - Forces
  - Material codes
    - ACI, ASCE
- IBC 2003 (ASCE 7-02, ACI 318-02)

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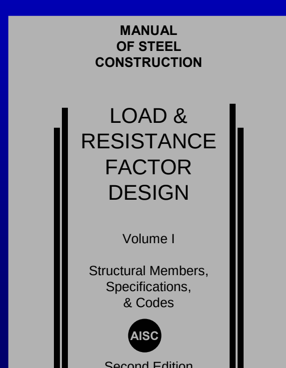
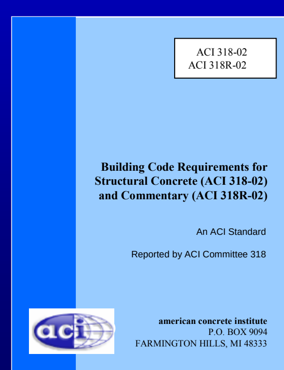
Material Codes

International Building Code





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Shake Table Test – Flat Plate

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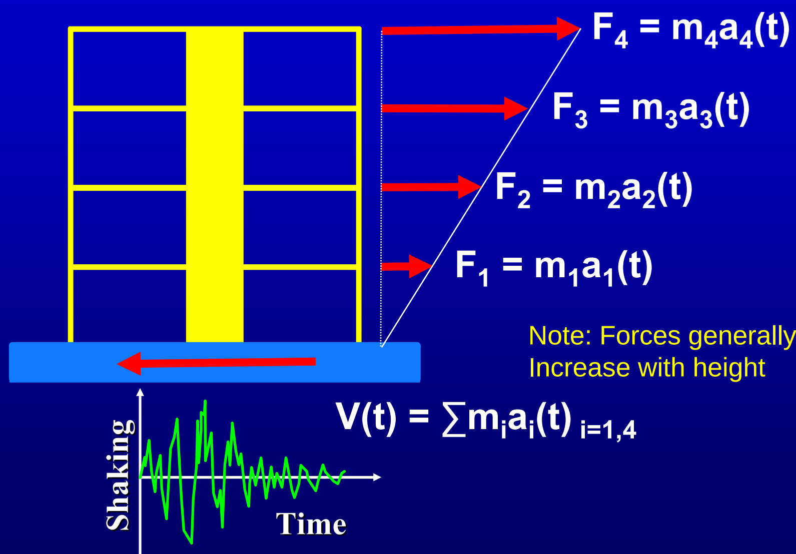
Earthquake Building Response



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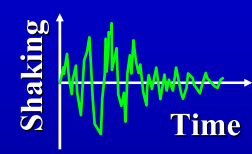
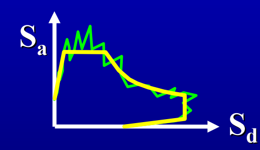
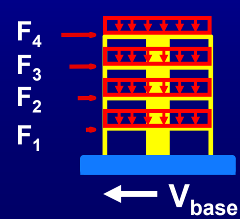
Building Response Analysis

- In general, three types of analyses are done to design buildings subjected to earthquakes
  - Response History Analysis
    - Linear or nonlinear approach to calculate time varying responses (P, M, V, δ)
  - Response Spectrum Analysis
    - Linear approach to calculate modal responses (peak values) and combine modal responses
  - Equivalent Lateral Force
    - Nonlinear approach used for rehabilitation (e.g., FEMA 356)
    - Linear approach – assume response is dominated by first mode response (very common)







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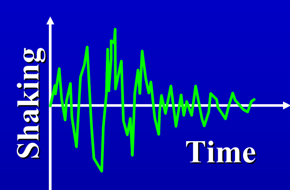
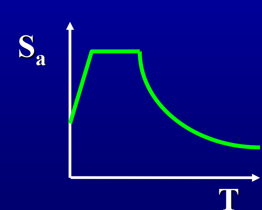
Building Response Analysis

- **Response History Analysis**
  - Analyze structure by applying acceleration history at base of structure
  - Typically requires use of several records
  - Elastic or inelastic response
  - Time consuming and results can vary substantially between records
- **Response Spectrum Analysis**
  - Elastic response
  - Determine peak responses for each mode of response
  - Combine modal responses (SRSS, CQC)





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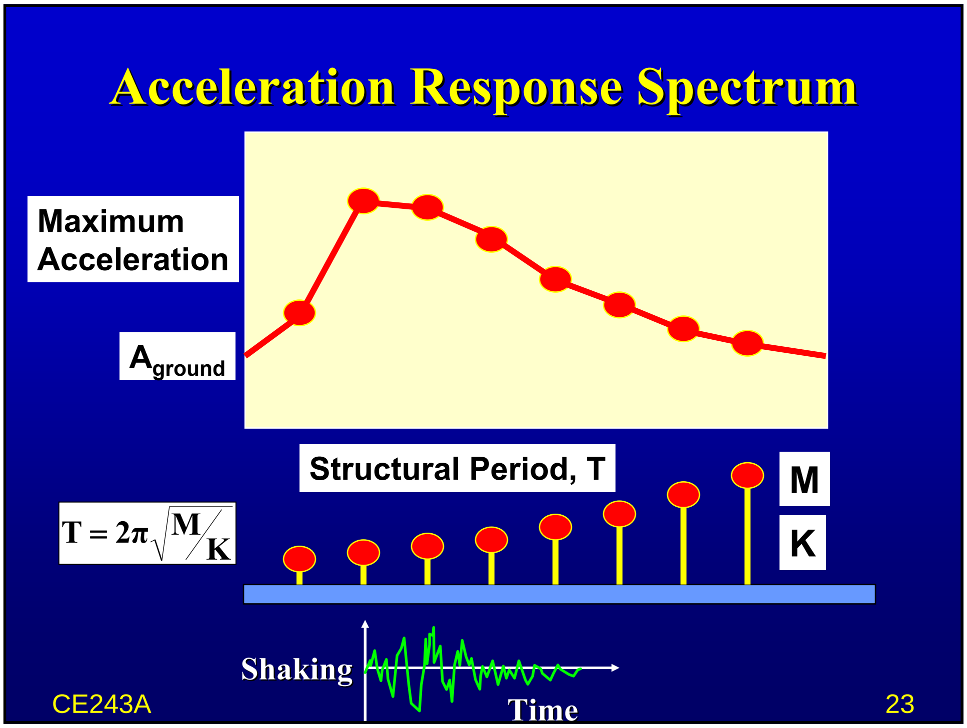
Acceleration Response Spectrum
Maximum
Acceleration
A ground
Structural Period, T
T = 2π √(M/K)
M
K
Shaking
Time
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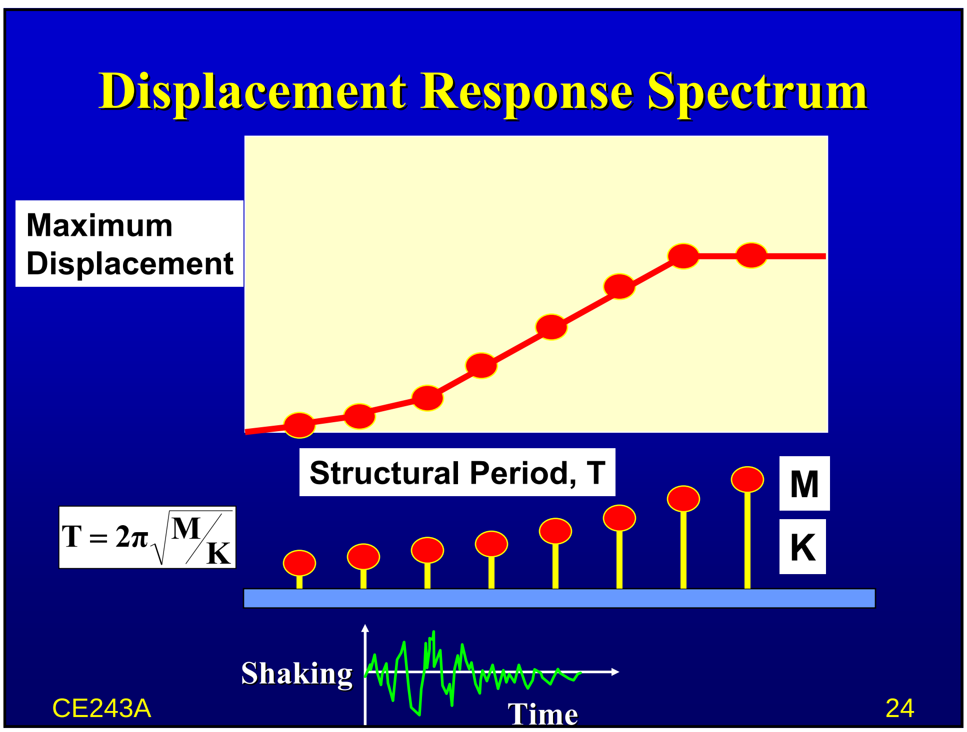
Displacement Response Spectrum
Maximum
Displacement
Structural Period, T
T = 2π √(M/K)
M
K
Shaking
Time
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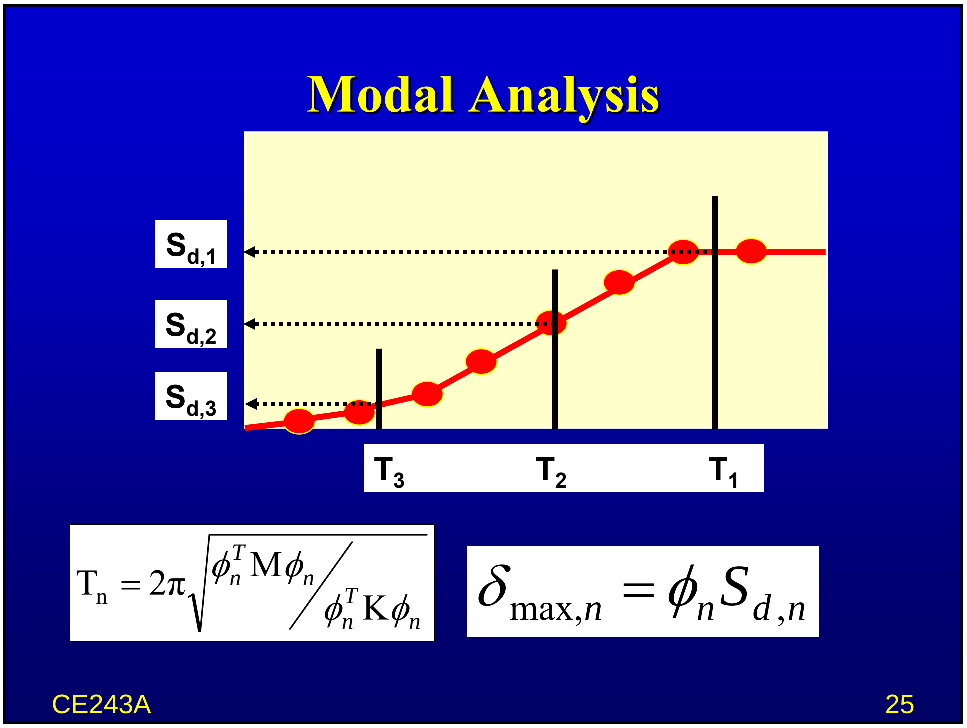
Modal Analysis
$S_{d,1}$
$S_{d,2}$
$S_{d,3}$
T_3
T_2
T_1
$T_n = 2\pi\sqrt{\phi_n^T M \phi_n / \phi_n^T K \phi_n}$
$\delta_{max,n} = \phi_n S_{d,n}$
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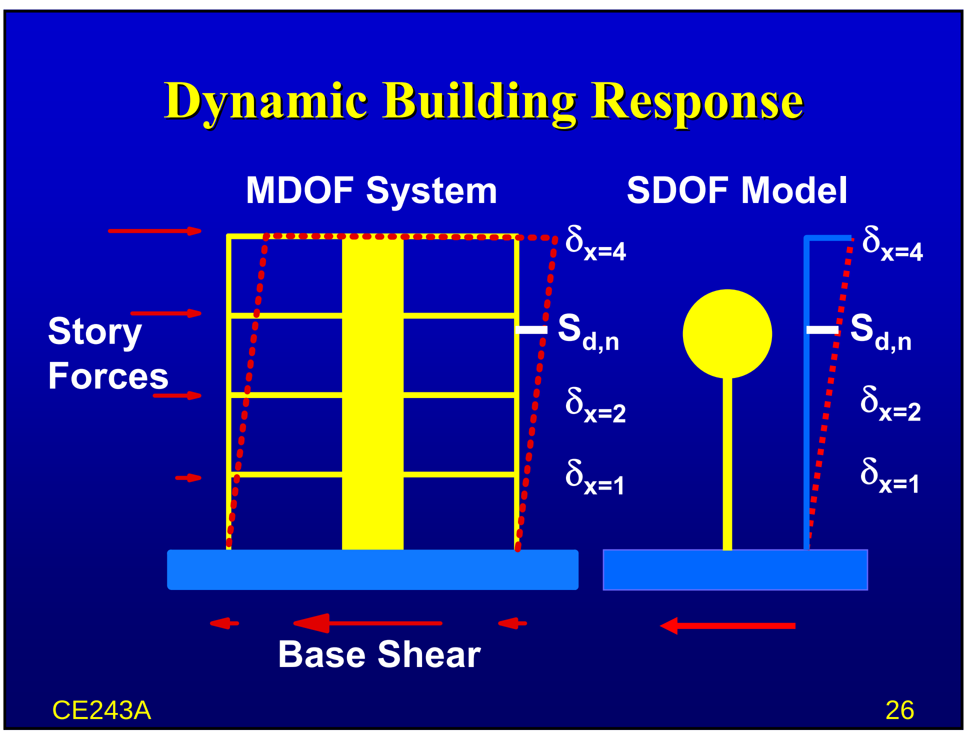
Dynamic Building Response
MDOF System
SDOF Model
Story Forces
$\delta_{x=4}$
$S_{d,n}$
$\delta_{x=2}$
$\delta_{x=1}$
$\delta_{x=4}$
$S_{d,n}$
$\delta_{x=2}$
$\delta_{x=1}$
Base Shear
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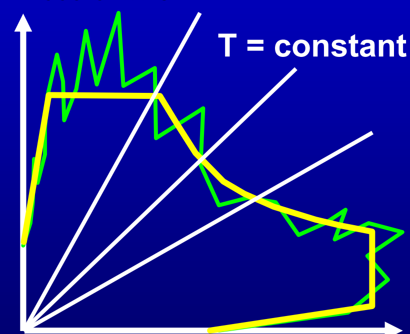
ADRS Spectrum

- Alternative format for response spectrum
- "Capacity Spectrum" approach – ATC 40
- Spectrum for a given earthquake versus smooth spectrum



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Code Analysis Procedures

- UBC-97 and IBC-2000
  - Equivalent static analysis approach
  - Response spectrum approach
  - Response (Time) history approach
  - Other (Peer review)
- FEMA 273/356 & ATC 40
  - Linear Static & Dynamic Procedures (LSP, LDP)
  - Nonlinear Static Analysis (NSP) "pushover"
  - Nonlinear Dynamic Procedure (NDP)

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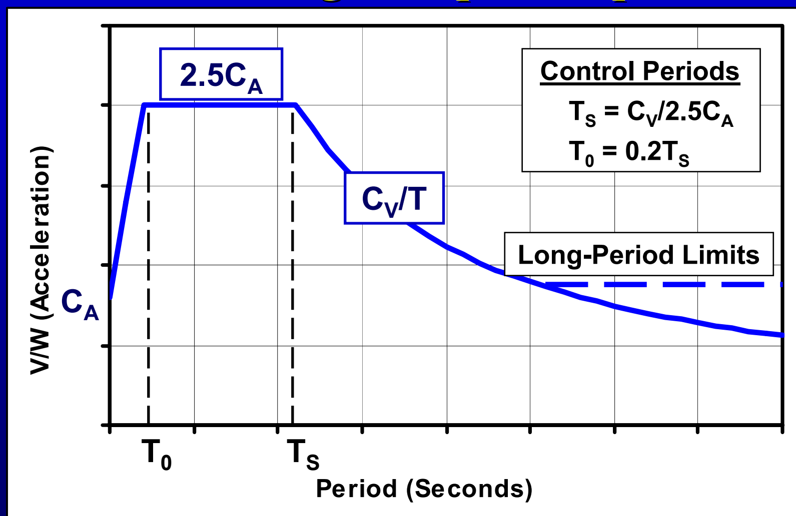
1997 UBC Design Response Spectrum



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UBC-97: Response Spectrum Analysis

$$V_{base} = \frac{C_v I}{RT} W \qquad \text{Eq. (30-4)}$$

$$V_{base} \leq \frac{2.5 C_a I}{R} W \qquad \text{Eq. (30-5)}$$

$$V_{base} \geq 0.11 C_a I W \qquad \text{Eq. (30-6)}$$

C_a = Seismic Coefficient (Acceleration)
C_v = Seismic Coefficient (Velocity)

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Modal Analysis

- Eigen Analysis
  - Requires mass (M) and stiffness (K) matrices
    - M is often assumed to be diagonal
    - K (e.g., from direct stiffness assembly)
  - Frequencies (ω, $T=2\pi/\omega$) and mode shapes (Φ)
    - Mode shapes ϕ are columns of Φ matrix (orthogonal property)
- Modal Analysis – solve uncoupled equations

$$[M]\{\ddot{v}\}+[C]\{\dot{v}\}+[K]\{v\}=\{p\}(t); \quad \{v\}=[\Phi]\{y\}$$
$$M_n=[\Phi]^T[M][\Phi]=\{\phi_m\}^T[M]\{\phi_n\} \quad \mathrm{m=n}$$
$$M_n\ddot{y}_n+C_n\dot{y}_n+K_n y_n=\phi_n^T p(t) \quad \text{solve for } y_n$$

Combine modal responses (e.g., SRSS, CQC)

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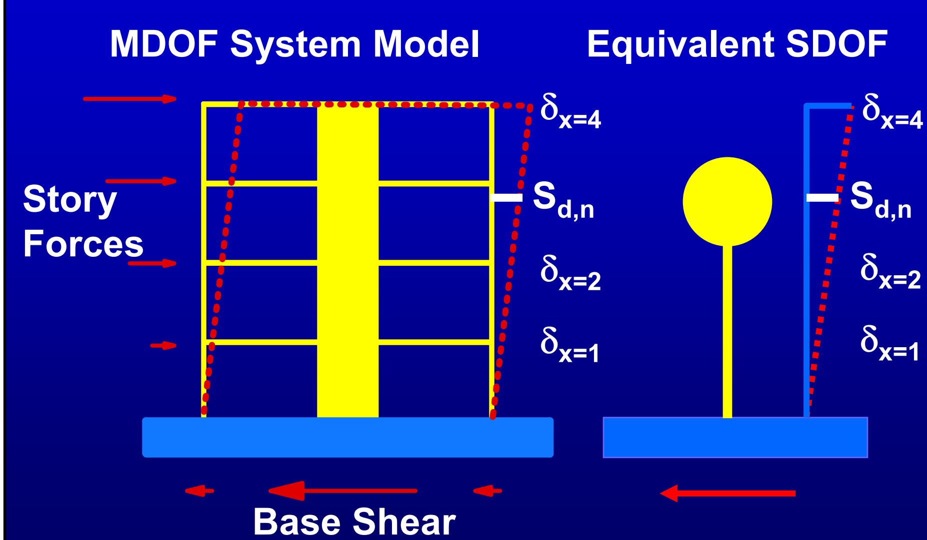
UBC-97 Approach: Response Spectrum



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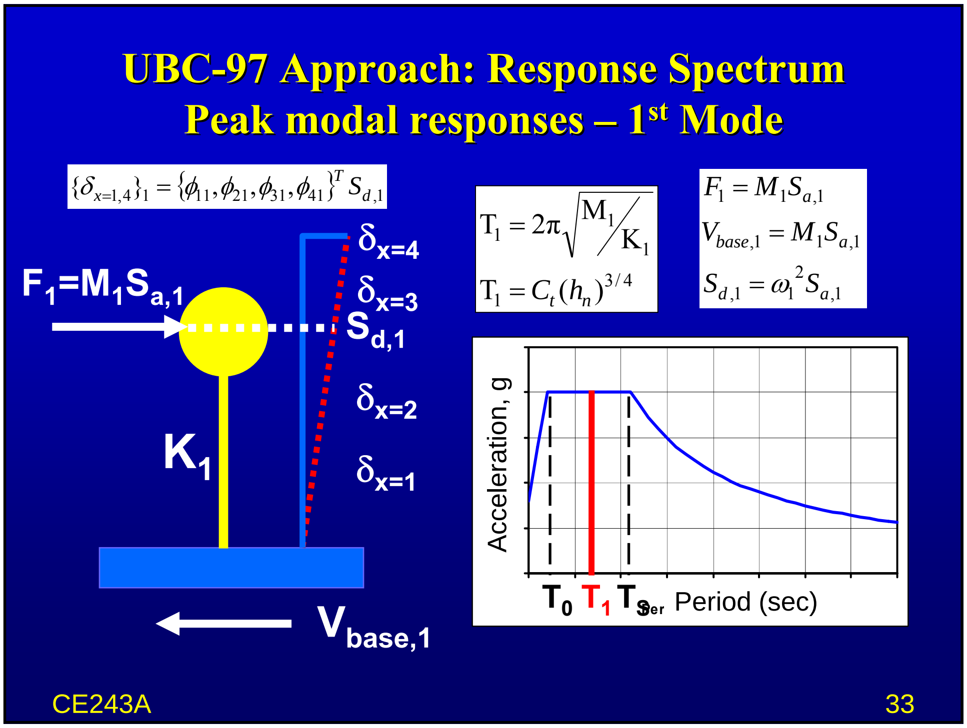
UBC-97 Approach: Response Spectrum
Peak modal responses – 1st Mode
$\{\delta_{x=1,4}\}_1 = \{\phi_{11}, \phi_{21}, \phi_{31}, \phi_{41}\}^T S_{d,1}$
$T_1 = 2\pi\sqrt{M_1/K_1}$
$T_1 = C_t (h_n)^{3/4}$
$F_1 = M_1 S_{a,1}$
$V_{base,1} = M_1 S_{a,1}$
$S_{d,1} = \omega_1^2 S_{a,1}$
$F_1=M_1S_{a,1}$
K_1
$\delta_{x=4}$
$\delta_{x=3}$
$S_{d,1}$
$\delta_{x=2}$
$\delta_{x=1}$
$V_{base,1}$
Acceleration, g
T_0 T_1 T_S Period (sec)
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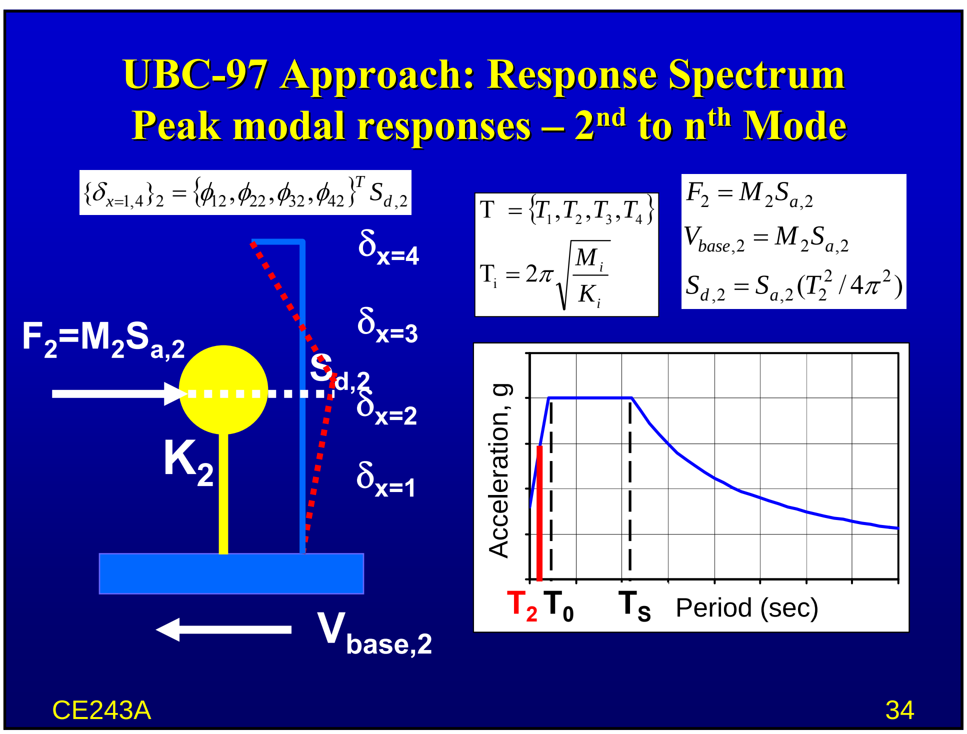
UBC-97 Approach: Response Spectrum
Peak modal responses – 2nd to nth Mode
$\{\delta_{x=1,4}\}_2 = \{\phi_{12}, \phi_{22}, \phi_{32}, \phi_{42}\}^T S_{d,2}$
$T = \{T_1, T_2, T_3, T_4\}$
$T_i = 2\pi\sqrt{\frac{M_i}{K_i}}$
$F_2 = M_2 S_{a,2}$
$V_{base,2} = M_2 S_{a,2}$
$S_{d,2} = S_{a,2}(T_2^2/4\pi^2)$
$F_2=M_2S_{a,2}$
K_2
$\delta_{x=4}$
$\delta_{x=3}$
$S_{d,2}$
$\delta_{x=2}$
$\delta_{x=1}$
$V_{base,2}$
Acceleration, g
T_2 T_0 T_S Period (sec)
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UBC-97 Approach: Response Spectrum Modal Combinations

- Peak modal responses do not occur at the same time, that is, the peak roof displacement for mode one occurs at t_1 , whereas the peak displacement for mode two occurs at t_2, and so on. Therefore, peak modal responses must be combined based on the correlation between modes.
- Modal Combination Approaches
  - SRSS: Square-root-sum-squares, works well for systems with well-separated modes (2D models)
  - CQC: Complete-Quadratic-Combination (3D)

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UBC-97 Approach: Response Spectrum Mass Participation

- The (force) participation of each mode can be gauged by the mass participation factor.

$$PF_{m,n} = \frac{\{\phi_n\}^T[M]\{r=1\}}{\{\phi_n\}^T[M]\{\phi_n\}}$$

- Typical mass participation factors: PF_m
  - Frame buildings: 1st Mode – 80 to 85%
  - Shear wall buildings: 1st Mode – 60 to 70%
  - To achieve 100% mass participation, all modes must be included in the modal analysis

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UBC-97 Approach: Response Spectrum Specific Requirements

- 1631.5.2 - For regular buildings, include sufficient modes to capture 90% of participating mass. In general, this is relatively few modes
- 1631.5.3 - Modal combinations – Use appropriate methods (SRSS, CQC). For 3D models with closely spaced modes – need CQC.
- 1630.5.4 – R factors and limits on reducing base shear where response spectrum analysis is used
- 1630.5.5 – Directional effects: consider seismic forces in any horizontal direction (1630.1)
- 1630.5.6 – Account for torsion

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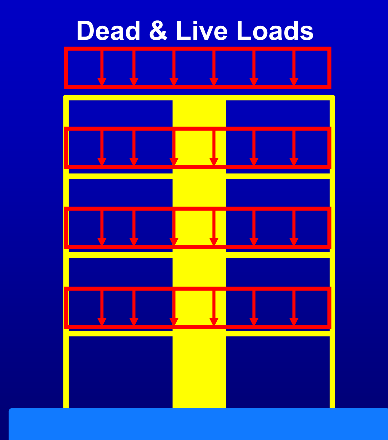
UBC-97 Approach: Response Spectrum



- Combine response spectrum analysis results with analysis results for gravity forces
- Load combinations (1612)
  - Same as new ACI load combinations
- Drift limits (1630.10)
  - *h_s = Story height*
  - *Δ_s = Displ. for code level forces*

$$\Delta_m = 0.7R\Delta_s$$
$$\mathrm{T} < 0.7\ \mathrm{sec}:\ \Delta_m < 0.025h_s$$
$$\mathrm{T} \geq 0.7\ \mathrm{sec}:\ \Delta_m < 0.025h_s$$

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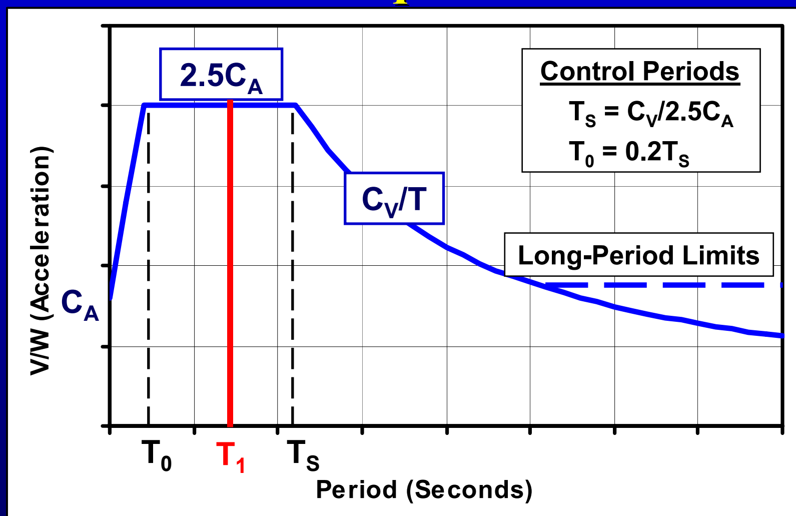
1997 UBC – Equivalent Static



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UBC-97 Base Shear Equations
Equivalent Static Analysis

$$V_{base} = \frac{C_v I}{RT} W \qquad \text{Eq. (30-4)}$$

$$V_{base} \le \frac{2.5 C_a I}{R} W \qquad \text{Eq. (30-5)}$$

$$V_{base} \ge 0.11 C_a I W \qquad \text{Eq. (30-6)}$$

C_a = Seismic Coefficient (Acceleration)
C_v = Seismic Coefficient (Velocity)

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UBC-97 Approach: Equivalent Static

$$C_v = 0.40 N_v \quad \text{For Z} = 0.4, \text{S}_\text{B} \quad (\text{Table 16-R})$$

$$C_a = 0.40 N_a \quad \text{For Z} = 0.4, \text{S}_\text{B} \quad (\text{Table 16-Q})$$

Z = Seismic Zone Factor (0.075 to 0.4)
S = Soil Profile Type
N_v = Near Source Coefficient (velocity)
Seismic Source A (M > 7.0, SR > 5 mm/yr)
Distance = 5 km ➔ N_v = 1.6 (Table 16-T)
N_a = Near Source Coefficient (acceleration)
Seismic Source A (M > 7.0, SR > 5 mm/yr)
Distance = 5 km ➔ N_a = 1.2 (Table 16-S)

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UBC-97 Equivalent Static Analysis

$$V_{base} = \frac{C_v I}{RT} W \qquad \text{Eq. (30-4)}$$

I = Importance Factor (1.0 to 1.25; Table 16-K)
W = Building Seismic Dead Load
R = Force Reduction Coefficient (Table 16-N)
T = Fundamental Structural Period

$$T = C_t (h_n)^{3/4} = 0.02(48\,ft)^{3/4} = 0.37\,\text{sec}$$

C_t = Coefficient (e.g., 0.02 for rc walls)
h_n = Building height (feet)

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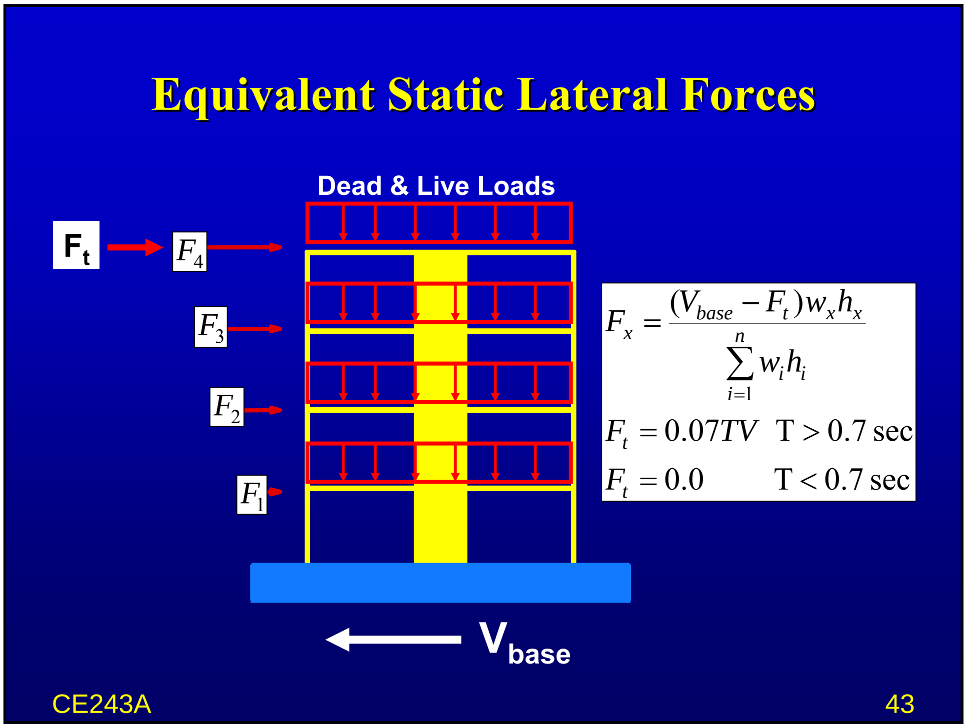
Equivalent Static Lateral Forces
Dead & Live Loads
F_t
F_4
F_3
F_2
F_1
$F_x = \frac{(V_{base} - F_t) w_x h_x}{\sum_{i=1}^{n} w_i h_i}$
$F_t = 0.07TV \quad T > 0.7\ \text{sec}$
$F_t = 0.0 \quad T < 0.7\ \text{sec}$
V_{base}
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Lateral Force Resisting System
LFRS
"Gravity" System
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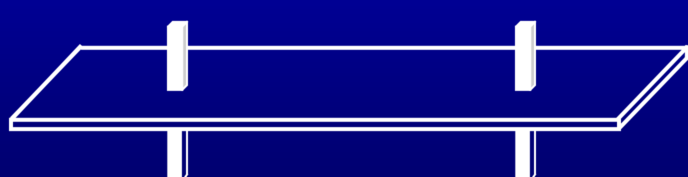
"Non-Participating" System

- Also referred to as: "Gravity" System
- Flat plate floor systems (Gravity loads)
  - Efficient and economical
  - Easy to form, low story heights
  - Strong column – weak beam concept



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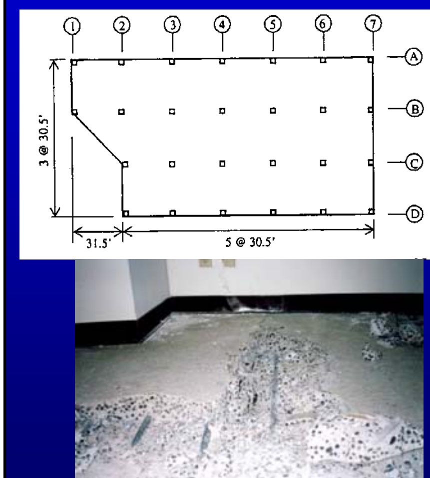
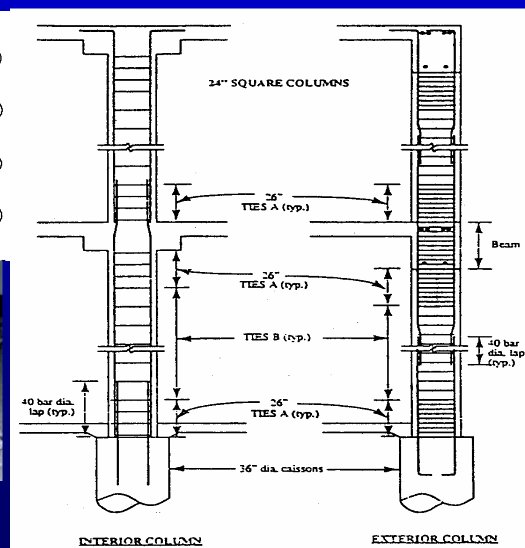
Perimeter LFRS and Interior "GFRS"





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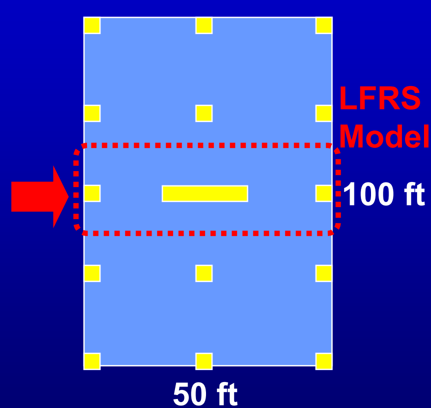
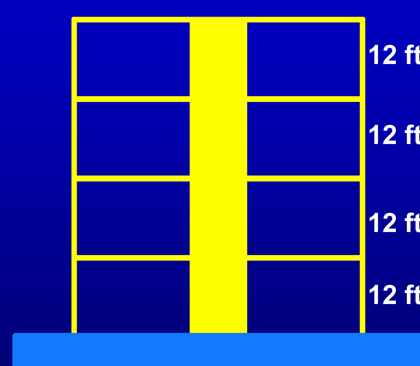
UBC-97: LFRS Design
Equivalent Static or Response Spectrum



Floor Plan
Note: Neglecting torsion



Elevation View LFRS

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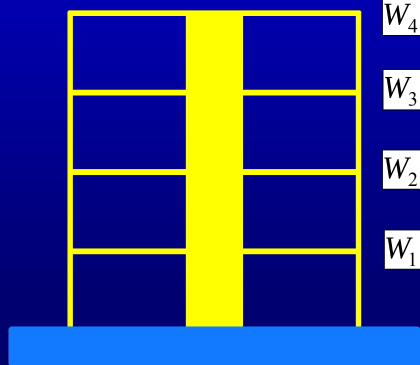
UBC-97 Equivalent Static Analysis

$$V_{base} = \frac{C_v I}{RT} W = \frac{0.4(1.6)(1.0)}{R(T = C_t h_n^{3/4})} W$$



$$W_4 = (100' \text{ x } 50')(100 \text{ psf}) = 500 \text{ kips}$$

$$W_3 = (100' \text{ x } 50')(100 \text{ psf}) = 500 \text{ kips}$$

$$W_2 = (100' \text{ x } 50')(100 \text{ psf}) = 500 \text{ kips}$$

$$W_1 = (100' \text{ x } 50')(100 \text{ psf}) = 500 \text{ kips}$$

$$W = 500 \text{ kips (4 floors)} = 2000 \text{ kips}$$

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UBC-97 Equivalent Static Analysis

$$V_{base} = \frac{C_v I}{RT} W = \frac{0.4(1.6)(1.0)}{R(T = C_t h_n^{3/4})} (W = 2000 \text{ kips})$$

R = Force Reduction Coefficient (Table 16-N)
Accounts for nonlinear response of building
(Building strength, ductility, damping)

R = 1 is associated with elastic response

Typical Values:
R = 8.5 for a rc special moment frame
R = 5.5 for a rc wall building

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UBC-97 Equivalent Static Analysis

$$V_{base} = \frac{C_v I}{RT} W = \frac{0.4(1.6)(1.0)}{R(0.63)} W$$

$$V_{base} = \frac{0.64}{R(0.37)} W = \frac{1.73}{R} W = \frac{1.73g}{R} M$$

$$V_{base} \leq \frac{2.5 C_a I}{R} W = \frac{2.5(0.4)(1.2)}{R} W = \frac{1.2g}{R} M$$

$$V_{base} = 1.2(2000)/R = 1 = 2400\ kips \ \ (\text{elastic})$$

$$V_{base} = 2400/(R = 5.5) = 435 \text{ kips} \ \ (\text{design})$$

R > 1.0 requires inelastic response
Structure must be specially detailed to control inelastic behavior

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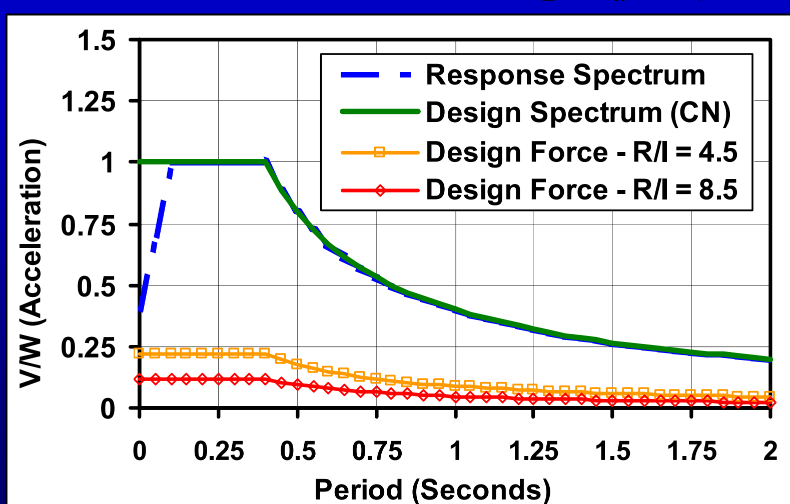
1997 UBC Seismic Criteria
(Seismic Zone 4, Soil Type S_B, $N_a = N_v = 1$)



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Confinement

Ties @ 18" o.c. Spiral @ 3" o.c.

1971 San Fernando Earthquake

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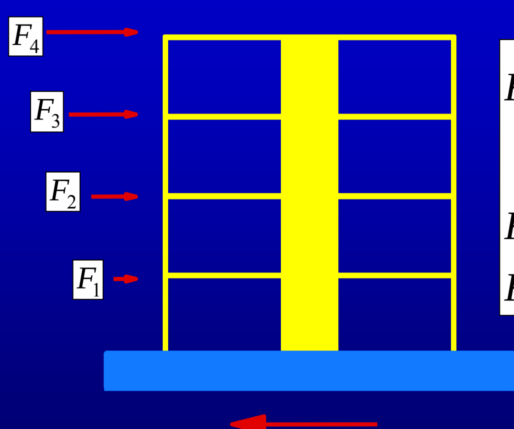
UBC-97 Equivalent Static Analysis



$$F_x = \frac{(V_{base} - F_t) w_x h_x}{\sum_{i=1}^{n} w_i h_i}$$

$$F_t = 0.07TV \quad T > 0.7 \text{ sec}$$

$$F_t = 0.0 \quad T < 0.7 \text{ sec}$$

Base Shear V_{base} = 435 kips

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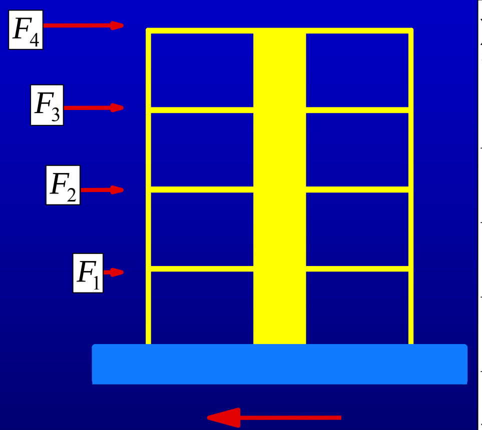
UBC-97 Equivalent Static Analysis



Base Shear
V_{base} = 435 kips

$$\sum_{i=1}^{n} w_i h_i = (500\text{ kips})(12'+24'+36'+48')$$
$$= 60{,}000\text{ kip - ft}$$
$$F_{x=4} = \frac{(435-0)(500^k)(48')}{60{,}000^{ft-k}} = 0.4V = 174^k$$
$$F_{x=3} = \frac{(435-0)(500^k)(36')}{60{,}000^{ft-k}} = 0.3V = 131^k$$
$$F_{x=2} = \frac{(435-0)(500^k)(24')}{60{,}000^{ft-k}} = 0.2V = 87^k$$
$$F_{x=1} = \frac{(435-0)(500^k)(12')}{60{,}000^{ft-k}} = 0.1V = 43^k$$
$$\sum_{x=1}^{4} F_x = 174+131+87+43 = 435\text{ kips}$$

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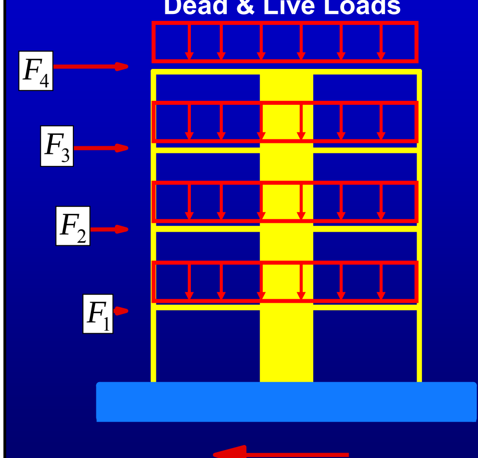
UBC-97 Equivalent Static Analysis



Base Shear = ρE_h

- **Load Combinations UBC-97 - S16.12.2.1**
  - **U = 1.2D + 0.5L + 1.0E**
  - **U = 0.9D +/- 1.0E**
  - **Where: E = $\rho E_h + E_v$**
    $E_v = 0.5C_a ID$ = 0.24D
- **U = 0.9D +/- 1.0($\rho E_h + E_v$)**
  U = (0.9+/-0.24)D +/- ρE_h
  ρ = redundancy factor $\geq$1.0
- **Conduct static analysis e.g., use SAP2000**

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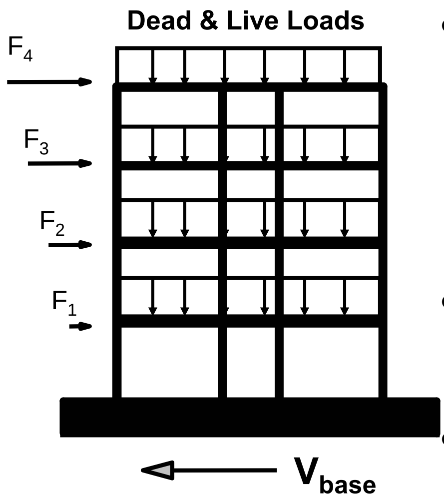
UBC-97 Equivalent Static Analysis



- **Load Combinations UBC-97 - S16.12.2.1**
  - **U = 1.2D + 0.5L + 1.0E**
  - **U = 0.9D +/- 1.0E**
  - **Where: $E = \rho E_h + E_v$**
    $E_v = 0.5 C_a I D = 0.24D$
- **$U = 0.9D +/- 1.0(\rho E_h + E_v)$**
  $U = (0.9+/-0.24)D +/- \rho E_h$
  ρ = redundancy factor ≥1.0
- **Conduct static analysis e.g., use SAP2000**

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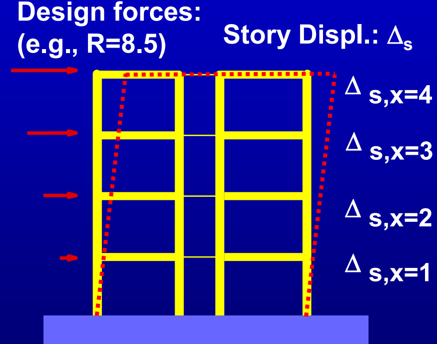
UBC-97: Drift & Drift Limits

- **1630.9 – Drift for all analysis is defined**
  - **Defines drift for Maximum Inelastic Response Displacement (Δ_M) and for Design Seismic Forces (Δ_S): $\Delta_M = 0.7R\Delta_S$**
- **1630.10 – Drift limits defined**
  - **Drift < 0.025 times story height if T < 0.7 sec**
  - **Drift < 0.02 times story height if T ≥ 0.7 sec**

Code level Design forces: (e.g., R=8.5)



Elevation View

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UBC-97 Requirements

- 1633 – Detailed systems design requirements
- 1633.1 General:
  - Only the elements of the designated LFRS shall be used to resist design forces
  - Consider both seismic and gravity (D, L, S)
  - For some structures (irregular), must consider orthogonal effects: 100% of seismic forces in one direction, 30% in the perpendicular direction

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UBC-97 Requirements

- 16333.2 Structural Framing Systems
- 1633.2.1 General:
  - Defined by the types of vertical elements used
- 1633.2.2 For structures with multiple systems, must use requirements for more restrictive system
- 1633.2.3 Connections – if resisting seismic forces, then must be on drawings
- 1633.2.4 Deformation compatibility

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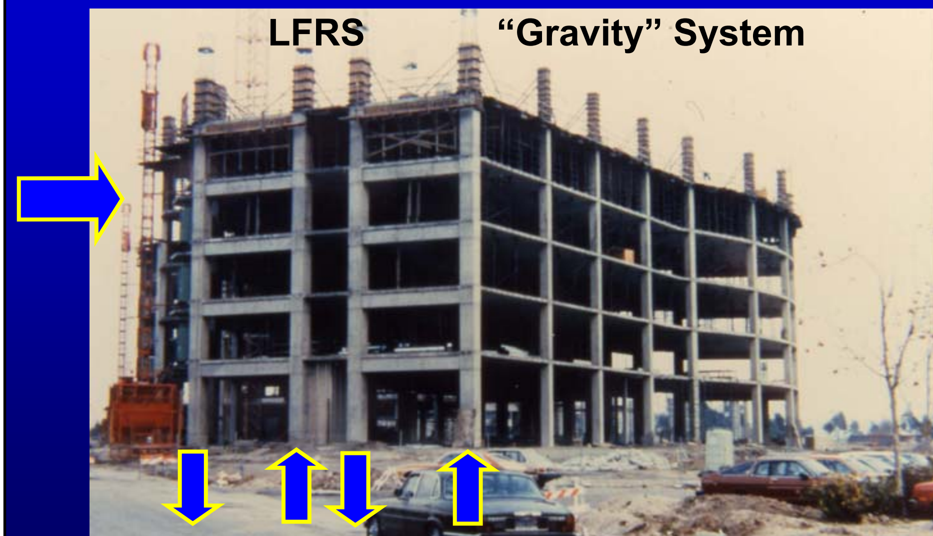
LFRS and Deformation Compatibility



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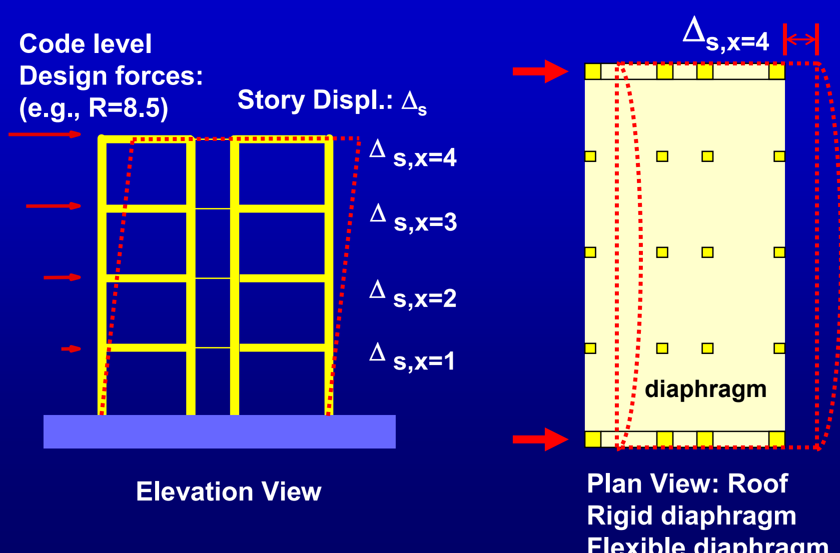
LFRS and Deformation Compatibility



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UBC-97 Requirements

- **1633.2.4 – Deformation compatibility**
  - **Requires that non-participating structural elements be designed to ensure compatibility of deformations with lateral force resisting system**
  - **Non-participating elements must be capable of maintaining support for gravity loads at deformations expected due to seismic forces**
  - **Design of LFRS:**
    - **Model LFRS and apply design seismic forces**
    - **Neglect lateral stiffness and strength of non-participating elements**

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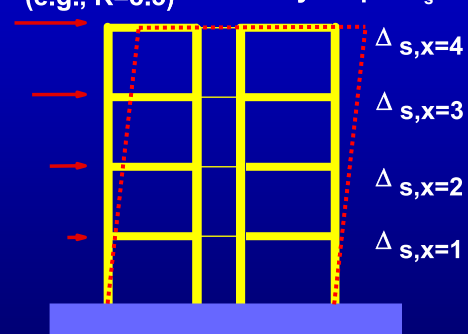
UBC-97 Requirements

- **1633.2.4 – Deformation compatibility**
  - **For LFRS**
    - $\Delta_M = 0.7R\Delta_S$ ***for lateral frame at each story***
    - **That is, compute story displacements for design seismic forces applied to the LFRS, then multiple by them by** ***0.7R***

Code level Design forces: (e.g., R=8.5)

Story Displ.: Δ_s



Elevation View

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UBC-97 Requirements

- 1633.2.4 – Deformation compatibility
  - Non-participating frame
    - Model the system (linear - element stiffness)
      - Shear and flexural stiffness limited to ½ gross section values
      - Must consider flexibility of diaphragm and foundation
    - Impose story displacements on the model of non-participating frame
      - The imposed displacements produce element forces, consider these to be ultimate
      - check stability (support for gravity loads)
      - Detailing requirements: 21.11 in ACI 318-02

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UBC-97 Requirements

- Other items of interest
  - Collectors (1633.2.6)
    - Must provide collectors to transfer seismic forces originating in other portions of the structure to the element providing the resistance to these forces
  - Diaphragms (1633.2.9)
    - Deflection of diaphragm limited by the permissible deflection of the attached elements
    - Design forces specified in (33-1)

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Reinforced Concrete: ACI 318-02 Chapter 21 – Seismic Provisions

- Provide transverse steel
  - Confinement, buckling
  - Maintain gravity loads
- Strong-column, weak-beam
  - Beam flexural yielding
- Capacity design
  - Beam & column shear
  - Joint regions
- Prescriptive requirements
  - Little flexibility
  - Quick, easy, and usually conservative

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