Chapter 2
Review of Seismic Design
Philosophies and Analysis Methods
CONTENT

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8. Need for Supplemental Damping and Seismic Isolation Systems
Major References

• Chapter 2
  – Sections 2.1 to 2.8
1. Introduction

- Brief review of current seismic design philosophies and analysis methods
- Supplemental damping and seismic isolation systems have evolved from and can be implemented in each of these seismic design philosophies and analysis methods
- Framework for the rest of the material covered in the course
2. Force-Based Seismic Design Procedure

• Principles and Objectives
  – Elastic spectral accelerations used to determine required lateral strength of equivalent elastic structure
  – Elastic strength divided by a force reduction factor $R$ representative of the inherent overstrength and global ductility capacity

\[ V = \frac{V_e}{R} \]
2. Force-Based Seismic Design Procedure

• Concept of Ductility

![Diagram of Portal Frame with labels: W=600 kN, T = 1.04 s, \( \xi = 5\% \)]

![Graph showing Base Shear Coefficient vs. Drift (%) with peak at 0.13 and 1.2 Drift (%)]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight, ( W )</td>
<td>600 kN</td>
</tr>
<tr>
<td>Lateral Stiffness, ( k )</td>
<td>2.22 MN/m</td>
</tr>
<tr>
<td>Fundamental Period, ( T )</td>
<td>1.04 s</td>
</tr>
<tr>
<td>Base Shear Coefficient</td>
<td>0.13</td>
</tr>
<tr>
<td>Drift at Yield</td>
<td>1.2%</td>
</tr>
</tbody>
</table>
2. Force-Based Seismic Design Procedure

- Concept of Ductility
2. Force-Based Seismic Design Procedure

- Response under El Centro Earthquake
  May 18, 1940, $M_L = 7.1$, North-South Component
2. Force-Based Seismic Design Procedure

- Responses for different lateral strength values, \( V_y \)

![Graphs showing frame displacement and base shear for different lateral strength values](image)
2. Force-Based Seismic Design Procedure

- Responses for different lateral strength values, $V_y$
2. Force-Based Seismic Design Procedure

- Maximum displacement is almost independent of lateral strength (Equal Displacements/Newmark’s Principle)
2. Force-Based Seismic Design Procedure

- Equal Displacements Principle

\[ \mu = \frac{\delta_{\text{max}}}{\delta_y} = \frac{V_E}{V_y} \approx R \geq 1 \]
2. Force-Based Seismic Design Procedure

- Linear Static Analysis Method

This analysis method is consistent with a single seismic performance level (usually life safety), and is based on the re-writing of Equation (2.1):

\[ V_y = \frac{V_E}{\mu_\Delta} \approx \frac{V_E}{R} \]  

(2.2)

- Typical Code Design Base Shear Equation, V:

\[ V = \frac{C_S \cdot S(T) \cdot I}{R} \cdot W \]

- Seismic coefficient, \( C_S \)
- Force reduction factor, \( R \)
- Seismic response factor, \( S(T) \)
- Seismic weight, \( W \)
- Importance factor, \( I \)

- Seismic Design Force at Level i, \( F_i \):

\[ F_i = \frac{W_i h_i}{N_f} \left( V - F_t \right) \]

\[ \sum_{j=1}^{N_f} W_j h_j \]
2. Force-Based Seismic Design Procedure

- Linear Dynamic Analysis Method
  - For tall and/or irregular structures
  - Linear modal superposition method
  - Input motion defined by design acceleration response spectrum
  - Statistical combination of modal maxima
  - Peak dynamic base shear scaled to static design base shear
  - Better evaluation of higher modes effects
2. Force-Based Seismic Design Procedure

• Limitations of Force-Based Seismic Design Procedures
  – Process uses estimate of elastic fundamental period
  – Force reduction factor $R$ based on judgment
  – Deformation limit-states not directly addressed
  – Equal displacement approximation inappropriate for short period structures
  – No consensus on definition of yield and ultimate displacements
3. Performance-Based Earthquake Engineering

- **Framework**

  Supplemental Damping & Seismic Isolation Systems

  ![Diagram](image)

  **Figure 2.4 Performance-Based Seismic Design Framework (adapted from SEAOC 1996, BSSC 1997, ASCE 2000)**

**Current Codes**
3. Performance-Based Earthquake Engineering

• Explicit Consideration of Residual Deformations

Figure 2.5 Performance Matrix Including Residual Deformations
4. Static Nonlinear Analysis Methods

• Monotonic Pushover Analysis
  – Monotonic lateral load pattern slowly increased until lateral capacity of the structure is reached
  – Seismic code equivalent static or first mode loading pattern often used
  – Capacity of the structure depends on loading pattern
4. Static Nonlinear Analysis Methods

• Monotonic Pushover Analysis
4. Static Nonlinear Analysis Methods

- Monotonic Pushover Analysis
  - Example (Carr, 2004)
4. Static Nonlinear Analysis Methods

• Adaptive Monotonic Pushover Analysis
  – Loading pattern reflects the deformation pattern of the structure at end of each loading step
  – Structural capacity independent of initial loading pattern
  – Several procedures developed
4. Static Nonlinear Analysis Methods

- Adaptive Monotonic Pushover Analysis
  - Example: Procedure proposed by Satyarno (1998)

At each step, after the initial step, a Modified Rayleigh Method process is used to estimate the tangent fundamental frequency of the structure. If $\psi$ is the displacement during the past increment due to incremental forces $\{g\}$

ie

$$[K_T]\{\psi\} = \{g\}$$

where $[K_T]$ is the current tangent stiffness matrix.

From the equation of free vibration

$$-\omega^2[M]\{\phi\} + [K_T]\{\phi\} = \{0\}$$

where $\omega$ is the current tangent fundamental natural frequency and $[M]$ is the mass matrix and $\{\phi\}$ is a mode shape of free vibration.
4. Static Nonlinear Analysis Methods

- Adaptive Monotonic Pushover Analysis
  

Let \( \{\psi\} \) be an estimate of the mode shape.

\[
\omega^2 \{\psi\}^T [M] \{\psi\} = \{\psi\}^T [K_T] \{\psi\}
\]

ie

\[
\omega^2 M^* = K^*
\]

and

\[
\omega^2 = \sqrt{\frac{K^*}{M^*}}
\]

Note:

\[
K^* = \{\psi\}^T [K_T] \{\psi\} = \{\psi\}^T \{g\}
\]

For the next step

\[
[K_T] \{\psi_t\} = \omega^2 [M] \{\psi\} = \{g_t\}
\]

so the new incremental load vector is a function of the mass, the equivalent frequency and the displaced shape of the structure. The increment is normalized so that the magnitude of the increment of displacement is similar to that of the first step.
4. Static Nonlinear Analysis Methods

- Cyclic Pushover Analysis
  - Cyclic load or displacement history supplied for a specified degrees of freedom.

Equivalent viscous damping ratio:

$$\xi_{eq} = \frac{E_D \Delta_t}{4\pi E_d} = \frac{E_D \Delta_t}{2\pi k_{eq} \Delta_s^2}$$
4. Static Nonlinear Analysis Methods

- Effective Period and Equivalent Viscous Damping

\[
\beta_{\text{eff}} = \frac{1}{4\pi} \cdot \frac{Eh}{Es} = \frac{2}{\pi} \cdot \frac{Q \cdot (u_{\text{max}} - u_y)}{k_{\text{eff}} \cdot u_{\text{max}}^2} = \frac{2}{\pi} \cdot \frac{(\mu - 1) \cdot (1 - \alpha)}{\mu \cdot (1 + \alpha \mu - \alpha)}
\]

\[
T_{\text{eff}} = T_e \cdot \sqrt{\frac{\mu}{1 + \alpha \mu - \alpha}}
\]

\[
\xi_{\text{eq}} = \beta_{\text{eff}}
\]

\[
T_{\text{eq}} = T_{\text{eff}}
\]
4. Static Nonlinear Analysis Methods

• Capacity Spectrum Analysis
  – Compares structural capacity (pushover curve) with structural demands (response spectrum).
  – Base shear and roof displacement from a non-linear pushover curve converted into equivalent spectral accelerations and displacements.
  – Graphical intersection of the two curves approximates peak structural response.
  – Non-linear inelastic behavior of structural system accounted for by effective viscous damping values applied to linear-elastic response spectrum.
4. Static Nonlinear Analysis Methods

- Capacity Spectrum Analysis

![Graph showing Capacity Spectrum Analysis](Image)
4. Static Nonlinear Analysis Methods

- Capacity Spectrum Analysis

Pushover curve → System Capacity curve

\[ S_D = \frac{x_{roof}^{(1)}}{\alpha_1 A_{roof}^{(1)}} \quad ; \quad S_A = \frac{V}{M_1^*} \]

- \( S_D \) = Spectral displacement
- \( S_A \) = Spectral acceleration
- \( x_{roof}^{(1)} \) = Roof displacement from pushover curve
- \( A_{roof}^{(1)} \) = First mode roof component
- \( \alpha_1 \) = First modal participation factor
- \( V \) = Base shear from pushover curve
- \( M_1^* \) = First modal mass
4. Static Nonlinear Analysis Methods

- Capacity Spectrum Analysis
5. Direct Displacement-Based Design

- **Origin:**

- **Basic concept:**
  - Establishment of target displacement limits for different pairs of seismic hazard and performance levels

- **Linear substructure modeling:**
  - Equivalent linear single-degree-of-freedom (SDOF) system
  - Equivalent lateral stiffness at target displacement limit
  - Equivalent viscous damping at target displacement limit
Step 1
Define target Displacement $\Delta_t$
Define seismic hazard in terms of spectral displacement

Step 2
Select value of $\xi_{eq}$ corresponding to the target displacement

Step 3
Determine $T_{eff}$ from displacement spectrum for corresponding $\xi_{eq}$

Step 4
Compute effective lateral stiffness:
$$k_{eff} = \frac{4\pi^2 W_{eff}}{g^2 T_{eff}^2}$$

Step 5
Compute design base shear
$$V_b = k_{eff} \Delta_t$$
Distribute base shear
Design structural elements for a strength $V_b$ at $\Delta_t$

Step 6
Determine the force-deflection characteristic of the structure
Compute the actual equivalent equivalent damping $\xi_{eq}'$

Step 7: CHECK
Is $\xi_{eq} = \xi_{eq}'$?

No  Yes

Design Complete

Figure 2.9 Flowchart of Direct-Displacement Seismic Design
5. Direct Displacement-Based Design

- Step 1: Definition of target displacement and seismic hazard
  - Define target displacement that structure should not exceed under a given seismic hazard level
  - Define design relative displacement response spectrum

\[
S_{D \text{ Code}} = \frac{T_{eq}^2}{4\pi^2} S_{A \text{ Code}}
\]

\[
S_D \zeta_{eq} = \sqrt{\frac{0.10}{0.05 + \zeta_{eq}}} S_{D \text{ Code}}
\]

\[
S_{D T_r} = \left( \frac{T_r}{474} \right)^{0.44} S_{D \text{ Code}}
\]

Transform spectral accelerations into spectral displacements
Scale for damping (Eurocode 8)
Scale for hazard level (FEMA 450)
5. Direct Displacement-Based Design

- Step 1: Definition of target displacement and seismic hazard

Figure 2.10 Empirical Modification Factors for Damping
5. Direct Displacement-Based Design

- Step 2: Determination of Equivalent Viscous Damping

\[ \zeta_{eq} = \frac{E_D \Delta_t}{2\pi k_{eq} \Delta_t^2} \]

- Add nominal damping ratio (e.g. 2% of critical)
5. Direct Displacement-Based Design

• Step 3: Determination of Effective Elastic Period
5. Direct Displacement-Based Design

- Step 4: Computation of Effective Lateral Stiffness

\[
k_{\text{eff}} = \frac{4\pi^2 W_{\text{eff}}}{gT_{\text{eff}}^2}
\]  

(2.9)

where \( W_{\text{eff}} \) is the effective seismic weight acting on the structure and \( g \) is the acceleration of gravity.
5. Direct Displacement-Based Design

• Step 5: Computation of Design Base Shear

The design base shear at the target displacement $V_b$ (see Figure 2.9c) is then computed by:

$$V_b = k_{eff} \Delta_t$$  \hspace{1cm} (2.10)

This base shear is distributed along the height of the structure, and structural elements are designed such that the strength of the system at the target displacement is equal to the design base shear. For structures with elements with well defined yield displacements, an equivalent base shear at first yield is derived from the design base shear $V_b$ at the target displacement allowing for a conventional load and resistance factor design to be used. After the yielding elements are designed, well known capacity design principles are used to complete the design process for all other elements.
5. Direct Displacement-Based Design

• Step 6: Determination of Actual Force-Deflection Characteristic

The actual force-deflection characteristic of the structure is then derived, and the correct value of equivalent viscous damping $\xi'_{eq}$ is computed and compared to the assumed value $\xi_{eq}$.

• Step 7: Verification

If the actual viscous damping of the system is equal to the viscous damping of the system assumed in step two, the design process is complete. If not, the process is repeated from step 2 by replacing the equivalent damping by the new value.
5. Direct Displacement-Based Design

• Advantages:
  – No estimation of the elastic period of the building is required
  – Force reduction factors do not enter the design process
  – Displacements drive the design process
  – The relationship between the elastic and inelastic displacements is not required
  – The yield displacement does not enter the design process

• Disadvantages:
  – Requires knowledge of system-level behavior
  – Global non-linear monotonic load-displacement behavior (pushover)
  – Variation of global equivalent viscous damping with displacement amplitude
  – Linear substructure modeling
6. Nonlinear Dynamic Analysis

- For very tall and/or highly irregular important structures
- Time-integration of equations of motion
- Nonlinear structural model needed
  - Cyclic behavior of structural elements deemed to respond in the inelastic range of the material needs to be included
  - Realistic representation of limit states
- Ground motion input represented by an ensemble of acceleration time-histories
  - Scaled historical ground acceleration time-histories
  - Synthetic records
- Usually performed at the end of the design process for verification purposes
7. Incremental Dynamic Analysis

- To investigate seismic capacity of structural systems
- Nonlinear dynamic analyses performed for an ensemble of earthquake ground motions scaled to a given intensity level

\[ \text{Lognormal CDF}(y) = \Theta \left[ \frac{\ln(y) - \hat{m}_y e^{\hat{\beta}/2}}{\hat{\beta}} \right] \]
8. Need for Supplemental Damping and Seismic Isolation Systems

- Main aim of current seismic design philosophies: avoiding catastrophic failures and loss of life
- Cost associated with loss of operation following a moderate/strong earthquake not currently accounted for in the design process
- Critical facilities must be designed to achieve significantly higher performance levels
- Building owners and insurance companies increasingly considering impact of a major earthquake as an economic decision tool
- Supplemental damping and seismic isolation systems needed for economical implementation of performance-base design
Questions/Discussions