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.

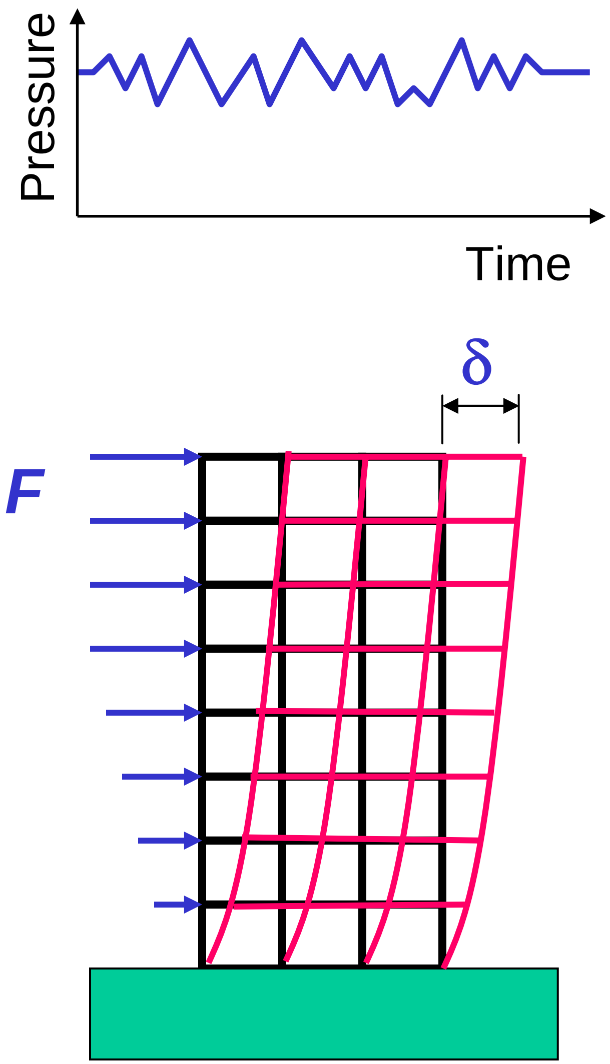
Deformations are **monotonic (unidirectional).**

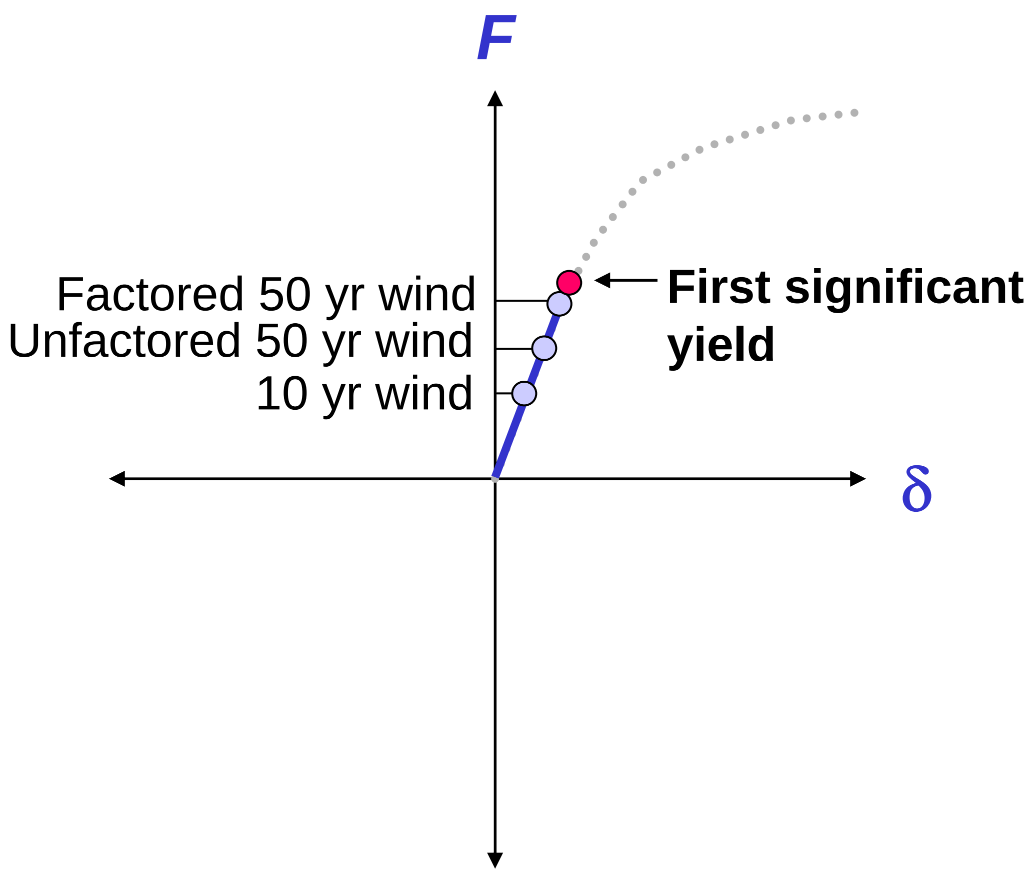
Structure is designed to respond **elastically** under factored loads.

The controlling life safety limit state is **strength**.

Enough strength is provided to resist forces elastically.

Behavior Under Wind Excitation





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.**

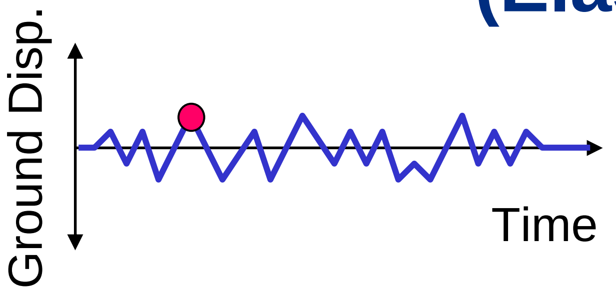
Deformations are fully **reversed.**

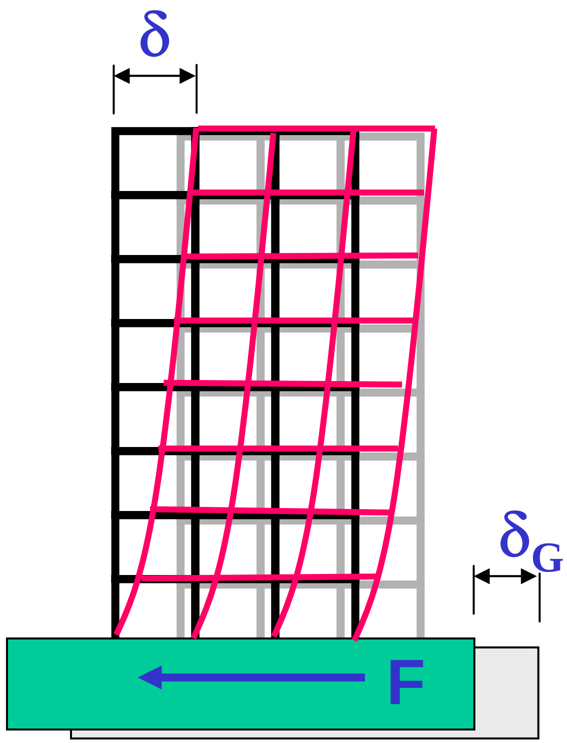
Structure is designed to respond **inelastically** under factored loads.

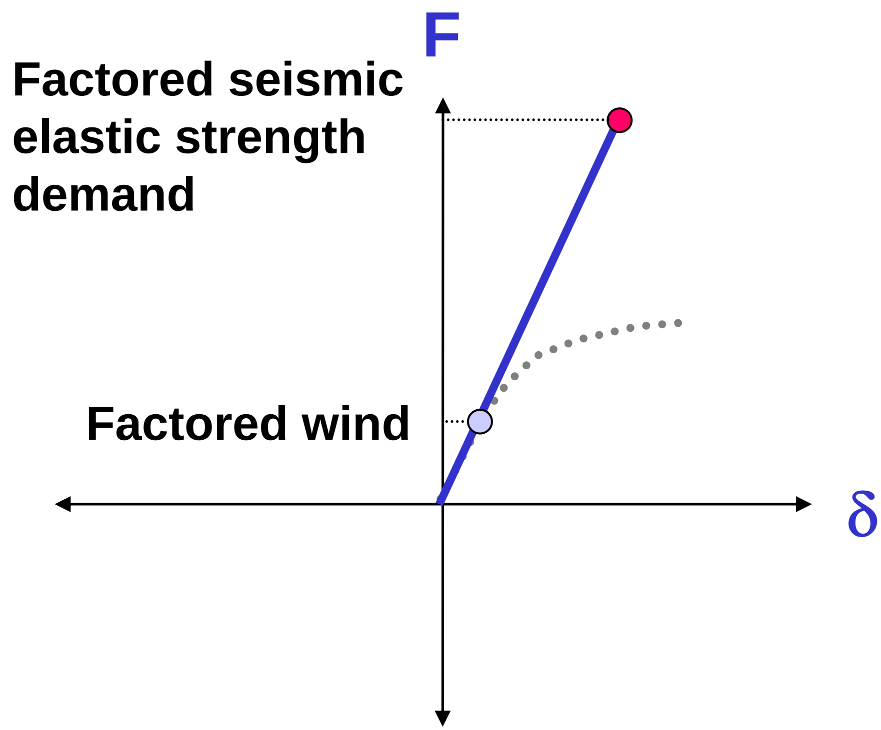
Controlling life safety limit state is **deformability.**

Enough strength is provided to ensure that inelastic deformation demands do not exceed deformation capacity.

Behavior Under Seismic Excitation (Elastic Response)

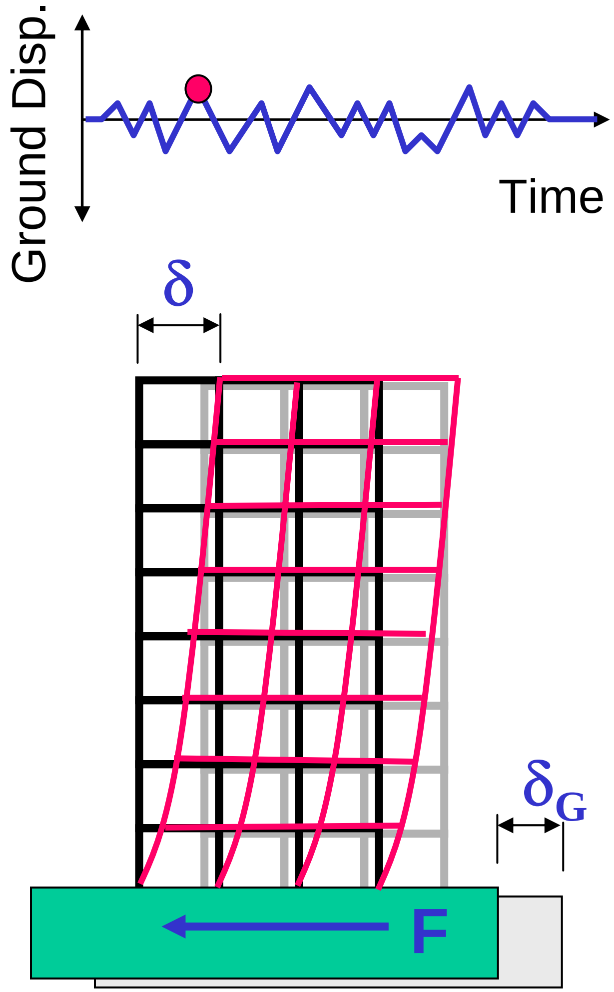


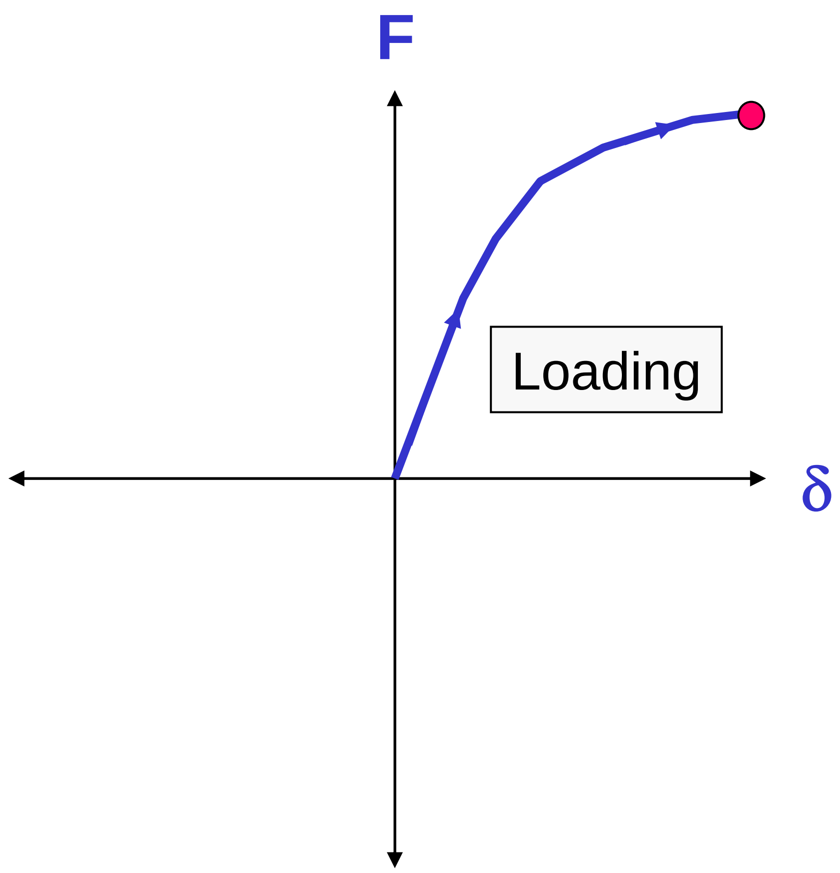




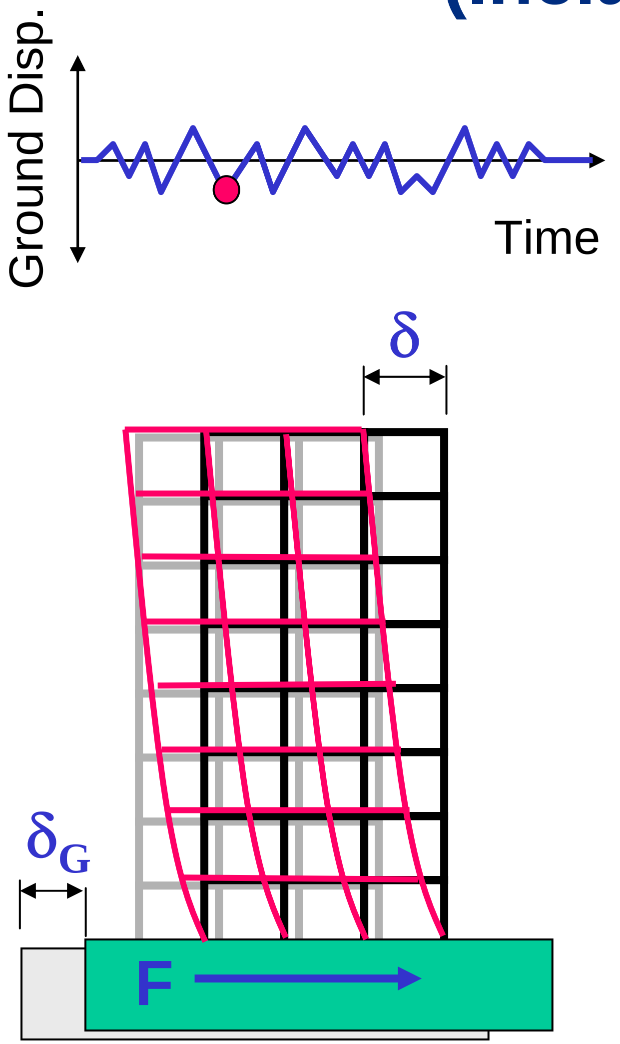
In general, it is not economically feasible to design structures to respond elastically to earthquake ground motions.

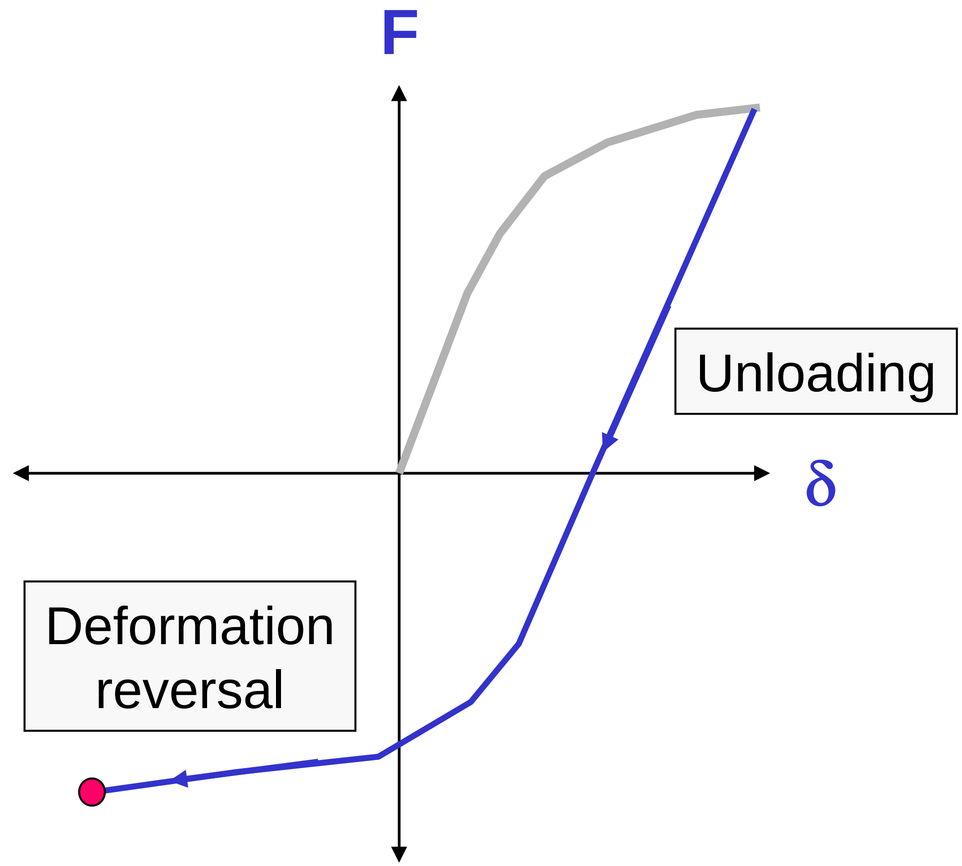
Behavior Under Seismic Excitation (Inelastic Response)



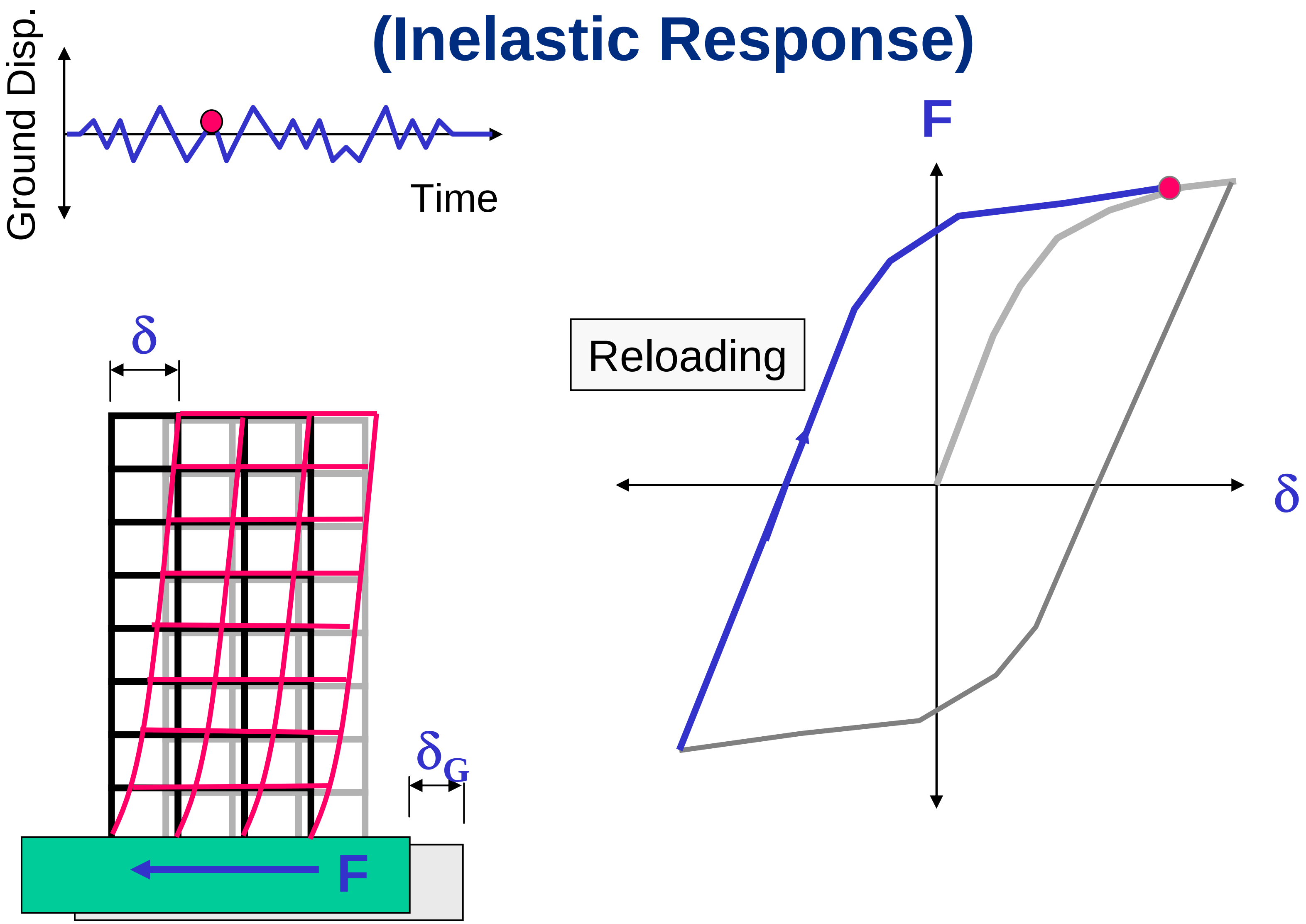


Behavior Under Seismic Excitation (Inelastic Response)

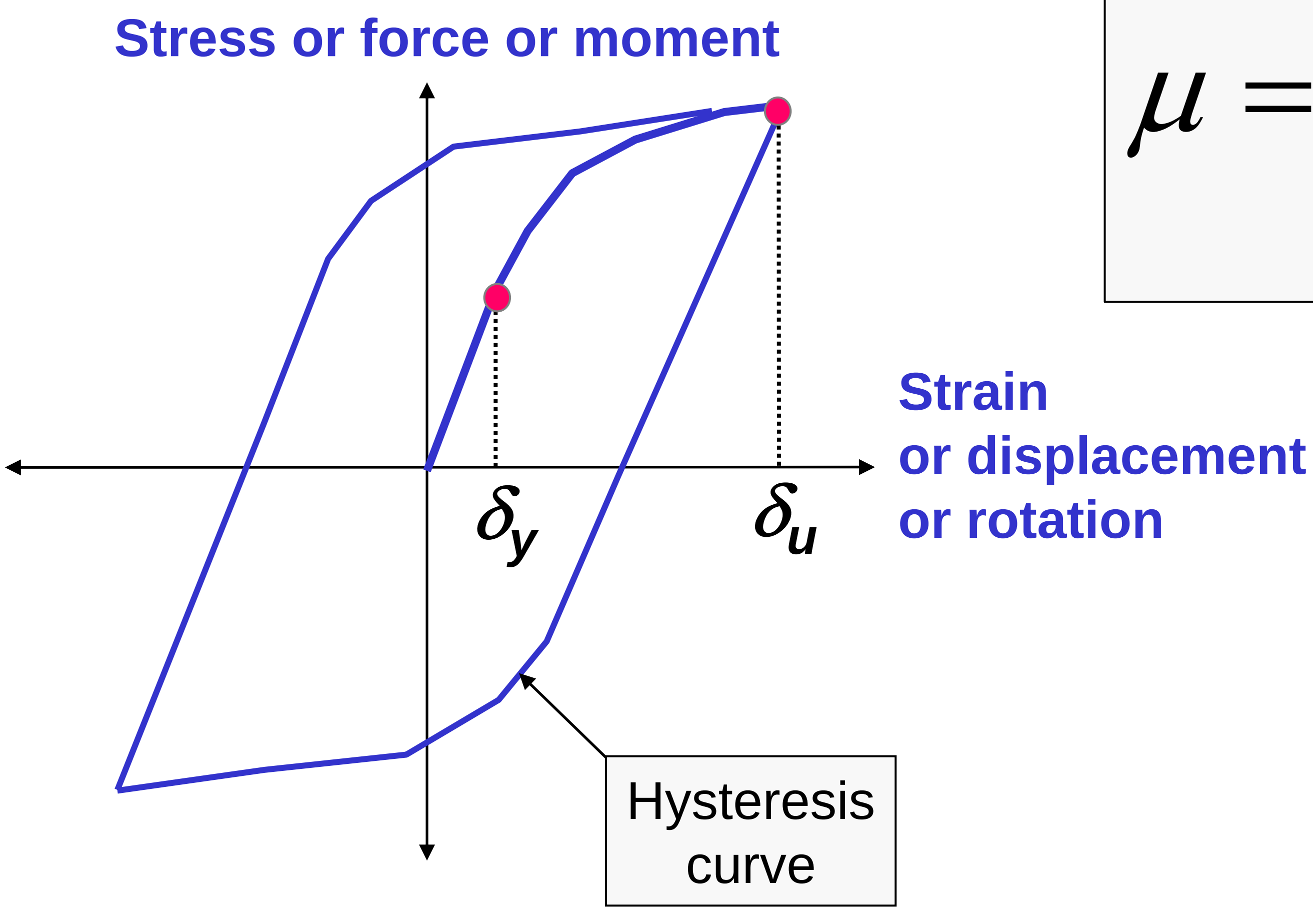




Behavior Under Seismic Excitation (Inelastic Response)

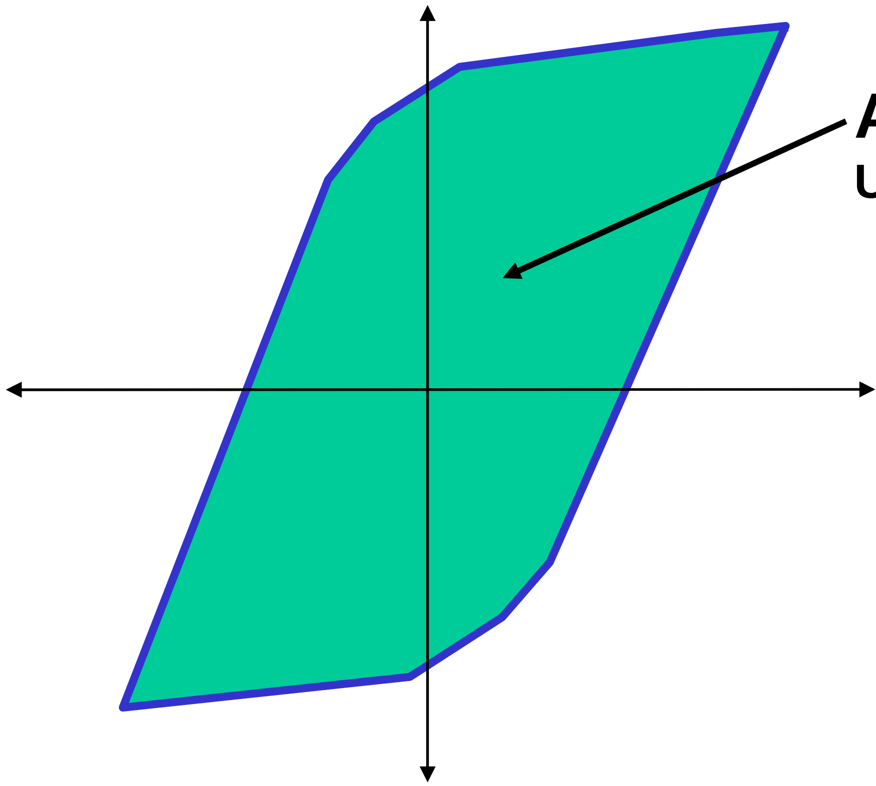


Definition of Ductility, μ



$$\mu = \frac{\delta_u}{\delta_y}$$

Definition of Energy Dissipation, Θ



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.

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

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

Concept of Controlled Damage

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

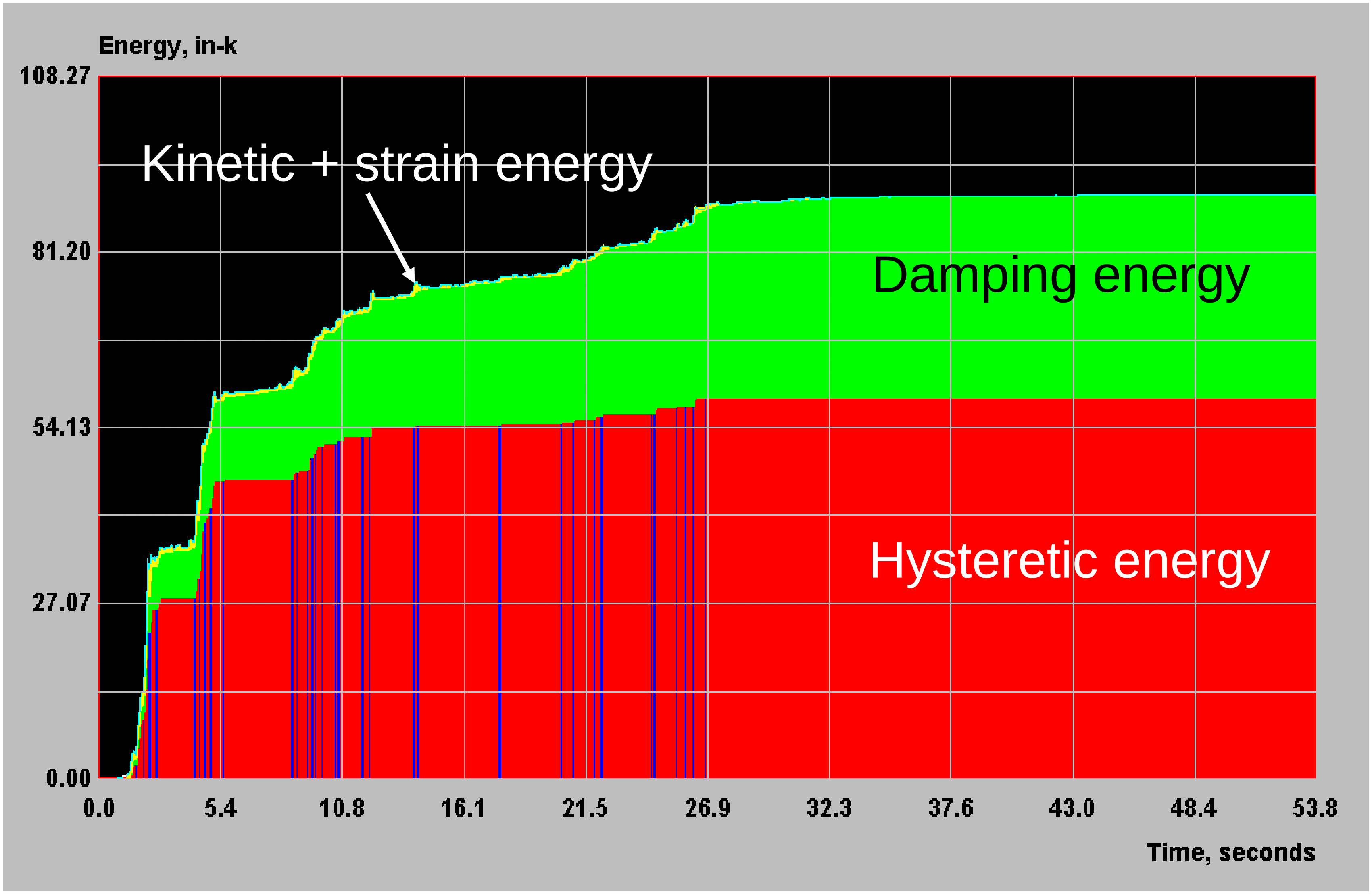
E_S = Elastic strain energy

E_K = Kinetic energy

E_D = Viscous damping energy

E_H = Hysteretic energy

Typical Energy Time History



$$Damage = \frac{\delta_{\max}}{\delta_{ult}} + 0.15 \frac{E_H}{F_y \delta_{ult}}$$

- Yielding is necessary for affordable design.
- Yielding causes hysteretic energy dissipation.
- Hysteretic energy dissipation causes damage.

Therefore, **damage is necessary for affordable design**

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

Structural	Nonstructural	Combined
(1) IMMEDIATE OCCUPANCY	**(A) OPERATIONAL**	**(1-A) OPERATIONAL**
(2) Damage Control Range	**(B) IMMEDIATE OCCUPANCY**	**(1-B) IMMEDIATE OCCUPANCY**
(3) LIFE SAFETY	**(C) LIFE SAFETY**	**(3-C) LIFE SAFETY**
(4) Limited Safety Range	**(D) HAZARDS REDUCED**	**(5-D) HAZARDS REDUCED**
(5) COLLAPSE PREVENTION		

Earthquake Hazard Levels (FEMA 273)

Probability	MRI	Frequency
50%-50 year	72 years	Frequent
20%-50 year	225 years	Occasional
10%-50 year **(BSE-1)**	474 years	Rare
2%-50 year* **(BSE-2)**	2475 years	Very rare

*2003 *NEHRP Recommended Provisions* maximum considered earthquake.

Performance Objectives (FEMA 273)

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

Performance Level

		Immediate Occ.	Operational	Life Safety	Collapse Prev.
Earthquake	72 year	a	b	c	d
	225 year	e	f	g	h
	474 year	i	j	**k**	l
	2475 year	m	n	o	**p**

"Basic Safety Objective" is design for **k** and **p**.

Performance Objectives (FEMA 273)
Enhanced Safety Objectives

Performance Level

Earthquake		Immediate Occ.	Operational	Life Safety	Collapse Prev.
	72 year	a	b	c	d
	225 year	e	f	g	h
	474 year	i	**j**	k	l
	2475 year	m	n	**o**	p
	5000 year				**x**

"Enhanced Safety Objective" is designed for **j** , **o** , and **x**.

Steps in the Seismic Design of a Building

1. Develop Concept
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8. Final Detailing
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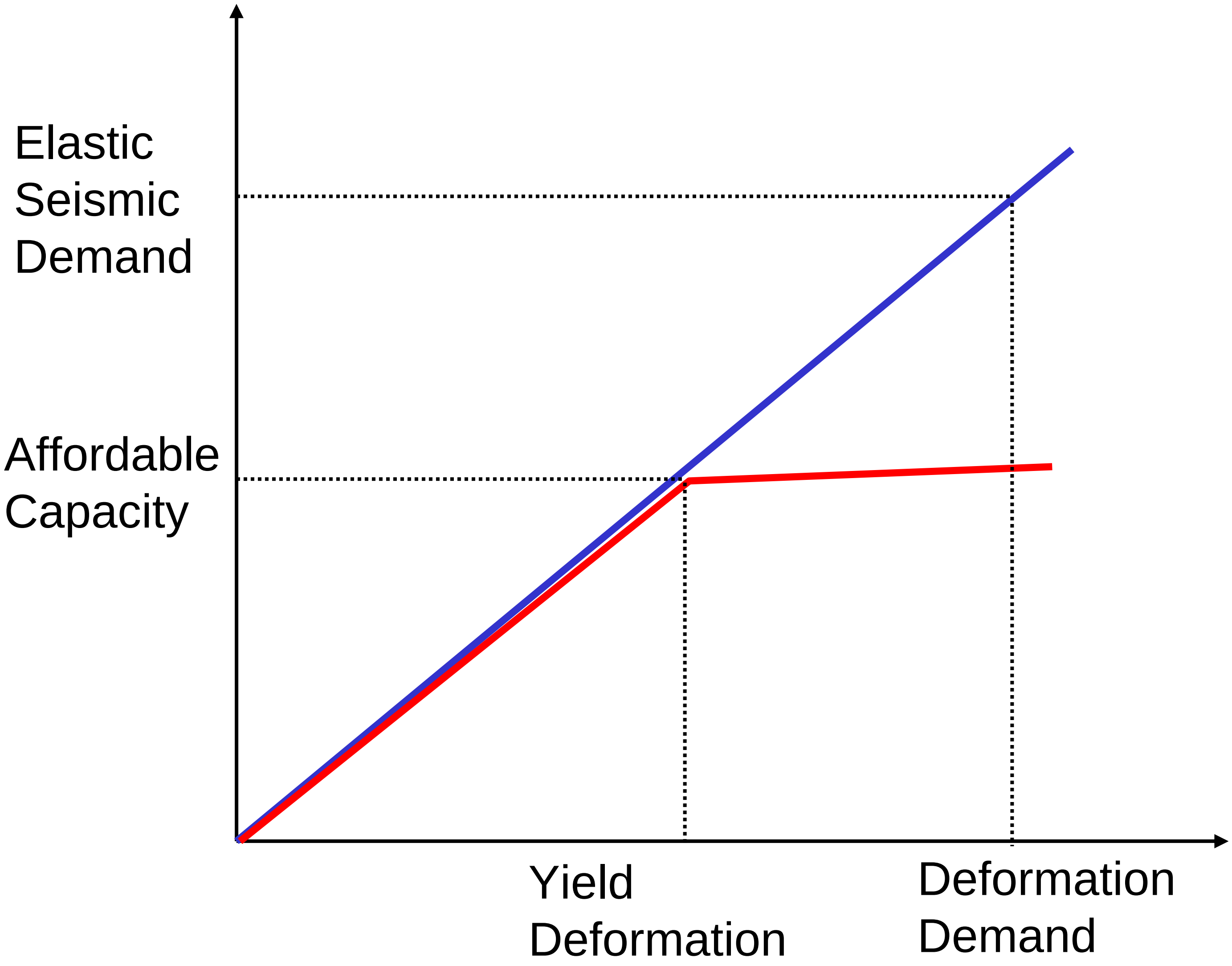
Definitions

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

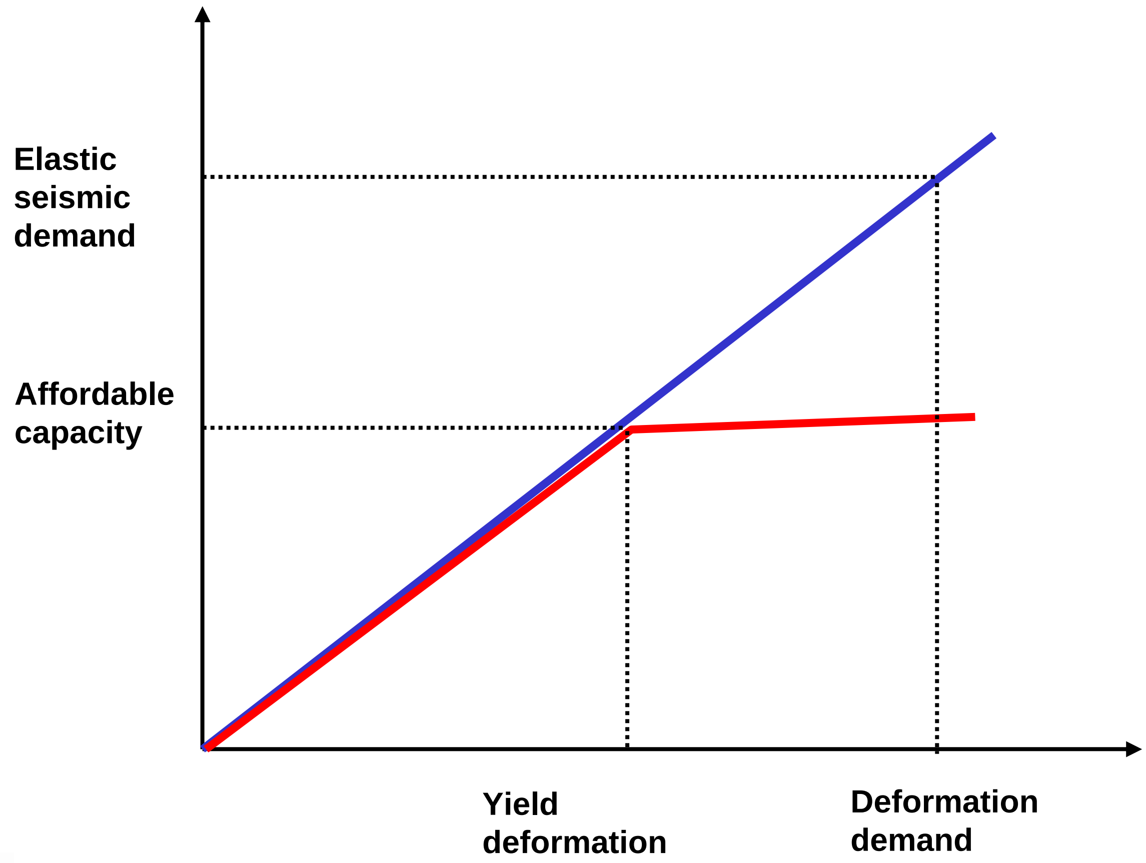
Affordable Capacity: The capacity governed by reasonable (ordinary) building costs in the geographic area of interest.

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

The Role of Design



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

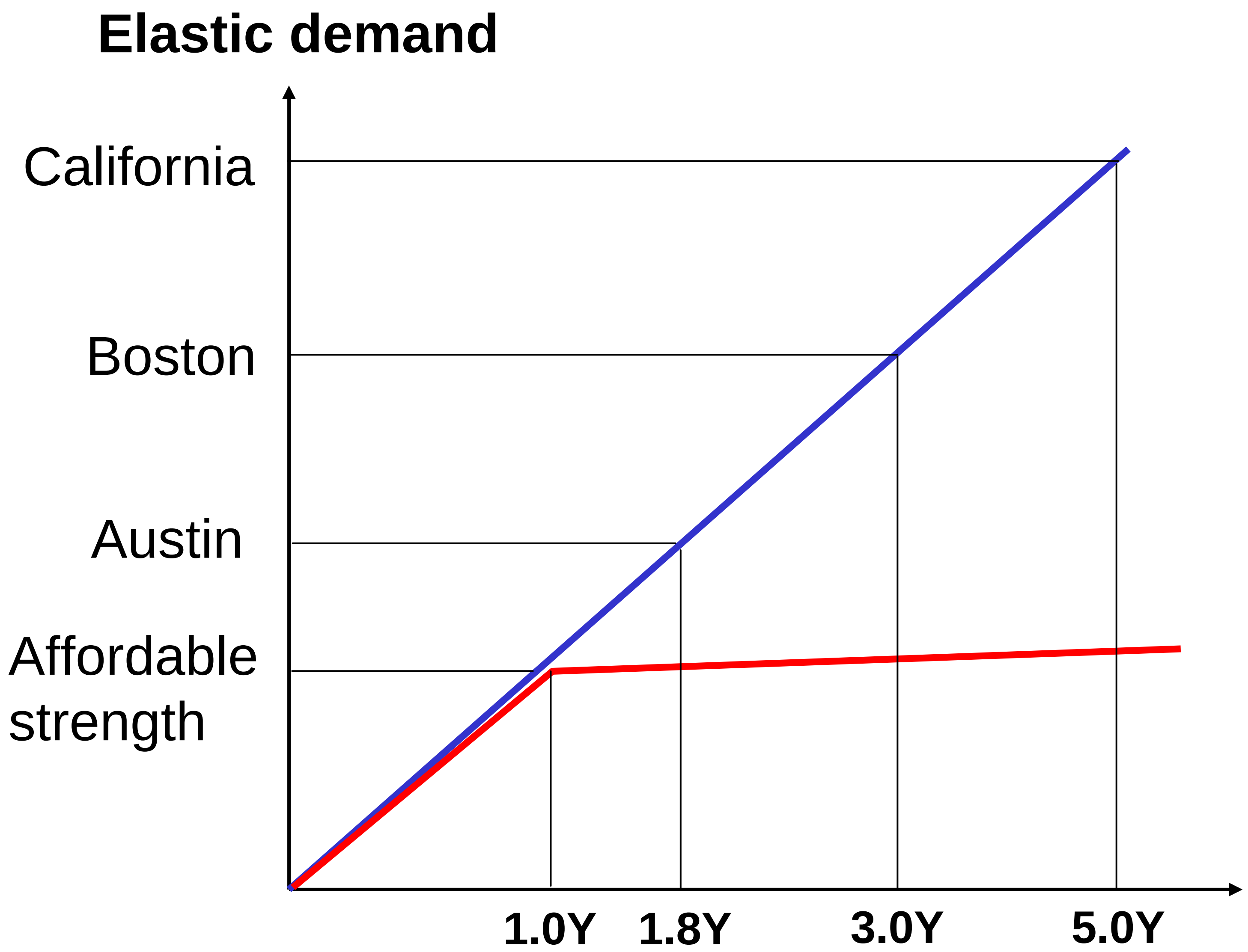


The Role of Design

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.


Elastic demand
California
Boston
Austin
Affordable strength
1.0Y
1.8Y
3.0Y
5.0Y

Limitation

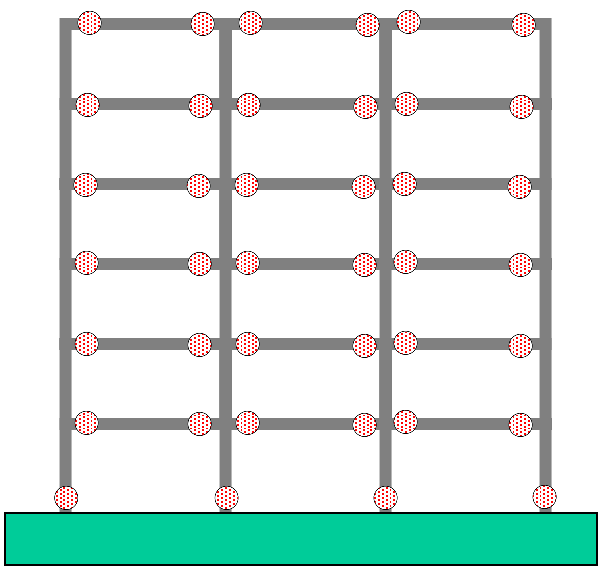
The ductility demand cannot exceed the ductility supply.

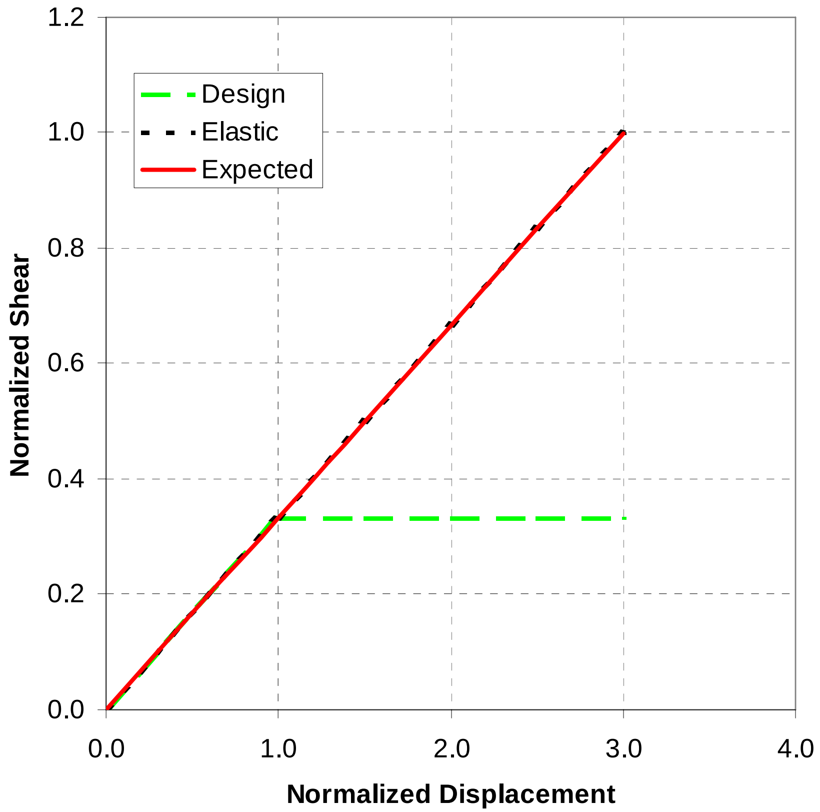
Moment Frame Ductility Supply	
Ordinary detailing	1.5
Intermediate detailing	2.5
Special detailing	5.0

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

No special detailing required

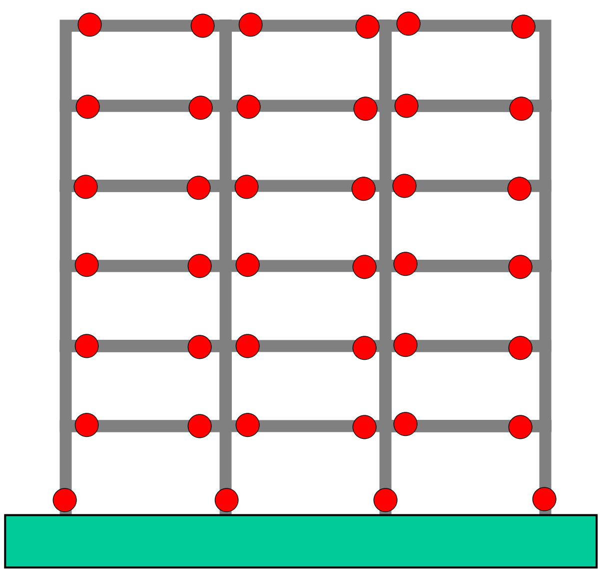


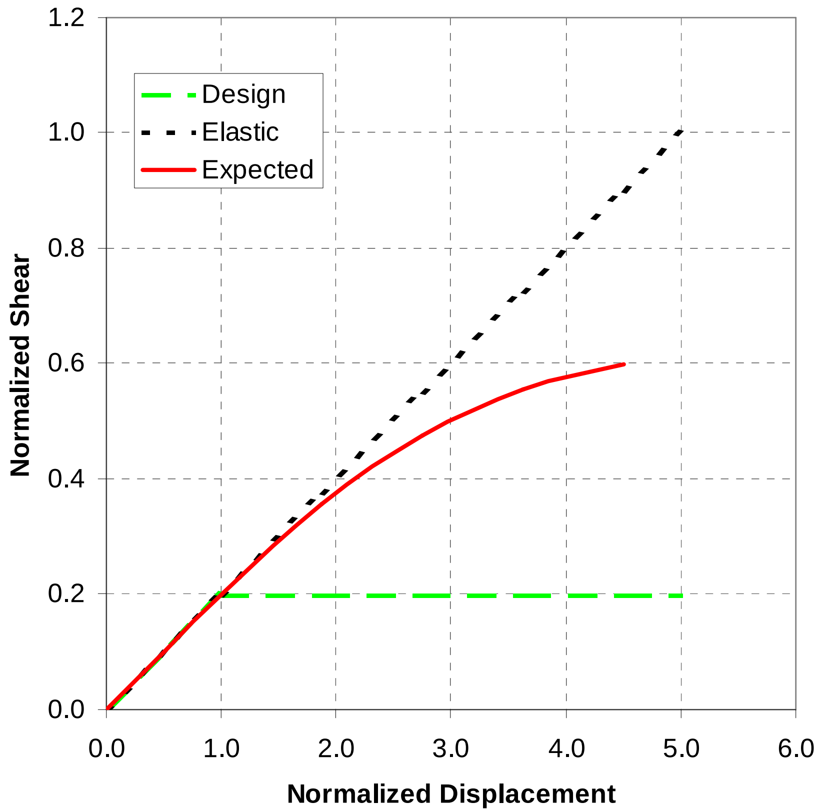


Advantages:
Architectural simplicity, low detailing cost
Disadvantages:
Higher base shear, highly restricted use

Intermediate Concrete Moment Frame

DETAILING REQUIREMENTS:
- Continuous top and bottom reinforcement
- Special requirements for shear strength
- Special detailing in critical regions



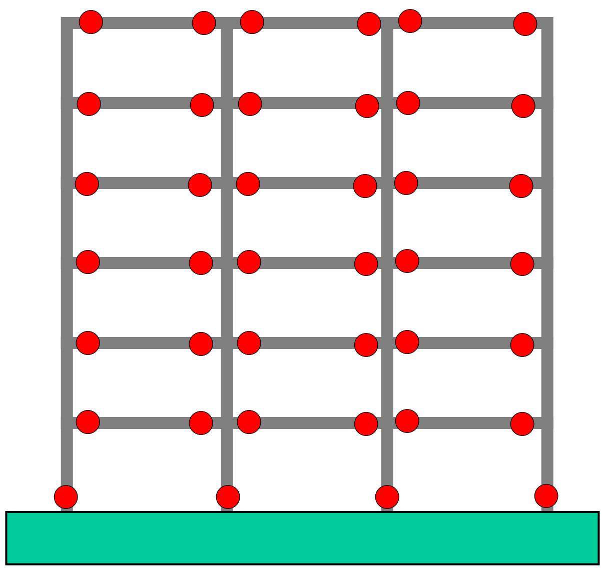


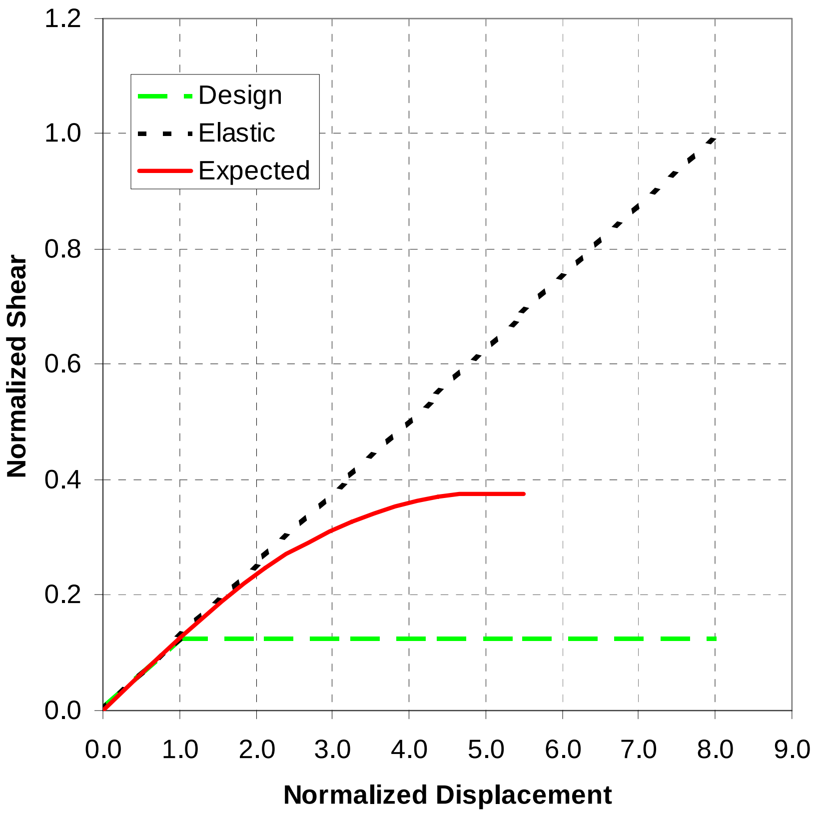
Advantages:
Architectural simplicity, relatively low base shear, less congested reinforcement
Disadvantages:
Restricted use

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

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.

What if Supplied Ductility Cannot Meet the Demand?

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

- Increase affordable capacity
  (pay a higher seismic premium)

- Reduce elastic seismic demand
  - Base isolation
  - Added damping

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.

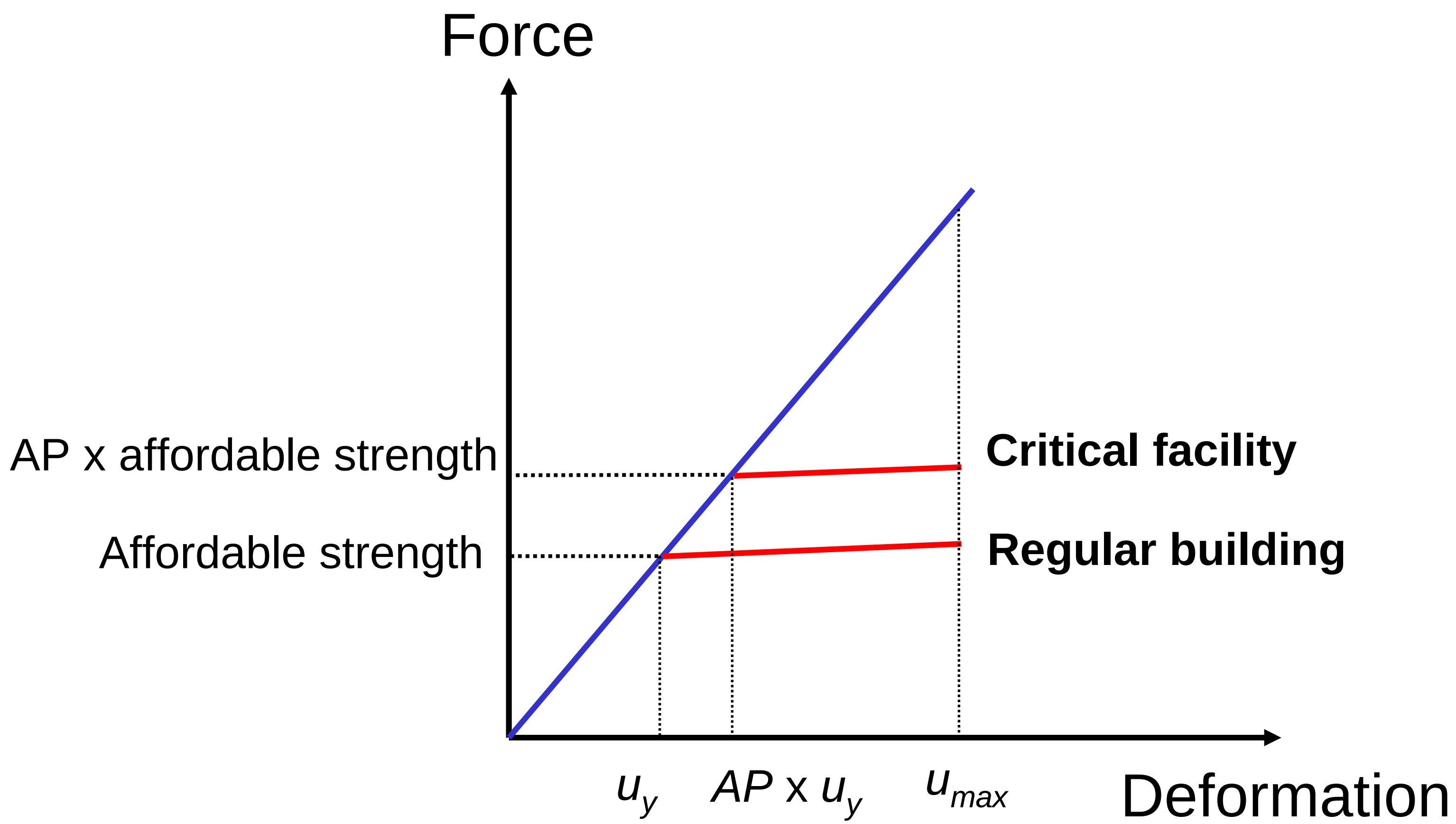
Note: Comments are without regard to building code requirements

Essential Facilities: How To Provide More Protection?

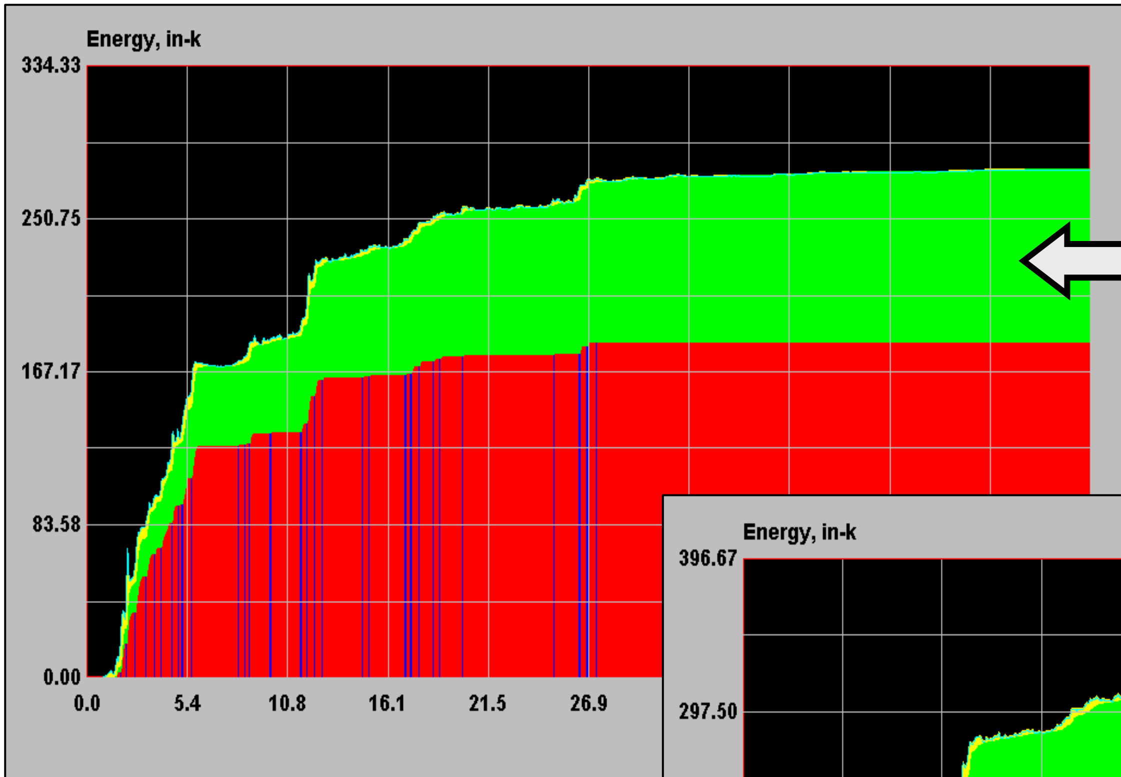
$$\text{Ductility demand} = \frac{\text{Elastic seismic demand}}{\text{Affordable capacity}}$$

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

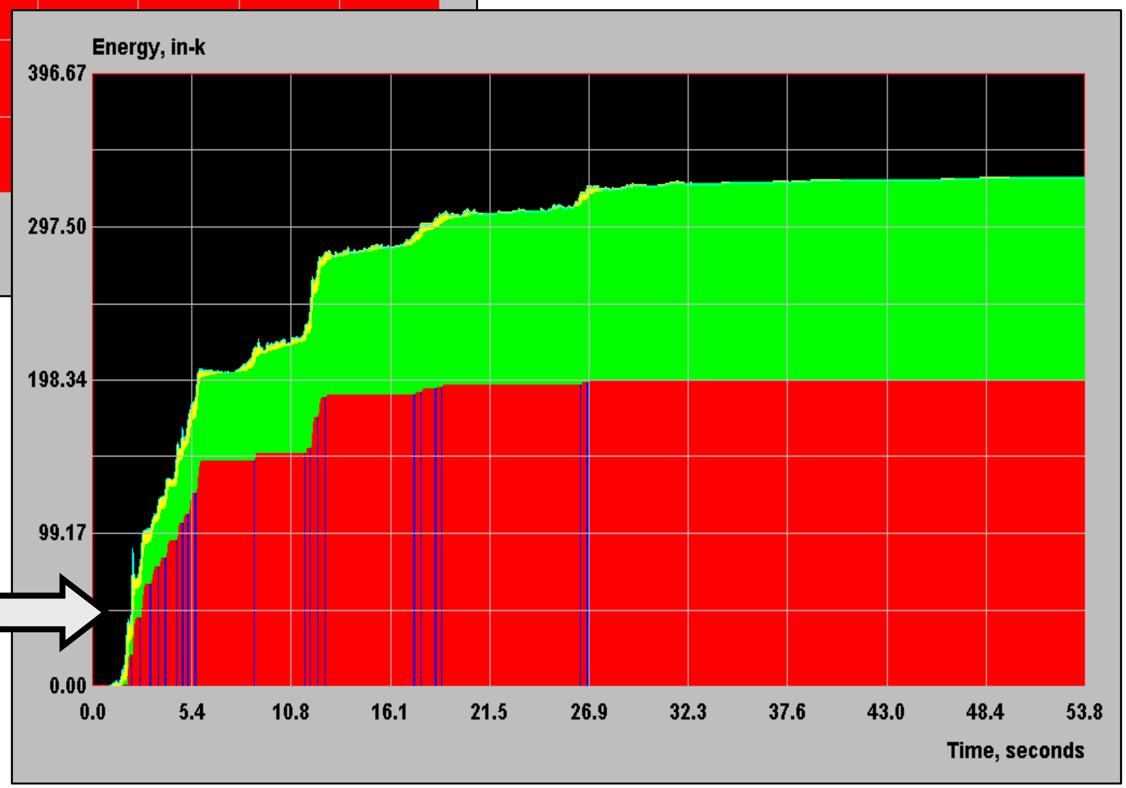
Reduction in Ductility Demand Is in Direct Proportion to Additional Premium Paid



AP = Additional premium (1 in *NEHRP Provisions*)



Strength index = 1.0
Max drift = 2.2 in.
Duct. demand = 4.4
Max E_H = 183 in-k



Strength index = 1.5
Max drift = 2.4 in.
Duct. demand = 3.1
Max E_H = 199 in-k

Damage Reduction Is Apparent in Denominator of Second Term

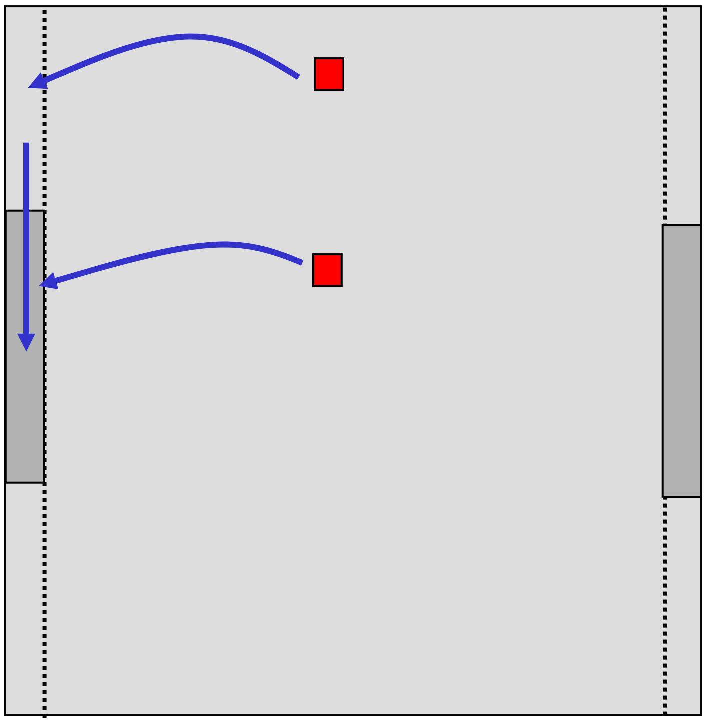
$$Damage = \frac{\delta_{\max}}{\delta_{ult}} + 0.15\frac{E_H}{AP \times F_y \delta_{ult}}$$

System Concepts

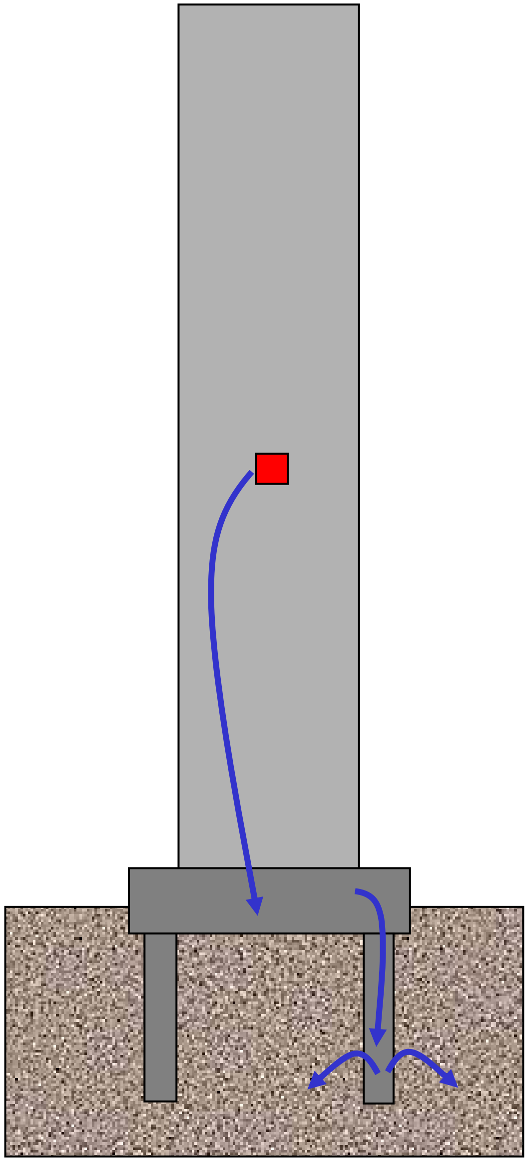
Optimal performance achieved by:

- 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

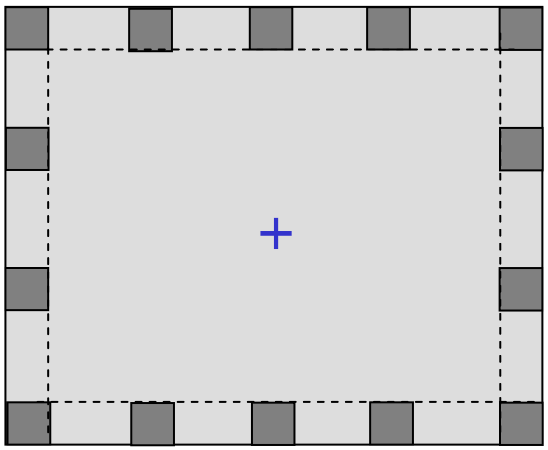


Plan

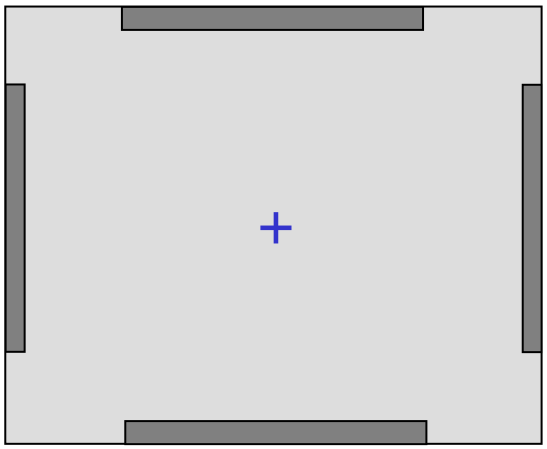


Elevation

Which System is Better?



System A

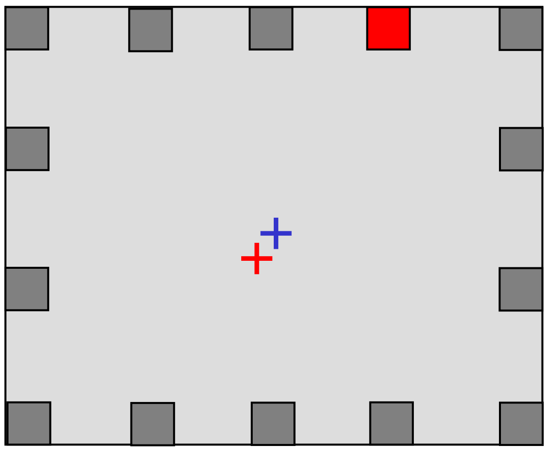


System B

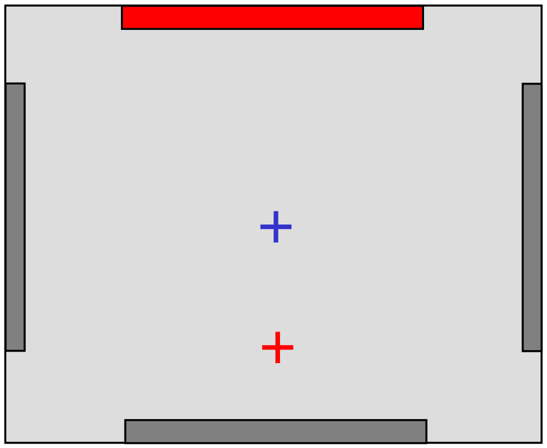
Overall strength of System A = System B

Systems have same overall deformation capacity.

Which System is Better?



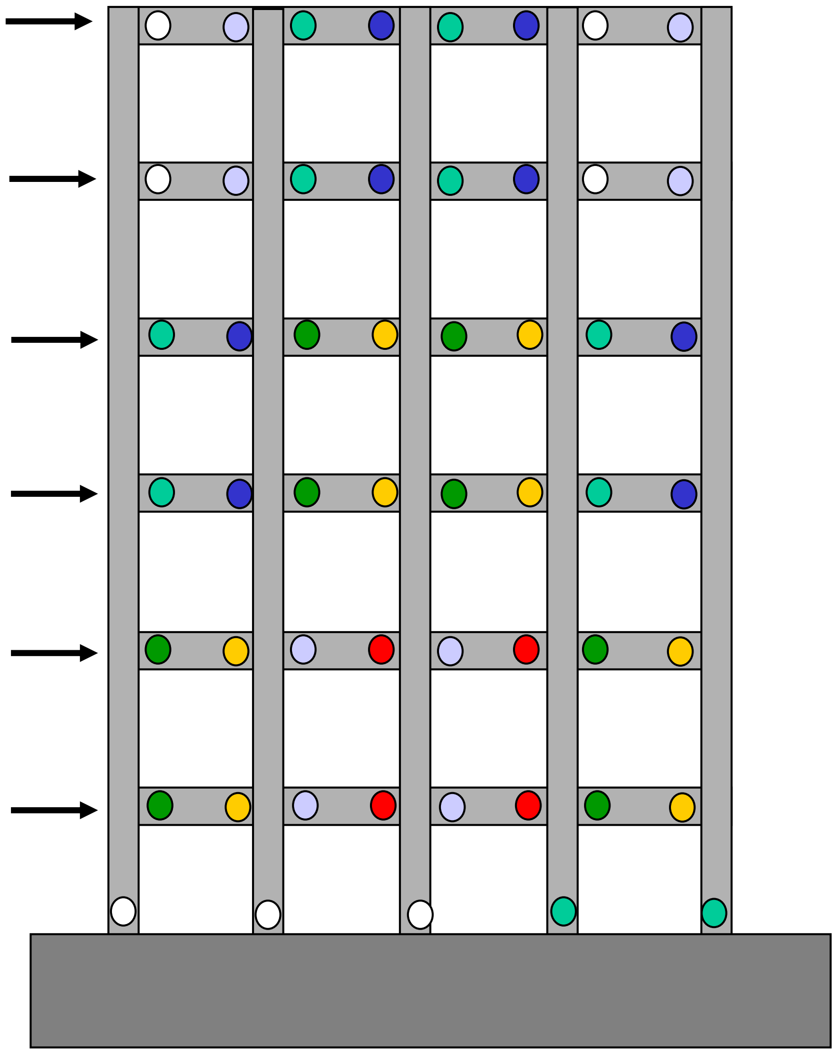
System A



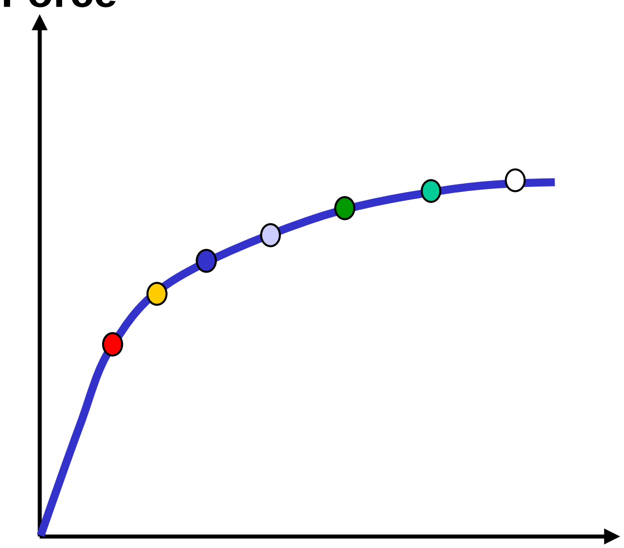
System B

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

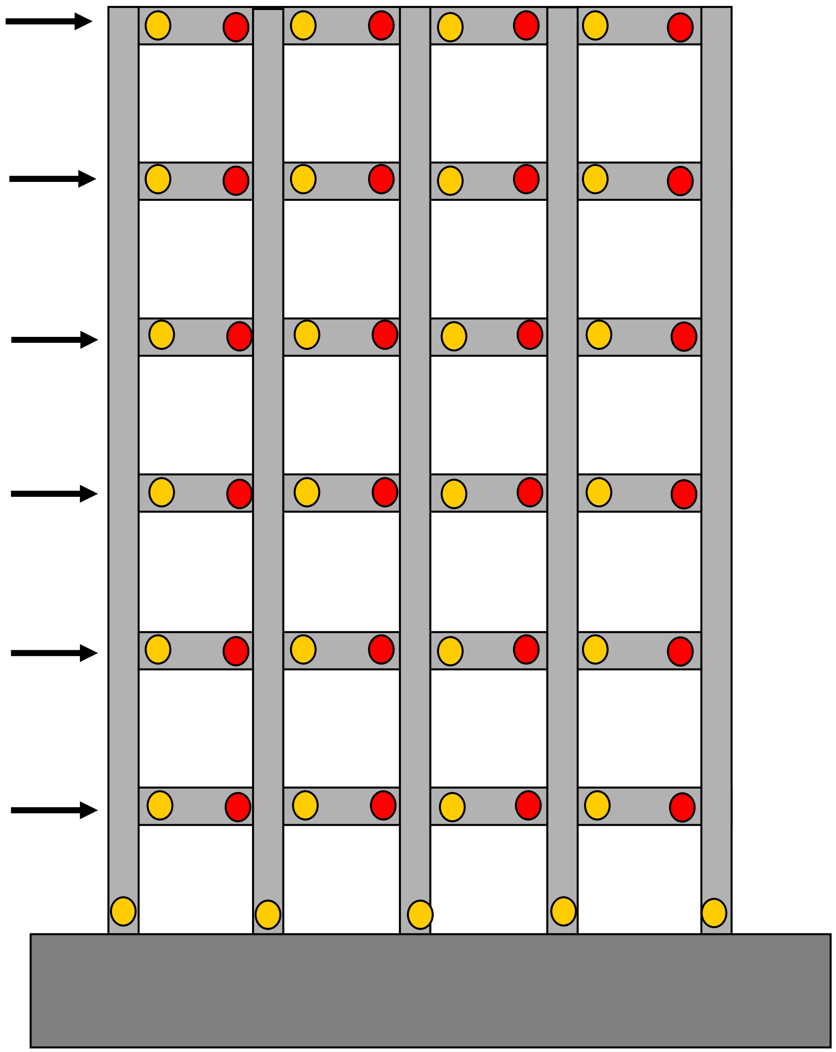
Increase Local Redundancy by Designing Hinge Sequence



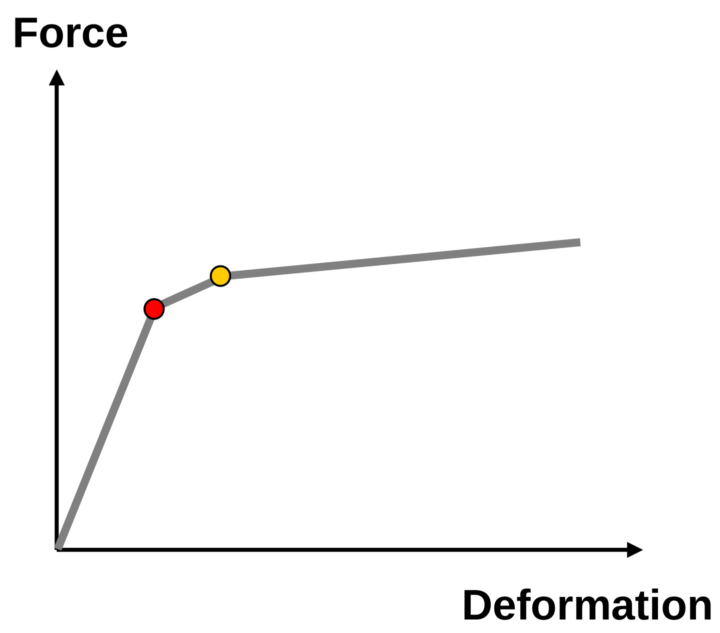
Hinge sequence



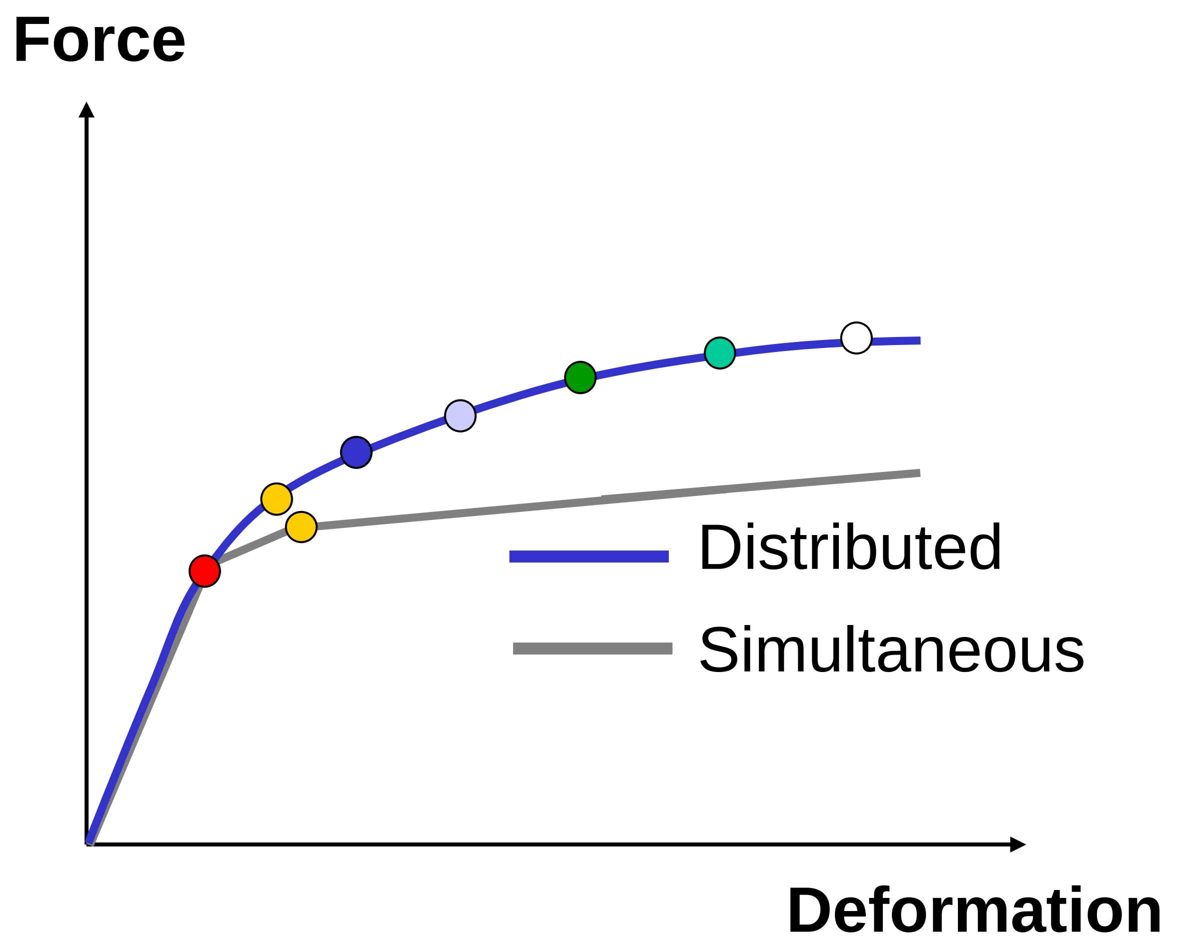
Versus Simultaneous Hinging



Hinge sequence



Distributed vs Simultaneous Hinging

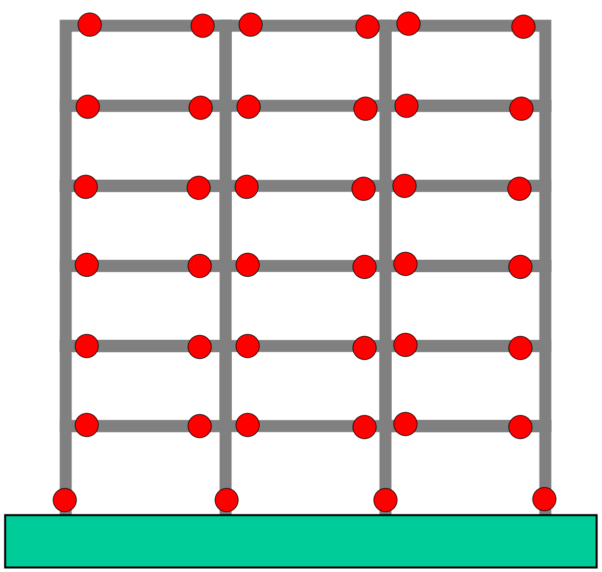


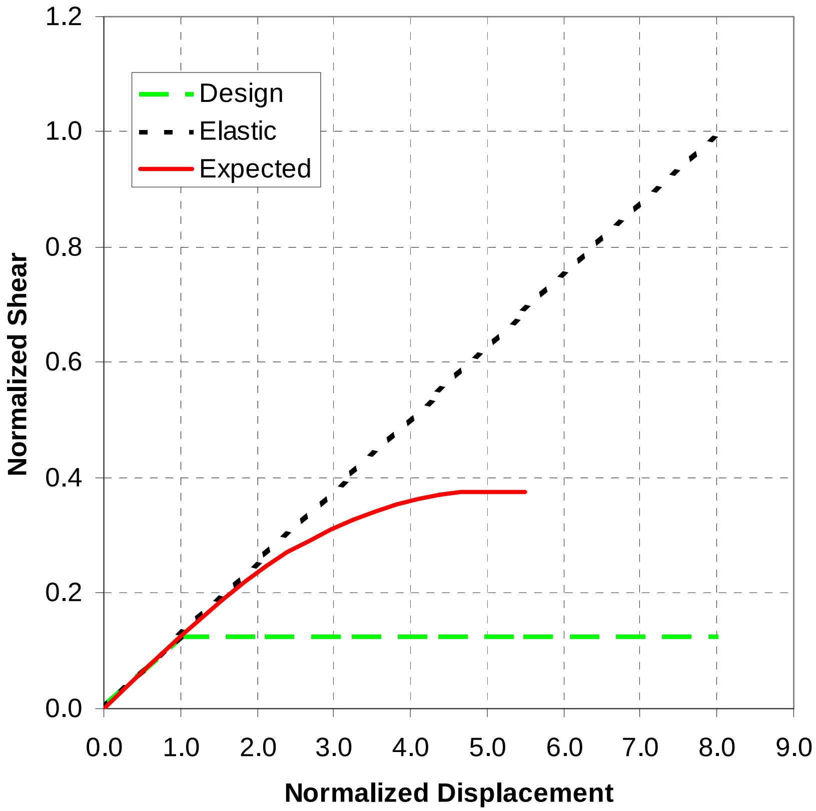
Simultaneous: Less apparent overstrength
Less post-yield stability

Special Concrete Moment Frame

DETAILING REQUIREMENTS

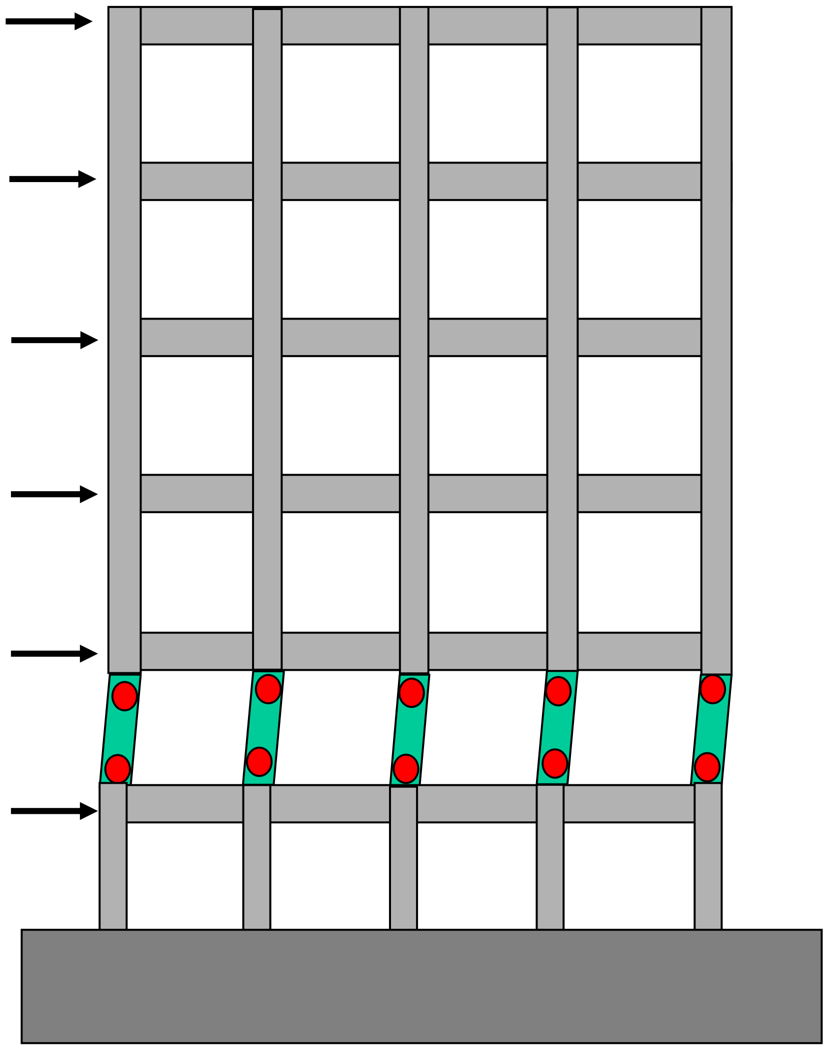
- Restrictions on steel grades
- Continuous top & bottom reinforcement
- Joint shear strength requirements
- Strong column - weak beam
- Use of maximum probable strength
- Closely spaced ties in critical regions

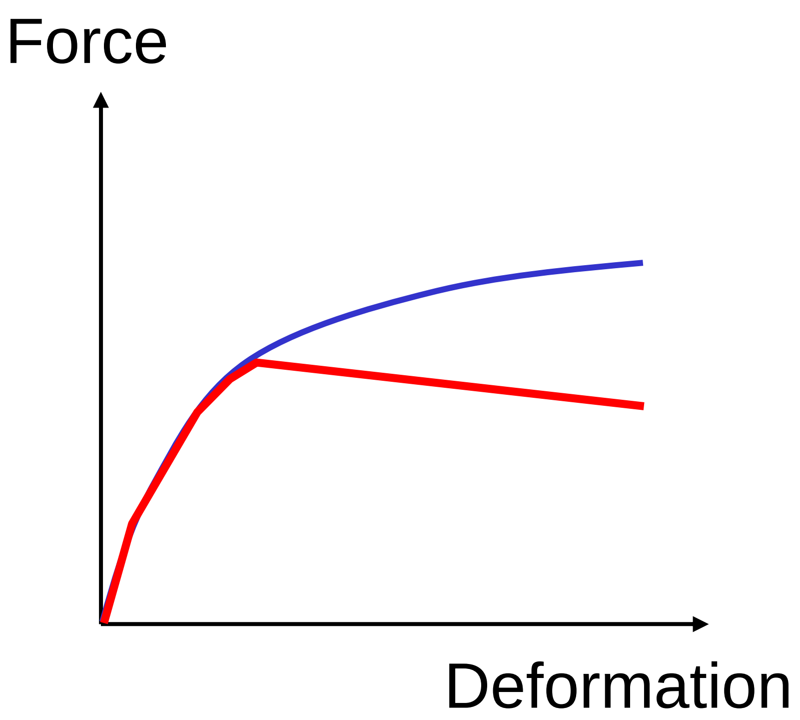




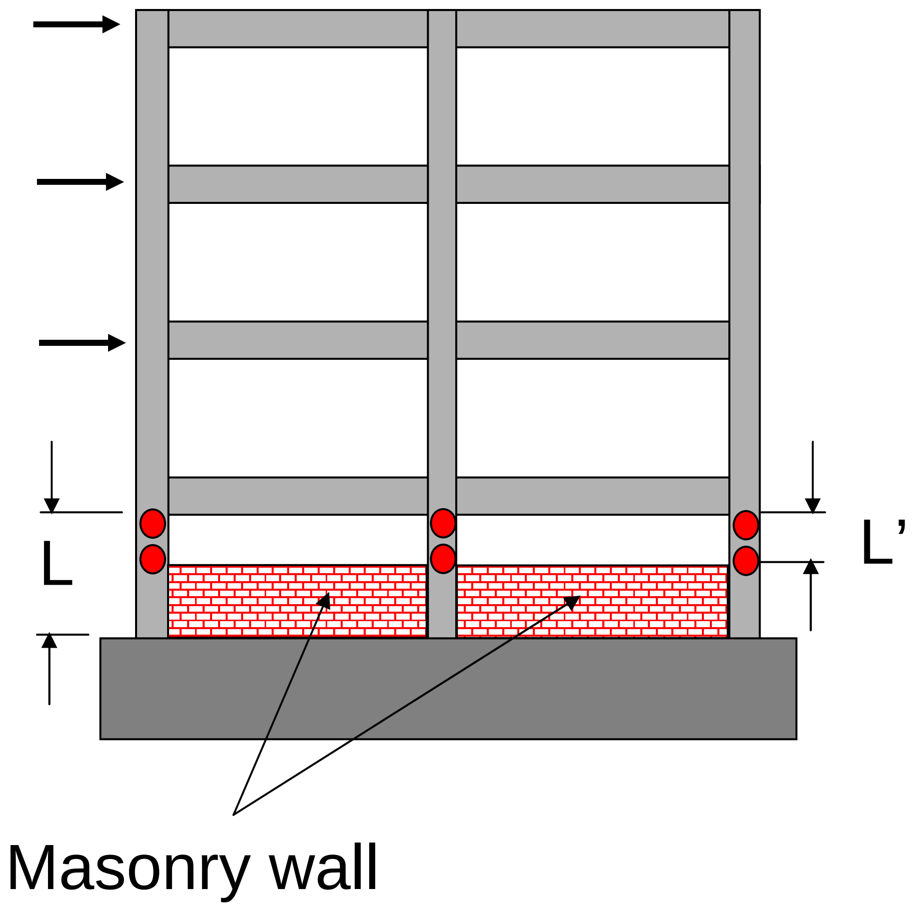
Advantages:
Architectural simplicity, relatively low base shear
Disadvantages:
Drift control, congested reinforcement

Avoid Undesirable Mechanisms





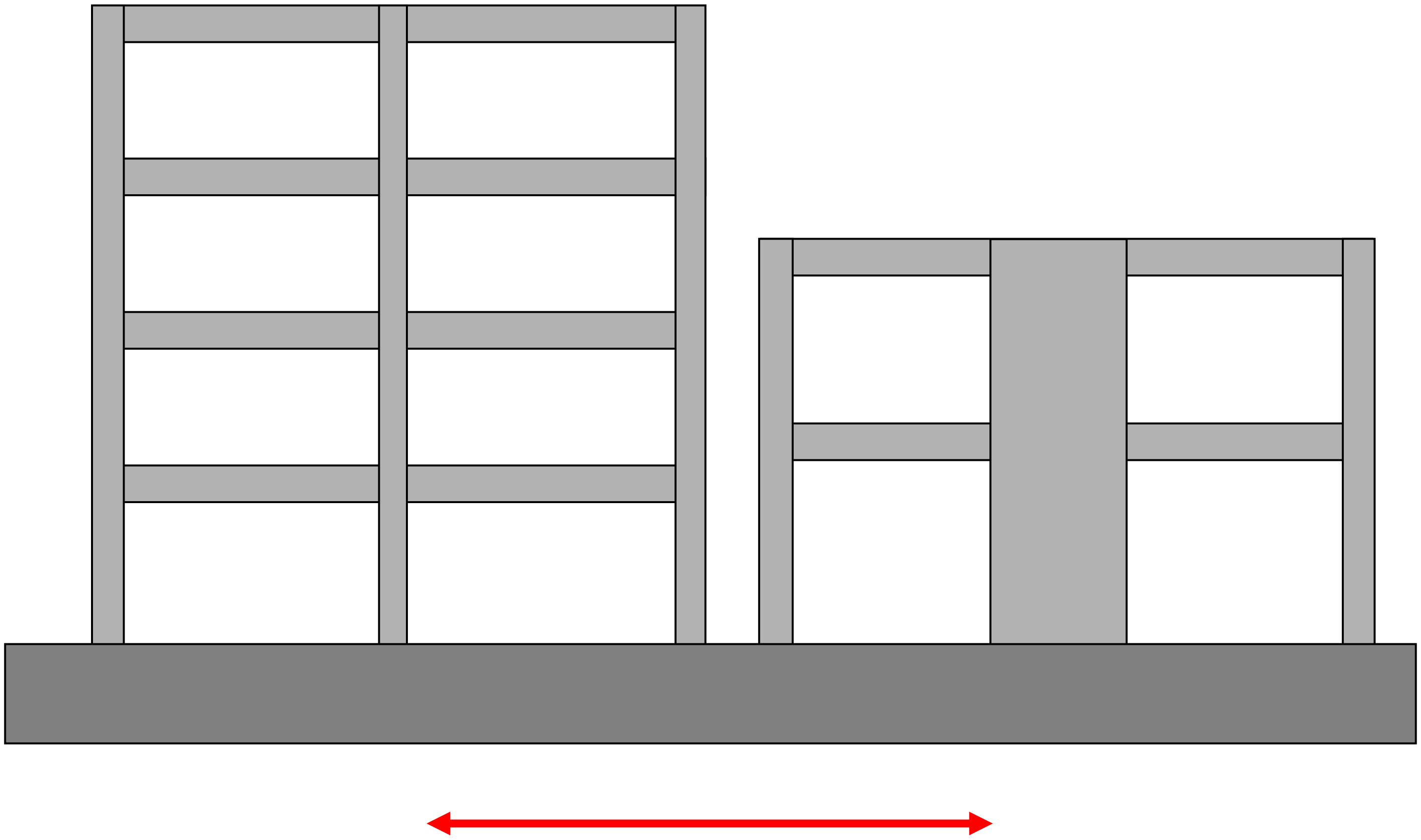
Avoid Accidental Mechanisms



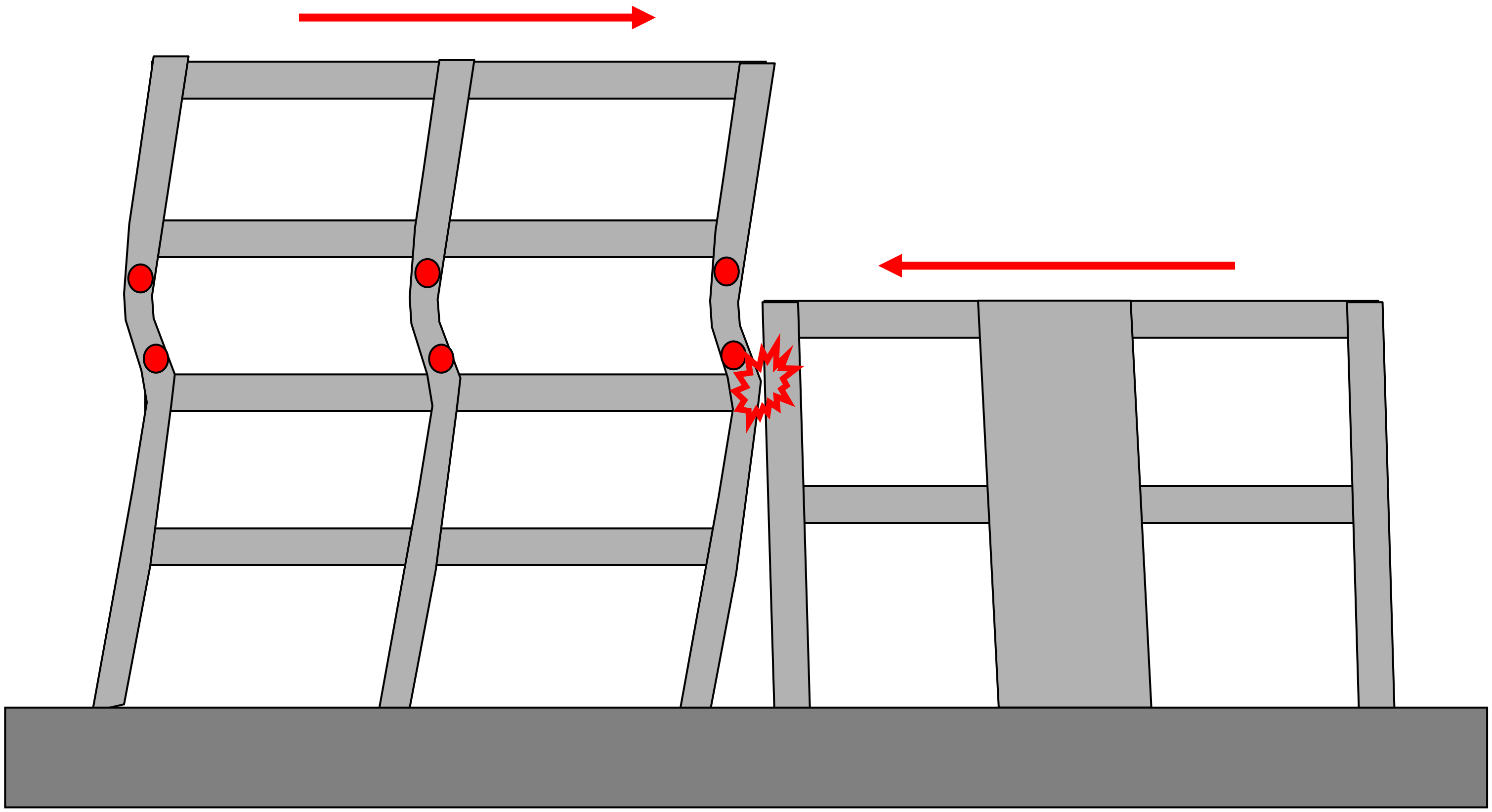
$$V_{design} = 2M_p/L$$

$$V_{actual} = 2M_p/L'$$

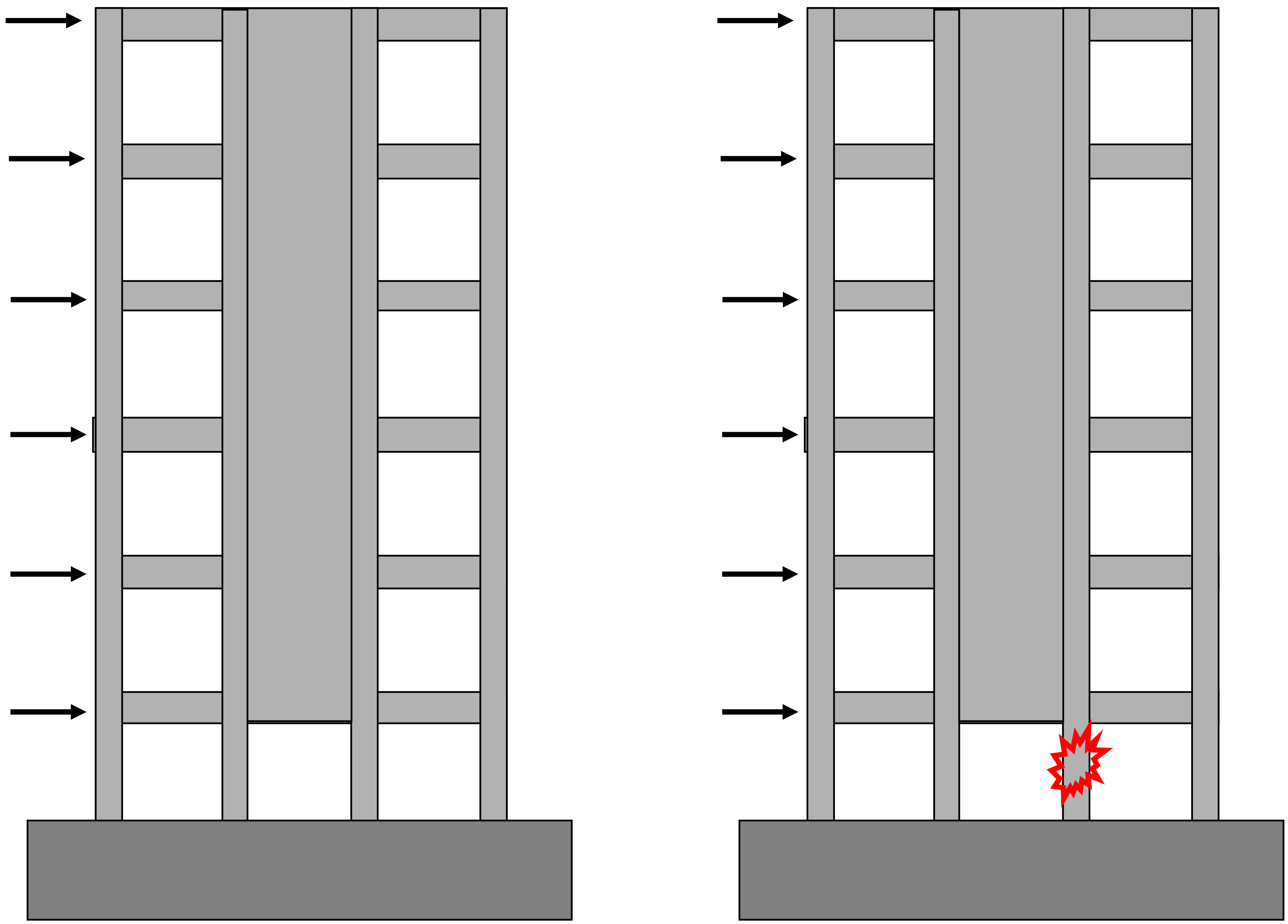
Avoid Accidental Mechanisms



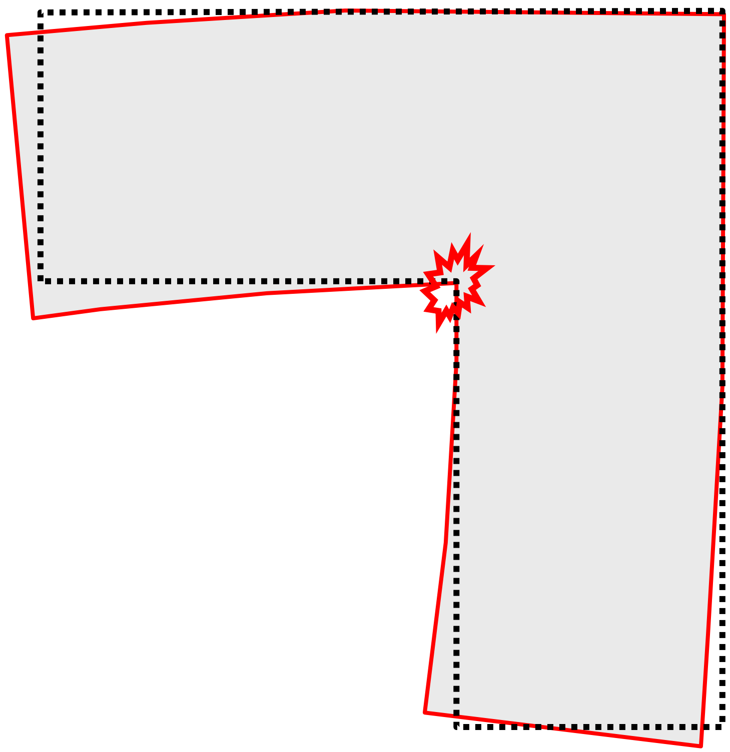
Avoid Accidental Mechanisms



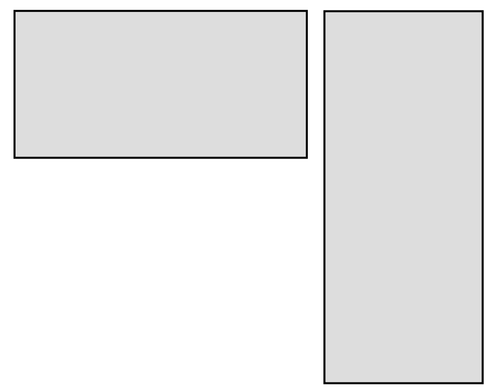
Avoid Situations Where the Loss of One Element Is Catastrophic



Avoid Re-entrant Corners (or Reinforce Accordingly)

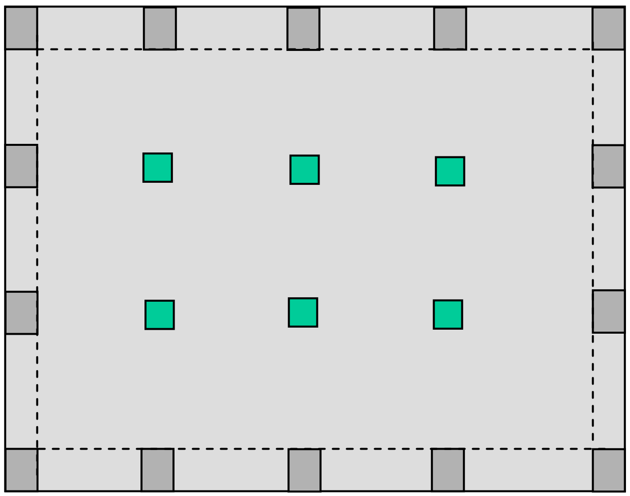


Structurally: Improved



Architecturally Dubious

Protect “Nonstructural” Elements



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)**
6. Proportion Components
7. Evaluate Performance (Linear or Nonlinear Analysis)
8. Final Detailing
9. Quality Assurance

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

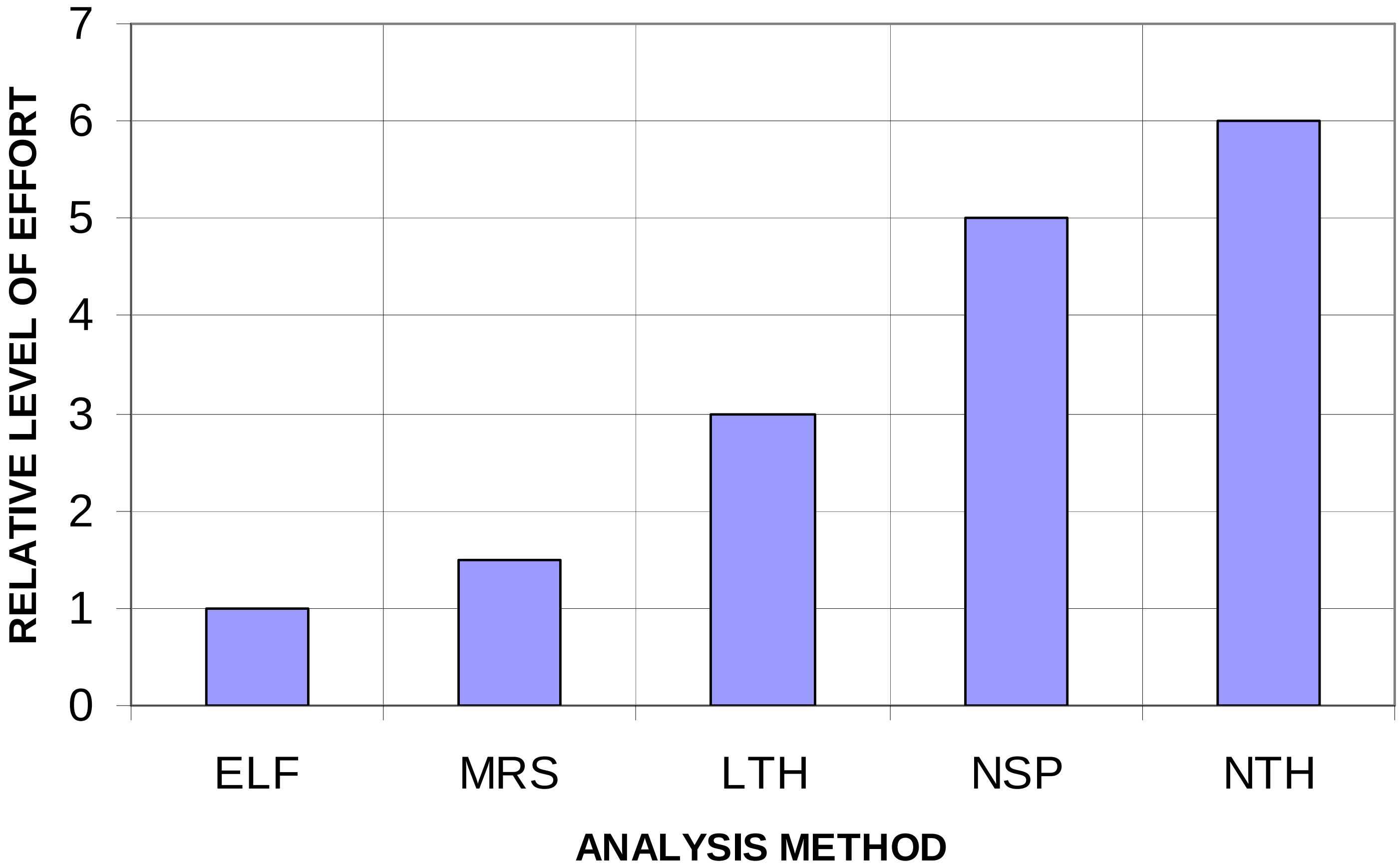
MRS: Good enough for design

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.)

Structural Analysis: Relative Level of Effort



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