Understanding and Coping with Risks of Living in Earthquake Country

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Primer

• Earthquakes are Newtonian

\[ \text{Force} = \text{Mass} \times \text{Acceleration} \]

• Structures can resist only so much force

Demand < Capacity
Primer

Capacity > demand?

![Graph showing force vs. displacement with load capacity indicated by a dashed line.]

![Images of a broken piece of chalk and a knotted piece of cord.]

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**Diagram Explanation:**

- **Force** vs. **Displacement** graph illustrates the relationship between the applied force and the resulting displacement.
- The graph shows a sharp increase in force followed by a gradual decrease, indicating the material's load capacity.
- The dashed line represents the load capacity, beyond which the material will break or fail.

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**Image Notes:**

- The broken chalk image suggests a comparison of capacity and demand, possibly indicating that the demand exceeds the capacity, leading to the material's failure.
- The knotted cord image may symbolize a situation where capacity is exceeded, causing a failure or breakage, much like a knot that cannot be undone.

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**Related Concepts:**

- **Primer**
- **Capacity**
- **Demand**
- **Load Capacity**
- **Failure**
- **Broken Chalk**
- **Knot**

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**Further Reading:**

- Studies on material failure and load capacity in engineering and physics.
- Case studies on structural integrity and material limitations.
Primer

Capacity > demand?

![Graph showing force vs. displacement with load capacity and demand points.]

![Image of damaged building after earthquake.]
SHOULD WE WORRY?
Strawberry Creek moves northward about 1-2 inches a year relative to Berkeley Hills.
SHOULD WE WORRY?
San Francisco 1906
SHOULD WE WORRY?
Warning: I am an engineer
\[ \lambda(DV) = \int \int \int G(DV \mid DM) dG(DM \mid EDP) dG(EDP \mid IM) d\lambda(IM) \]
RISK = PROBABILITY \times HARM
Risk Assessment Depends on Context
Risk Assessment Depends on Context

Informed individual acceptance of risk
Risk Assessment Depends on Context

Presumptive Freedom from Public Risks
Risk Assessment Depends on Context

Presumptive Freedom from Public Risks
Acceptable Risks

Perspective Differs Amongst:
- Owners
- Engineers
- Government Agencies
- Insurance and Finance
Managing Risk

- Accept / Ignore
- Transfer
- Reduce Probability of Occurrence
- Reduce Vulnerability
- Reduce Exposure
RISK = PROBABILITY x HARM

For probabilistic seismic risk assessment

SEISMIC RISK = HAZARD X VULNERABILITY X EXPOSURE
Earthquakes

Sources

• Meteor Impact
• Volcanoes
• Reservoir Induced
• Well Injection
• Tectonic
  – Associated with continental drift
    • at edges of continental plates
    • mid-continent
    • mid-ocean ridges
Rate of Occurrence

Frequency of Occurrence of Earthquakes
Based on Observations since 1900

<table>
<thead>
<tr>
<th>Descriptive Level</th>
<th>Map Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Great</td>
<td>Darker shades in the map.</td>
</tr>
<tr>
<td>Major</td>
<td>Medium shades in the map.</td>
</tr>
<tr>
<td>Strong</td>
<td>Lighter shades in the map.</td>
</tr>
<tr>
<td>Moderate</td>
<td>Lightest shades in the map.</td>
</tr>
<tr>
<td>Light</td>
<td>Very light shades in the map.</td>
</tr>
<tr>
<td>Minor</td>
<td>Palest shades in the map.</td>
</tr>
<tr>
<td>Very Minor</td>
<td>Palest shades in the map.</td>
</tr>
</tbody>
</table>
Largest Earthquakes in US
Elastic Rebound Theory

Fault

Straight Fence

Initial Time
Elastic Rebound Theory
Elastic Rebound Theory

Initial Time

Fault Offset 13 ft
Elastic Rebound Theory

Fault

Straight Fence

Initial Time

Permanent Displacement

A

B

C

D

d
time

d
time
Basic Types of Faulting

- Surface Faulting
  - Strike-slip
  - Dip slip/thrust
  - Combinations

- Mid-Plate events
  - No apparent fault rupture due to depth or cover by alluvial deposit

- Subduction zones
  - Common in Japan, Mexico, Pudget Sound, South America

Diagram:

- Strike-slip Faulting
  - Left lateral rupture

- Normal Faulting
  - Extension
  - Foot Wall
  - Hanging Wall

- Reverse Faulting
  - Shortening
Major Faults in California
Faulting in Northern and Southern CA
Earthquake Shaking in Bay Area

1906 San Francisco

1989 Loma Prieta
Travel Paths: WUS vs CEUS

MMI VII: Considerable damage to poorly built structures
Sources of Damage

Damage caused by:

- Ground shaking
- Fault rupturing
- Liquefaction and soil movement
- Slope instability and landslides
- Tsunami and seiche
- Fire
- Flooding
- Interaction with adjacent structures (pounding)
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Hilo, Hawaii following 1960 M 9.5 Chilean Earthquake (61 fatalities)

14-meter tall tsunami in 1946 resulting from M 7.8 Alaskan Earthquake caused 159 fatalities
Sources of Damage

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December 2004 Sumatra Earthquake
Tsunami Videos (see:http://www.asiantsunamivideos.com/)

Dec. 26, 2005 Banda Aceh, Indonesia
Sources of Damage

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Earthquake-Related Hazards: Tsunami Engineering

• Probabilistic hazards in a form consistent with ground motion

72 year
Probabilistic Wave Height and Velocity Estimates

475 year

2500 years
Probabilistic Tsunami Hazard Analysis

- Probabilistic hazards in a form consistent with ground motion hazard estimates

Probabilistic Inundation Maps
(plus wave height and velocity maps)
Tsunami Engineering
Risk Assessment and Mitigation
Other Earthquake Related Hazards: Fire Following Earthquakes

Aging infrastructure can trigger fires

Will earthquake damage prevent effective fire suppression in tall buildings?

New research initiatives on:
- Vulnerability of fuel and water supply systems to earthquakes
- Case studies of fires in tall buildings following earthquakes

Will resources be available to fight urban fires?
Predicting Earthquake Hazards
Predicting Earthquake Hazards

We can predict an earthquake a few to several seconds before it gets to you.

This can be useful for critical facilities and certain occupancies
Large project on this at Berkeley in EPS
Estimating Earthquake Hazards

Seismic source characterization

• Locate faults or source regions
• Characterize fault (strength of materials, slip rate, when were last events, how big were past events, etc.)
• Examine catalogs of similar past earthquakes to estimate max. size earthquake possible
• Estimate time between quakes of different size
Estimating Earthquake Hazards

California Faults

- S. San Andreas: 59%
- Hayward-Rodgers Creek: 31%
- San Jacinto: 31%
- N. San Andreas: 21%
- Elsinore: 11%
- Calaveras: 7%
- Garlock: 4%

30-Year Earthquake Probability

- 100%
- 10%
- 1%
- 0.1%
- 0.01%
- 0.001%

San Francisco Bay Region Earthquake Probability

- 63% probability for one or more magnitude 6.7 or greater earthquakes from 2007 to 2036.

Increasing probability along fault segments

Expanding urban areas
Estimating Earthquake Hazards

Seismic Wave Travel Path

- Divide fault(s) up in to possible segments that could rupture
- Estimate probability (frequencies) of each segment rupturing
- From catalogs, determine probable size of event from each segment
- For that size and distance to each segment, estimate ground shaking characteristics at site
- Compute probable characteristics of shaking at a site resulting from all possible earthquakes
Estimating Earthquake Hazards

Account for Local Soil Effects

• Compute stiffness and strength of soil
• Estimate effects of soil on ground motions

Thus, different soils will damage different buildings
Estimating Earthquake Hazards

Net result
Estimating Earthquake Hazards

For Design:

Uniform Hazard Response Spectrum

- 2% probability of Exceedence in 50 yrs
- 10% probability of exceedence in 50 yrs
- 50% probability of exceedence in 30 yrs

Time histories from databases, synthetic ground motions, or finite fault models
Computer models to predict motions
All of this is highly uncertain

• The past is no guarantee of future events
• Engineers and public often take median expectations as deterministic predictions
  – Large coefficients of variation
  – Actual outcome can be far far worse, or better.
• Statistical and numerical methods suspect
  – Short history of events
  – Heterogeneous data sets
  – Epistemic uncertainties
  – Statistical distributions not bounded by theory
Risks of Conveying Risk to Public

2009 L’Aquila Earthquake

• Seven Scientists and Engineers (one a Berkeley grad) sentenced to six years in prison for manslaughter

• Members of Government Panel: National Commission for the Forecast and Prevention of Major Risks
Risks of Conveying Risk to Public

2009 L’Aquila Earthquake

- Commission gave advice in a meeting 6 days before the earthquake, and a day after the strongest in an ongoing swarm of small earthquakes that shaken the area around L'Aquila.

- The prosecutor accused them of convincing some of the town's residents to stay indoors on the night of the quake instead of seeking shelter outside, as they were used to doing when tremors happened.

- Judge said they had analyzed the risk of a major quake in a "superficial, approximate and generic" way and that they were willing participants in a "media operation" to reassure the public.

- The judge said the scientists were not convicted for failing to predict an earthquake, something he says was impossible to do, but for their complete failure to properly analyze, and to explain, the threat posed by the swarm.

- They have appealed their conviction.
Engineering Challenge

Design structures that are:

• Safe
• Robust such that they will behave well in spite of great uncertainties in ground motions (and computer modeling and actual behavior)
• Resilient
• Sustainable
• Affordable
RISK = PROBABILITY x HARM

For probabilistic seismic risk assessment

SEISMIC RISK = HAZARD x VULNERABILITY x EXPOSURE
What are earthquake engineers in US trying to accomplish?

Preserve Life Safety and Prevent Collapse!
Building codes are minimum standards for public safety

• Stated purpose:
  – Provide minimum provisions for design and construction of structures to resist effects of seismic ground motions
  – “...to safeguard against major structural failures and loss of life, not to limit damage or maintain function.”

Designed to protect life in extreme event, but damage is expected
Building codes do not provide earthquake proof structures

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Designed to protect life in extreme event, but damage expected
Building codes do not provide earthquake proof structures

Most building codes are INDIRECT

- Numerous provisions:
  - If satisfied, provide assurance that structure is safe
  - Are not directly related to outcomes

- Wide variation in seismic performance expected for similar structures

Intended 90% confidence of preventing collapse in earthquake with 2% frequency of being exceeded in 50 years.
Wide variety of building and ground motion characteristics

Robust structures and systems needed to account for great variability in earthquake and structural characteristics
Nonstructural Elements: Life Safety and Economic Concerns

2010 Chile Earthquake
Santiago Mid-Rise Building (Yanev)
Structures Should Not Be Considered in Isolation: Disaster vs Catastrophe

Natural disasters cause wide-spread moderate to severe damage that may strain the ability of a community to respond and recover.

Widespread damage can have substantial long-lasting social, economic and cultural impact on the well-being and vitality of a city and nation.
Resilient Communities

• Provide citizens, organizations and businesses the ability at a minimum to “shelter in place” following earthquakes
  – Without this, recovery is slow and impact large

• Communities need at least:
  – Basic infrastructure and lifelines
  – Key public/government services
  – Housing
  – Business continuity for employment and services
  – Schools
  – Food
Next challenge for engineers: Earthquake-Resilient Structures

In *Earthquake Engineering*, our future challenge is to develop new or improved structures and infrastructure systems that:

- protect public safety, and are economical, but that
- can be constructed quickly with minimal disruption to the public and to the environment, and
- can withstand strong earthquake ground shaking (and other hazards) safely, with little disruption or cost associated with post-earthquake inspections and repairs.
Common Characteristics of Disaster Resilient Structures

- Earthquake resisting system that controls distribution of inelastic deformations
- Durable and/or easily replaceable energy dissipating regions/devices
- Easy and safe post-event inspection
Vulnerabilities

- Human toll
- Property losses
- Disruption of function
- Moving from a disaster to catastrophe
The Earthquake Divide

• Casualties in Representative Earthquakes

<table>
<thead>
<tr>
<th>Event</th>
<th>M</th>
<th>Deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 New Zealand</td>
<td>6.3</td>
<td>185</td>
</tr>
<tr>
<td>2011 Japan</td>
<td>9.0</td>
<td>1,575*</td>
</tr>
<tr>
<td>2010 Chile</td>
<td>8.8</td>
<td>500</td>
</tr>
<tr>
<td>1994 Northridge</td>
<td>6.7</td>
<td>33</td>
</tr>
<tr>
<td>1995 Kobe, Japan</td>
<td>7.2</td>
<td>6,400</td>
</tr>
<tr>
<td>1989 Loma Prieta</td>
<td>6.9</td>
<td>57</td>
</tr>
<tr>
<td>1987 Whittier Narrows</td>
<td>5.9</td>
<td>3</td>
</tr>
<tr>
<td>1971 San Fernando</td>
<td>6.6</td>
<td>65</td>
</tr>
<tr>
<td>1906 San Francisco</td>
<td>7.9</td>
<td>375 (3000+)</td>
</tr>
</tbody>
</table>

* Includes 1,331 deaths due to exposure following quake, and 18 recue workers; 14,308 more drowned; more than 2000 are still missing.
Want to avoid this
Protecting public from injuries from collapse of structures

Achieving “Life Safety” remains a major issue for developing countries and other regions susceptible to large but low probability events

Education - Enforcement - Low Cost Toughness
Engineering Effective in Reducing Loss of Life

Recent Earthquakes Demonstrate that Quality Engineering and Construction Matter!

Sendai, Japan

Structural damage due to ground shaking was relatively light for new structures even in regions of heavy shaking
Older buildings vulnerable (Sendai shown)
Older facilities remain vulnerable to earthquakes

Earthquake damages have prompted numerous seismic evaluation and retrofit programs:
- Mandated for critical facilities
- At change in ownership, occupancy and substantial remodeling
- Voluntary upgrades

Research-backed consensus standards exist and these are being continually improved by research
Examples of Retrofit Buildings on Berkeley Campus
“Non-Structural” Damage - Sendai
“Non-Structural” Damage - Tokyo

Concert Hall – Kawasaki (near Tokyo)

Moderate Shaking PGA ~ 0.15g

Ref: http://sankei.jp.msn.com

unoccupied at time of earthquake
Nonstructural Elements Also Pose Life Safety Concerns

2010 Chile Earthquake
Santiago Mid-Rise Building (Yanev)
Holistic risk-oriented view: Performance-Based Seismic Design

Seismic Hazard Analysis
\( \lambda (im) \)
IM: intensity measure

Response Analysis
\( G(edp \mid im) \)
EDP: Engineering Demand Parameter

Damage Analysis
\( G(dm \mid edp) \)
DM: Damage Measure

Loss Analysis
\( G(dv \mid dm) \)
DV: Decision Variable

\[
\lambda(DV > dv) = \int \int \int G(dv \mid dm) G(dm \mid edp) G(edp \mid im) d\lambda(im)
\]

Probabilistic Assessment of:
- Cost of repair and loss of function
- Downtime
- Casualties
- Embodied energy

Ground motion selection and scaling

Hazard Analysis and Mapping

Engineering Seismology

HPC simulation

Performance Databases

Consequence Functions

Fragility Functions

Loss Assessment
Improving engineering tools: High Performance Simulation

OpenSees - Open Source, object oriented framework for seismic simulation of geotechnical and structural models

New Development Efforts by PEER:
- Optimization and reliability analyses
- New elements
- Graphical user interfaces
- Integrated PBEE tools

http://opensees.berkeley.edu or NEES.org
Our predictions of the future depend on computer models.
Pursuing Fundamental Knowledge: Behavior of Reinforced Concrete Columns

Tests undertaken to validate concepts and numerical models used in PBEE

Can we devise more resilient systems that are more reliable to analyze?

41 expert teams participated

PEER-NEES RC Column Blind Analysis Contest - 2010

Full-scale 1D tests of circular column - Jose Restrepo, PI (PEER, Caltrans, UNR, FHWA, NEES@UCSD, NEEScomm & NSF)
Contributions of Damage to Economic Loss

Damage in traditional fixed base buildings is costly, widespread & disrupts occupants during repair.

Nonstructural components and contents contribute 60% to 80% of cost of buildings – they may contribute 60% to 100% of loss.
Archetype Buildings Considered

Note isolated structures are expected to be about $1 million more than fixed base cases due to excavation and construction of isolation plane.
Total Losses = Repair + Business Interruption

Business interruption cost of a three storey office building in downtown Oakland = $3550/day

(LoopNet, 2012)
Return on Investments

- Return on Investments
- Inflation Rate
  (Capitol Professional Services, 2011)
Indirect Contributions to Loss by Business Interruption (BI)

• Direct BI

Source: www.nytimes.com
Clean room in the Renesas Electronics Microcontroller Manufacturing Facility; Hitachinaka, Ibaraki Prefecture

Two weeks to complete initial damage assessments and begin repairs; partial operation targeted for June 2011

More than 2,000 external contractors have been hired to assist with repair work (Source: http://am.renesas.com)

Additional interruptions due to lack of electric power.

Courtesy: Carlos Cabrera, RMS

• Contingent BI

Source: www.nytimes.com
General Motors automobile assembly facility in Shreveport, Louisiana

Facility shut down for a week in March due to parts shortages

On April 22nd, Toyota announced that its manufacturing plants in North America were operating at 30% of capacity because of the parts supply situation.
Supply chains are complex and interdependent

Suppliers

Facility and Equipment

Customers
Supply chains are complex and interdependent
Structures Should Not Be Considered in Isolation: Disaster vs Catastrophe

Natural disasters cause wide-spread moderate to severe damage that may strain ability of a community to respond.

Widespread damage can have substantial long-lasting social, economic and cultural impact on the well-being and vitality of a city and nation.

- Wenchuan Earthquake
- Christchurch, NZ
- Hurricane Katrina
Disasters can transform into catastrophes

Natural disasters cause wide-spread moderate to severe damage that may strain ability of a community to respond.

Widespread damage can have substantial long-lasting social, economic and cultural impact on the well-being and vitality of a city and nation.
Resilient structures, networks and communities

When is a building safe enough?

The Resilient City
Part 1: Before the disaster

### Target States of Recovery for San Francisco's Buildings and Infrastructure

<table>
<thead>
<tr>
<th>Infrastructure Cluster Facilities</th>
<th>Phase 1 Hours</th>
<th>Phase 2 Days</th>
<th>Phase 3 Months</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Event occurs</td>
<td>4 24 72 30 40</td>
<td>36 36+</td>
</tr>
<tr>
<td><strong>Critical Response Facilities and Support Systems</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Hospitals</td>
<td></td>
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<tr>
<td>Police and fire stations</td>
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<td></td>
<td></td>
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<tr>
<td>Emergency Operations Center</td>
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<tr>
<td>Related utilities</td>
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<td></td>
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<tr>
<td>Roads and ports for emergency</td>
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<tr>
<td>CalTrain for emergency traffic</td>
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<tr>
<td>Airport for emergency traffic</td>
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<tr>
<td><strong>Emergency Housing and Support Systems</strong></td>
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<tr>
<td>95% resilience shelter in place</td>
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<tr>
<td>Emergency responder housing</td>
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<tr>
<td>Public shelters</td>
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<tr>
<td>90% related utilities</td>
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<tr>
<td>90% roads, pot facilities</td>
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<tr>
<td>and public transit</td>
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<tr>
<td>90% Muni and BART capacity</td>
<td></td>
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<tr>
<td><strong>Housing and Neighborhood Infrastructure</strong></td>
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<tr>
<td>Essential city service facilities</td>
<td></td>
<td></td>
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<tr>
<td>Schools</td>
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<td></td>
<td></td>
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<tr>
<td>Medical provider offices</td>
<td></td>
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<td></td>
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<tr>
<td>90% neighborhood retail services</td>
<td></td>
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<tr>
<td>95% of all utilities</td>
<td></td>
<td></td>
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<tr>
<td>95% roads and highways</td>
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<tr>
<td>90% transit</td>
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<tr>
<td>90% railroads</td>
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<tr>
<td>Airport for commercial traffic</td>
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</tr>
<tr>
<td>95% transit</td>
<td></td>
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<tr>
<td><strong>Community Recovery</strong></td>
<td></td>
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<tr>
<td>All residences repaired, remade or relocated</td>
<td></td>
<td></td>
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<tr>
<td>95% neighborhood retail businesses open</td>
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<tr>
<td>50% offices and workplaces open</td>
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<td>Non-emergency city service facilities</td>
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<tr>
<td>All businesses open</td>
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</tbody>
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Resilient Communities

- Provide citizens, organizations and businesses the ability to “shelter in place” following large earthquakes
  - Without this, recovery will be slow
- Communities need at least:
  - Basic infrastructure and lifelines
  - Key public/government services
  - Schools
  - Food
  - Housing
  - Business continuity for employment and services
Next challenge for engineers: Earthquake-Resilient Structures

In *Earthquake Engineering*, our future challenge is to develop new or improved structures and infrastructure systems that:

- protect public safety, and are
- economical,

but that

- can be constructed quickly with minimal disruption to the public and to the environment, and

- can withstand strong earthquake ground shaking (and other hazards) safely, with little disruption or cost associated with post-earthquake inspections and repairs.
Common Characteristics of Disaster Resilient Structures

- Earthquake resisting system that controls distribution of inelastic deformations
- Durable and/or easily replaceable energy dissipation regions/devices
- Easy and safe post-event inspection
- Protect structural and nonstructural elements, and contents, by limiting
  - Relative displacements
  - Accelerations
- Self-centering mechanism to minimize permanent displacements.
World Challenge: “Next Generation” Disaster Resilient Structures

- New systems that reduce post-earthquake disruption and speed recovery of normal operations – “Sheltering in place”

- Seismic Isolation
Partially Prestressed, Reinforced Concrete Self-Centering Column

Design method:
- Mild reinforcement reduced
- Prestressing force from a central unbonded tendon
- Same envelop Q-δ
- Peak displacements within 10% of RC column
- Residual displacements less than 20% of RC column
Response During Maximum Level Tests

100% of Los Gatos, Loma Prieta Earthquake Record
Similar Maximum Response Ductility = 13-14

Conventional RC Column  Partially Prestressed RC Column
Rocking Foundations: An easier way?

UC Berkeley and UC Davis

Mahin, Kutter, and Jeremic

For soils where spread footings are feasible, engineers often find that footing width needs to be increased, or anchored using piles, so a plastic hinge can develop in column

- Earthquake experience suggests foundation uplift can be an effective earthquake resistant mechanism

- Significant amounts of research confirms this

- Utilizes conventional construction and design technology
X+Y+Z Components - Los Gatos

For Fixed Base Column $\mu=5$
Protective Systems: Seismic Isolators and Supplemental Dampers

Lead Rubber Bearings

Viscous Dampers

Friction Pendulum Bearings
Applications of Protective Systems

Dumbarton Bridge
San Francisco Int. Airport
Computer Center, SF
Pasadena City Hall
Seismically Isolated Building
125% of largest record from Kobe
Seismic isolation designed typically to protect structure

Many nonstructural items are fragile and sensitive to vertical accelerations
Take Away

- Earthquakes are infrequent, but inevitable in most of California (and the world)
- Have a survival kit (cash, water, food, clothes, flashlight, etc.)
- Have a plan to meet up with friends and to contact important people in your lives.
Take Away

• Formal risk assessment can provide insight into planning, especially in comparing alternative strategies
• Engineering focus is moving (slowly towards) developing damage-resistant structures that minimize economic loss and allow rapid post-event recovery (resilience)
• Engineers decades ago, who built vulnerable buildings, thought they were doing a good job. So do we now.