CONCEPTS OF SEISMIC-RESISTANT DESIGN

Steps in the Seismic Design of a Building
1. Develop concept (design philosophy)
2. Select structural system
3. Establish performance objectives
4. Estimate external seismic forces
5. Estimate internal seismic forces (linear analysis)
6. Proportion components
7. Evaluate performance (linear or nonlinear analysis)
8. Final detailing
9. Quality assurance

Seismic Design Practice in the United States
• Seismic requirements provide minimum standards for use in building design to maintain public safety in an extreme earthquake.
• Seismic requirements safeguard against major failures and loss of life—they DO NOT necessarily limit damage, maintain function, or provide for easy repair.
• Design forces are based on the assumption that a significant amount of inelastic behavior will take place in the structure during a design earthquake.

Seismic Design Practice in the United States continued
• For reasons of economy and affordability, the design forces are much lower than those that would be required if the structure were to remain elastic.
• In contrast, wind-resistant structures are designed to remain elastic under factored forces.
• Specified code requirements are intended to provide for the necessary inelastic seismic behavior.
• In nearly all buildings designed today, survival in large earthquakes depends directly on the ability of their framing systems to dissipate energy hysteretically while undergoing (relatively) large inelastic deformations.

The Difference Between Wind-Resistant Design and Earthquake-Resistant Design
For Wind:
Excitation is an applied pressure or force on the facade.
Loading is dynamic but response is nearly static for most structures.
Structure deforms due to applied force.
Deformations are monotonic (unidirectional).
Structure is designed to respond elastically under factored loads.
The controlling life safety limit state is strength.
Enough strength is provided to resist forces elastically.

Behavior Under Wind Excitation

First significant yield
**The Difference Between Wind-Resistant Design and Earthquake-Resistant Design**

**For Earthquake:**
- Excitation is an applied displacement at the base.
- Loading and response are truly dynamic.
- Structural system deforms as a result of inertial forces.
- Deformations are fully reversed.
- Structure is designed to respond inelastically under factored loads.
- Controlling life safety limit state is deformability.
- Enough strength is provided to ensure that inelastic deformation demands do not exceed deformation capacity.

**Behavior Under Seismic Excitation (Elastic Response)**

**Factored seismic elastic strength demand**

**Factored wind**

In general, it is not economically feasible to design structures to respond elastically to earthquake ground motions.

**Behavior Under Seismic Excitation (Inelastic Response)**

**Loading**

**Unloading**

**Reloading**

**Definition of Ductility, \( \mu \)**

\[
\mu = \frac{\delta_u}{\delta_y}
\]

Stress or force or moment

Strain or displacement or rotation

Hysteresis curve
Definition of Energy Dissipation, $\Theta$

Stress or force or moment

Area = $\Theta$ = energy dissipated
Units = force x displacement

Strain or displacement or rotation

Basic Earthquake Engineering Performance Objective (Theoretical)

An adequate design is accomplished when a structure is dimensioned and detailed in such a way that the local ductility demands (energy dissipation demands) are smaller than their corresponding capacities.

$$\mu_{\text{Demand}} \leq \mu_{\text{Supply}}$$

$$\Theta_{\text{Demand}} \leq \Theta_{\text{Supplied}}$$

Concept of Controlled Damage

Seismic input energy = $E_S + E_K + E_D + E_H$

$E_S$ = Elastic strain energy

$E_K$ = Kinetic energy

$E_D$ = Viscous damping energy

$E_H$ = Hysteretic energy

Typical Energy Time History

$\text{Damping energy}$

$\text{Hysteretic energy}$

$\text{Kinetic + strain energy}$

The Role of Design

The role of “design” is to estimate the structural strength required to limit the ductility demand to the available supply and to provide the desired engineering economy.
**Design Philosophies**

New Buildings (FEMA 450, IBC 2003, ASCE 7-05)
- Force-based approach
- Single event (2/3 of 2% in 50 year earthquake)
- Single performance objective (life safety)
- Simple global acceptance criteria (drift)
- Linear analysis

Existing Buildings (ATC40, FEMA 273)
- Displacement-based approach
- Multiple events
- Multiple performance objectives
- Detailed local and global acceptance criteria
- Nonlinear analysis

**Building Performance Levels and Ranges**

<table>
<thead>
<tr>
<th>Structural</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) IMMEDIATE OCCUPANCY</td>
<td>(1-A) OPERATIONAL</td>
</tr>
<tr>
<td>(2) Damage Control Range</td>
<td>(1-B) IMMEDIATE OCCUPANCY</td>
</tr>
<tr>
<td>(3) LIFE SAFETY</td>
<td>(2-C) LIFE SAFETY</td>
</tr>
<tr>
<td>(4) Limited Safety Range</td>
<td>(5-D) HAZARDS REDUCED</td>
</tr>
<tr>
<td>(5) COLLAPSE PREVENTION</td>
<td></td>
</tr>
</tbody>
</table>

**Earthquake Hazard Levels (FEMA 273)**

<table>
<thead>
<tr>
<th>Probability</th>
<th>MRI</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%-50 year</td>
<td>72 years</td>
<td>Frequent</td>
</tr>
<tr>
<td>20%-50 year</td>
<td>225 years</td>
<td>Occasional</td>
</tr>
<tr>
<td>10%-50 year (BSE-1)</td>
<td>474 years</td>
<td>Rare</td>
</tr>
<tr>
<td>2%-50 year* (BSE-2)</td>
<td>2475 years</td>
<td>Very rare</td>
</tr>
</tbody>
</table>

*2003 NEHRP Recommended Provisions maximum considered earthquake.

**Performance Objectives (FEMA 273)**

Performance Objective: Building Performance Level + EQ Design Level = Performance Objective

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<tr>
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</thead>
<tbody>
<tr>
<td>72 year</td>
<td>a</td>
<td>b</td>
<td>c</td>
<td>d</td>
</tr>
<tr>
<td>225 year</td>
<td>e</td>
<td>f</td>
<td>g</td>
<td>h</td>
</tr>
<tr>
<td>474 year</td>
<td>i</td>
<td>j</td>
<td>k</td>
<td>l</td>
</tr>
<tr>
<td>2475 year</td>
<td>m</td>
<td>n</td>
<td>o</td>
<td>p</td>
</tr>
<tr>
<td>5000 year</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*“Basic Safety Objective” is design for k and p.*

**Performance Objectives (FEMA 273)**

Enhanced Safety Objectives

<table>
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<tr>
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<td>5000 year</td>
<td>x</td>
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*“Enhanced Safety Objective” is designed for j, o, and x.*

**Steps in the Seismic Design of a Building**

1. Develop Concept
2. Select Structural System
3. Establish Performance Objectives
4. Estimate External Seismic Forces
5. Estimate Internal Seismic Forces (Linear Analysis)
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7. Evaluate Performance (Linear or Nonlinear Analysis)
8. Final Detailing
9. Quality Assurance
Definitions

**Inherent Capacity:** That capacity provided by the gravity system or by gravity plus wind.

**Affordable Capacity:** The capacity governed by reasonable (ordinary) building costs in the geographic area of interest.

**Seismic Premium:** The ratio of the (reduced) seismic strength demand to the inherent capacity.

The Role of Design

If "affordable capacity" is relatively constant, then ductility demand is primarily a function of elastic seismic demand.

Because elastic seismic demand is a function of local seismicity, ductility demand is directly proportional to local seismicity.

Hence, California, which has higher seismicity than, for example, Austin, has a higher inherent ductility demand than does Austin.

Limitation

The ductility demand cannot exceed the ductility supply.

<table>
<thead>
<tr>
<th>Moment Frame Ductility Supply</th>
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</thead>
<tbody>
<tr>
<td>Ordinary detailing</td>
</tr>
<tr>
<td>Intermediate detailing</td>
</tr>
<tr>
<td>Special detailing</td>
</tr>
</tbody>
</table>

In California, the high seismicity dictates a high ductility demand (typically > 3); hence, only moment frames with special detailing may be used.
Ordinary Concrete Moment Frame

Advantages:
- Architectural simplicity, low detailing cost

Disadvantages:
- Higher base shear, highly restricted use

Intermediate Concrete Moment Frame

Advantages:
- Architectural simplicity, relatively low base shear
- Less congested reinforcement

Disadvantages:
- Restricted use

Special Concrete Moment Frame

Advantages:
- Architectural simplicity, relatively low base shear
- Drift control, congested reinforcement

Disadvantages:
- Restrictions on steel grades
- Continuous top & bottom reinforcement
- Joint shear strength requirements
- Strong column - weak beam
- Use of maximum probable strength
- Closely spaced ties in critical regions

In Austin, the relatively low seismicity dictates a low ductility demand (typically < 2); hence, intermediate and special detailing may be used. However, there is no motivation to use special detailing if the resulting design forces fall below the inherent capacity.

System Development (Summary)

Could I use an ordinary moment frame in California?
- Theoretically, YES if affordability is not an issue.
- Practically, NO as costs will be unreasonable.

Could I Use a special moment frame in Austin?
- Theoretically, YES but detailing would be governed by inherent strength requirements.
- Practically, NO as costs would be unreasonable.

Note: Comments are without regard to building code requirements.

Ductility demand = \( \frac{\text{Elastic seismic demand}}{\text{Affordable capacity}} \)

- Increase affordable capacity (pay a higher seismic premium)
- Reduce elastic seismic demand
  - Base isolation
  - Added damping
Essential Facilities: How To Provide More Protection?

Ductility demand = \( \frac{\text{Elastic seismic demand}}{\text{Affordable capacity}} \)

Reduce ductility demand by increasing affordable capacity (make system stronger).

Reduction in Ductility Demand Is in Direct Proportion to Additional Premium Paid

\[ AP = \text{Additional premium (1 in NEHRP Provisions)} \]

Damage Reduction Is Apparent in Denominator of Second Term

\[ \text{Damage} = \frac{\delta_{\text{max}}}{\delta_{\text{alt}}} + 0.15 \frac{E_H}{AP \times F_d \delta_{\text{alt}}} \]

System Concepts

Optimal performance achieved by:

- Providing competent load path
- Providing redundancy
- Avoiding configuration irregularities
- Proper consideration of "nonstructural" elements and components
- Avoiding excessive mass
- Detailing for controlled energy dissipation
- Limiting deformation demands

Concept of Competent Load Path

Plan

Elevation
**Which System is Better?**

System A  

System B

Overall strength of System A = System B  

Systems have same overall deformation capacity.

---

**Which System is Better?**

System A  

System B

What is the effect of a premature loss of one element?

---

**Increase Local Redundancy by Designing Hinge Sequence**

Hinge sequence

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**Versus Simultaneous Hinging**

Hinge sequence

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**Distributed vs Simultaneous Hinging**

Force  

Deformation

Simultaneous: Less apparent overstrength  

Less post-yield stability

---

**Special Concrete Moment Frame**

**DETAILING REQUIREMENTS**

- Restrictions on steel grades
- Continuous top & bottom reinforcement
- Joint shear strength requirements
- Strong column - weak beam
- Use of maximum probable strength
- Closely spaced ties in critical regions

**Advantages:**

Architectural simplicity, relatively low base shear

**Disadvantages:**

Drift control, congested reinforcement
Avoid Undesirable Mechanisms

Force vs. Deformation

Avoid Accidental Mechanisms

\[ V_{\text{design}} = \frac{2M_p}{L} \]
\[ V_{\text{actual}} = \frac{2M_p}{L'} \]

Masonry wall

Avoid Accidental Mechanisms
Avoid Situations Where the Loss of One Element Is Catastrophic

Avoid Re-entrant Corners (or Reinforce Accordingly)

Structurally: Improved
Architecturally Dubious

Protect “Nonstructural” Elements

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Structural Analysis
In the context of the *NEHRP Recommended Provisions*, the purpose of structural analysis is to estimate:
1. The forces required to proportion members
2. Global deformations (e.g., story drift)

What kind of analysis to use?
- Equivalent lateral force (ELF) analysis
- Modal response spectrum (MRS) analysis
- Linear time history (LTH) analysis
- Nonlinear static pushover (NSP) analysis
- Nonlinear dynamic time history (NTH) analysis
Structural Analysis

The analysis must be **good enough for design**. There should be no expectation that the analysis can predict actual response (linear or nonlinear).

**ELF**: Good enough for preliminary design but not final design

**MRS**: Good enough for design

**LTH**: Not significantly better than MRS

**NSP**: The Jury is deliberating

**NTH**: The best choice for predicting local deformation demands (Note: NTH is not required by NEHRP Recommended Provisions or IBC.)

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Seismic Design (and Analysis) Is as Much an Art as It Is a Science