Safe Enough? How Building Codes Protect Our Lives but Not Our Cities

Keith Porter, PE PhD
Research Professor, CU Boulder
California earthquakes

2 inches per year
California seismicity 1800-1994
1994 Northridge M6.7 was not big
Background on code hazard

- Map faults locations
- Treat background sources
- Estimate how frequently each source produces various size earthquakes
- Calculate shaking at each of many points for each possible earthquake
- For each point, calculate the frequency with which various levels of shaking are exceeded

Hazard curve

Exceedance frequency (events/year)

Shaking, $x$, units of gravity
Design each building for 2/3 MCE
More recently, for fixed annual probability of collapse

Seismic hazard

Seismic fragility

Exceedance frequency (events/year)

Failure probability

Shaking, $x$, units of gravity

Demand, $x$
Code performance objectives

• “The probability of collapse due to [2500-year] ground motions ... is limited to 10%, on average.... The probability of collapse for individual archetypes is limited to 20%....”

• “Collapse includes both partial and global instability of the seismic-force-resisting system, but does not include local failure of components not governed by global seismic performance factors, such as localized out-of-plane failure of wall anchorage and potential life-threatening failure of nonstructural systems.”
Risk-targeted design for $2/3 \text{MCE}_R$

ASCE 7-10: “The probabilistic [design] accelerations shall be taken as the ... acceleration that is expected to achieve a 1 percent probability of collapse within a 50-year period.”
<table>
<thead>
<tr>
<th>Peril</th>
<th>Deaths/100,000 pop/yr</th>
<th>Where, when</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart disease</td>
<td>258</td>
<td>US, 2000</td>
</tr>
<tr>
<td>Very poor building (earthquake)</td>
<td>67</td>
<td>24/7 occupancy</td>
</tr>
<tr>
<td>All accidents</td>
<td>36</td>
<td>US, 2000</td>
</tr>
<tr>
<td>Auto accidents</td>
<td>11</td>
<td>CA, 2001</td>
</tr>
<tr>
<td>Poor building (earthquake)</td>
<td>7</td>
<td>24/7 occupancy</td>
</tr>
<tr>
<td>Gas-industry job</td>
<td>4</td>
<td>US, 1995-2000</td>
</tr>
<tr>
<td>Handguns</td>
<td>3</td>
<td>US, 2004</td>
</tr>
<tr>
<td>Acceptable building (earthquake)</td>
<td>0.7</td>
<td>24/7 occupancy</td>
</tr>
<tr>
<td>New building (earthquake)</td>
<td>0.2</td>
<td>24/7 occupancy</td>
</tr>
<tr>
<td>CA earthquakes last ~50 yr</td>
<td>0.02</td>
<td>CA, 1952-2002</td>
</tr>
</tbody>
</table>
We’ve never chosen “safe enough”

Objectives calibrated to prior “implicit” goals but not deliberately chosen, objectives. E.g.,

- 1980: “The new probability-based load criterion should lead to designs which are essentially the same [level of safety]... as those obtained using current acceptable practice.” (ANS SP 577)

- IBC 2008 aims to be “consistent with ... expected performance ... in the Commentary of the 2003 NEHRP Provisions, namely that ‘if a structure experiences a level of ground motion 1.5 times the design level [i.e., if it experiences the 2500-year ground motion level], [it] should have a likelihood of collapse... [of] 10%.’”
What the code sees
What society sees
What happens in MCE shaking?

Let’s just rely on FEMA P-695 & history

- FEMA P-695: 10% collapse rate in code-compliant stock

- Red tags without collapse
  - Northridge 2,290 red tags in LA County; 200 soft story WF & 15 hillside houses “collapsed or came close;” unknown number of URM & RC collapses, maybe low 10s?
  - SF Marina in 1989: 40-50 red tags & 4 collapses
    
    Say 10 non-collapse red tags per collapse

- Yellow tags
  - Northridge LA County: 9,445 yellow tags, 2,290 red
    
    Say 4 yellow tags per red tag
What happens in MCE shaking?

<table>
<thead>
<tr>
<th></th>
<th>Ratio</th>
<th>Fraction of stock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collapse</td>
<td>10% of stock</td>
<td>10%</td>
</tr>
<tr>
<td>Red, not collapsed</td>
<td>10 red tags per collapse</td>
<td>Most of the rest</td>
</tr>
<tr>
<td>Yellow</td>
<td>4 yellow tags per red tag</td>
<td>Most of the rest</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>Virtually all</td>
</tr>
</tbody>
</table>

Reflects code-compliant buildings; older buildings would be worse
But the Big One ≠ MCE shaking

- Shaking varies by site
- Includes inter- and intra-event uncertainty
- Below-mean shaking at point X accompanies above-mean shaking at Y

Mostly less than MCE shaking, but high over large areas
Big One short-period motion in LA area

ShakeOut $\text{Sa}(0.3 \text{ sec}, 5\%)$  \hspace{1cm} ASCE 7-10 $S_s$, B soil ($F_a \approx 1.0$)

“Demand-to-design ratio” (DDR): the ratio of these
What happens at $DDR = 0.5$?

$$P(\text{collapse} \mid x = x_{MCE}) = 0.1 \approx \Phi(\ln(x_{MCE}/\theta)/\beta)$$

$$0.5 \leq \beta \leq 0.8$$

Collapse prob. at $DDR = 0.5$ is 0.7-1.6%
What happens at $DDR = 0.5$?

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Fraction of stock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collapse</td>
<td>1% of stock</td>
</tr>
<tr>
<td>Red</td>
<td>10 red tags per collapse</td>
</tr>
<tr>
<td>Yellow</td>
<td>4 yellow tags per red tag</td>
</tr>
<tr>
<td>Total</td>
<td></td>
</tr>
</tbody>
</table>

(Again, for 100% code-compliant stock)
What happens at 1% collapse rate

- 49% of buildings usable after earthquake
- 10% unsafe
- Limited use: 40%
ShakeOut (~150-year event)

DDR ≥ 0.5 over 7,000 km² of this map

Avg impairment rate 50% over 15,000 km²
M 7.0 Hayward Fault

$$DDR \geq 0.5$$ over 3,000 km$^2$
M 7.0 Hayward Fault

200-year event under UCERF 3
Using Aagaard et al. (2010) Sa(0.3)
~3 million people, 300,000 businesses

Many possible Big Ones, not 2500-year events, will cause urban catastrophe
1906 repeat (~200-year event)
Conventional shaking model, tall buildings

M7.9 San Andreas Sa(1.0 sec)
MCE_R S_1, B soil (F_v ≈ 1.3)
Stock isn’t code-compliant

CA highrise ages (Emporis 2007)

LA & Long Beach dwellings (American Housing Survey 2013)
But are existing buildings “the problem?”
Can code-compliant SoCal survive a 150-year earthquake?

- 49% of buildings usable after earthquake
- 10% unsafe
- Limited use: 40%
In a not-very-rare earthquake

- 2012 Los Angeles vacancy rates
  - Residential: 2-5%
  - Commercial: 11%
  - Industrial: 5%
- ShakeOut (150-year earthquake): 1800 deaths in 20 million affected population (20 deaths/100,000 people)
- ½ households and businesses in 15,000 km² leave
- ... and that’s *with* a code-compliant building stock

Does “society” know that’s what it is getting?
City councils and mayors “absolutely do not know” how badly a code-compliant building stock will perform in the aggregate

(Jones, pers. comm., 19 Nov 2013)
We may have a serious problem

And it’s not just the existing buildings
How we got here

4 assumptions
Assumption 1: greater seismic resilience of the building stock is difficult to achieve

- Housner (1956) “it would be quite costly to design for lateral forces of this magnitude”
- Housner and Jennings (1982): “It is not economical to design every structure to resist the strongest possible earthquake without damage” and therefore codes “permit yielding and structural damage in the event of very strong shaking.”
Broad Center for Biological Sciences

+10%

+2%
CUREE-Caltech Woodframe Project

Small house: 1200 sf, 2 bdrm, 1 ba

Large house: 2,400 sf, 3 bdrm, 2½ba

Townhouse: 2,000 sf, 3+2

Apartment building: 10 850-sf units

Animations by Doron Serban (CUREE)
CUREE-Caltech large house

Reitherman and Cobeen (2003)
• Design to conventional objectives: $221,000
• Immediately occupiable: $229,000
• 3% difference (½ a bathroom remodel)
Retrofit benefit-cost ratio can reach 8

*Brace cripple walls of CUREE-Caltech small house, not every small house

Benefit (2002 US$)

- 7 - 1,400 (0 < BCR < 1)
- 1,401 - 2,800 (1 < BCR < 2)
- 2,801 - 5,600 (2 < BCR < 4)
- 5,601 - 11,000 (4 < BCR < 8)

Cost: $1400
Retrofit benefit-cost ratio can reach 8

* Add wood shearwalls on apartment building*

BCR: up to 7 i.e., *this* apartment building, not *every* one
Assumption 2: public unwilling to pay increased initial costs for better seismic performance

- ATC-3-06 (1978) were unable to provide figures on the probable costs to make buildings remain functional after a rare earthquake, but codified the assumption that it is economically infeasible to do so
- Nobody asked the public what they would be willing to pay
San Francisco Community Action Plan for Seismic Safety

“The CAPSS project of the San Francisco Department of Building Inspection (DBI) was created to provide ... a plan ... to reduce earthquake risks in existing, privately-owned buildings, ... and also to develop ... guidelines that will expedite recovery....”

Here: one aspect of CAPSS focusing on soft-story dwellings
4,400 wood framed buildings in SF susceptible to soft-story damage in earthquakes
45,000 dwelling units, 89,000 residents
7% of housing, 8% of population
90% are rental units
2100 businesses, 84% with ≤5 employees
CAPSS Public Advisory Committee

- Neighborhood groups
- Landlords
- Tenants
- Affordable housing advocates
- Architects, engineers
- Seismologists
- Historic preservation interests
Public Advisory Committee concerns

- Population that lives, works, owns them
- Contribution to neighborhood character
- Effects of a few scenario earthquakes
- Financial impact on neighborhood
- How to fund repair
- How to fund retrofit
CAPSS scenario earthquakes

Scenario Earthquakes considered in study:
- Hayward fault; magnitude 6.9 (rupture length: 36 km)
- San Andreas fault; magnitude 6.5 (rupture length: 18 km)
- San Andreas fault; magnitude 7.2 (rupture length: 60 km)
- San Andreas fault; magnitude 7.9 (rupture length: 198 km)

ATC, 2009: Here Today, Here Tomorrow
4 design levels & performance goals

• As-is
• Retrofit 1 – safe but not repairable – address obvious lack of shear walls
• Retrofit 2 – safe and usable after repair – brace ground story
• Retrofit 3 – safe and usable during repair – increased stiffness to reduce drift-related damage

Photos: Anderson Niswander Construction
M 7.2 San Andreas event, as-is

600 buildings (of 2,800 analyzed) collapse
1,200 non-collapsed buildings red tagged
36,000 residents displaced long-term
800 businesses displaced long-term

ATC, 2009: Here Today, Here Tomorrow
M 7.2 San Andreas event, as-is

- **Impact on residents** – displaced long term from jobs, schools, support services – low income or elderly
- **Impacts on housing** – 50% not usable after 4 years
- **Impacts on owners** – lack of repair resources
- **Impacts on businesses** – small business failures
- **Impacts on neighborhoods** – loss of residents, buildings and character, shift to lower income residences, inability to support housing repair
Same M7.2 event with retrofit

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Direct Construction Costs Estimated for Four Representative Multi-Unit, Wood-Frame Soft-Story Buildings for Each Retrofit Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Per Building</td>
</tr>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>Retrofit Scheme 1</td>
<td>$65,000</td>
</tr>
<tr>
<td>Retrofit Scheme 2*</td>
<td>$105,000</td>
</tr>
<tr>
<td>Retrofit Scheme 3*</td>
<td>$93,000</td>
</tr>
</tbody>
</table>
Retrofit means more people can stay in their homes

Shelter in place

Figure 16. Approximate distribution of damage tags before and after three retrofit schemes in a scenario magnitude 7.2 earthquake on the San Andreas Fault. The number of tags in each category could vary as shown in Table 2.
Same M7.2 event with retrofit

As-is

Retrofit 3

Wood Frame Buildings with 3+ Stories and 5+ Residential Units with Significant Ground Floor Openings - San Andreas M7.2 "As-Is"

Wood Frame Buildings with 3+ Stories and 5+ Residential Units with Significant Ground Floor Openings - San Andreas M7.2 Retrofit 3
Retrofit has other benefits

A possible soft-story outcome (M 7.2):

- 14,600 buildings collapsed
- 110,120 non-collapses are red tagged
- 5,300–36,000 residents displaced long-term
- 120,800 businesses displaced long-term
Public Advisory Committee key recommendations

• Establish a program that requires owners to evaluate, and to retrofit if found deficient

• Buildings should be retrofitted to a standard that will allow most of them to be occupied after a large earthquake

• Incentives to encourage voluntary retrofits

• Working group to develop implementation plan
Some surprises of CAPSS

What one might expect
• Voluntary standards
• Minimum standards
• Conflict between tenants and landlords

What committee called for
• Mandatory retrofits
• Highest standards
• Consensus between tenants and landlords
• Agreed to share costs
FOR IMMEDIATE RELEASE:
Tuesday, February 5, 2013
Contact: Mayor’s Office of Communications, 415-554-6131

*** PRESS RELEASE ***

MAYOR LEE, PRESIDENT CHIU & SUPERVISOR WIENER INTRODUCE LEGISLATION MANDATING SEISMIC SAFETY RETROFIT FOR SOFT-STORY RESIDENTIAL BUILDINGS

Legislation Requires Seismically Retrofitting Large Woodframe Soft-Story Residential Buildings as Part of Earthquake Safety Implementation Program to Prepare City & Residents for Recovery & Rebuild After Major Earthquake

San Francisco, CA—Today Mayor Edwin M. Lee, Board President David Chiu and Supervisor Scott Wiener introduced legislation mandating the seismic retrofit of the City’s large wood-frame soft-story residential buildings, a historic step forward to ensure San Francisco’s resilience and safety. The legislation is also co-sponsored by Supervisors Norman Yee, Mark Farrell, London Breed and Eric Mar.
Assumption 3: public has no role setting seismic performance goals

• Ellingwood et al. (1980): A58 standards committee represents “those substantially concerned with [the standard’s] scope and provisions.” Committee members include “a broad-spectrum group of … researchers, … code groups, industry, professional organizations and trade associations.” No owners or tenants.
Non-engineers can participate in setting community seismic performance goals

Feb 2012 *Urbanist*: SPUR interpreted CAPSS study, addressed:

1. How much SF housing needs to meet shelter-in-place standards?
2. What engineering criteria should be used to determine whether a home has adequate shelter-in-place capacity?
3. What needs to be done to enable residents to shelter in place for days and months after a large earthquake?
Earthquake Country Alliance

We’re all in this together.

“The Bay Area Earthquake Alliance, which is composed of 182 member groups and organizations, coordinates earthquake awareness and preparedness activities throughout the San Francisco Bay Area. The Alliance is a part of the Earthquake Country Alliance, a statewide alliance linking organizations and individuals that provide earthquake information and services.”
Assumption 4: current seismic provisions encode the proper performance measures and goals

- 2010-: single-building long-term collapse risk, disguised to work like 1980-2009
Notice the dissonance

**International Building Code**
- An earthquake with ~1/2500 year shaking
- 1% collapse probability in 50 years
- 10% collapse probability given 2/3 x 2500-year shaking

**Preparedness Now Video**
- An earthquake that happens once in 150 years
- Community-level impacts
- 1,500 buildings collapsed
- 300,000 significantly damaged
- 1,800 killed
- 53,000 injured
- 255,000 homeless
- $213B in damage
- Many people trapped
- 1,600 fires started...
Notice the dissonance

10% collapse rate in MCE *may* be tolerable to society...

... when the Big One strikes a remote community

... probably *not* when it strikes a metropolis
A way forward?

Ellingwood et al. (1980) were concerned that seismic and wind safety were “relatively low when compared to that for gravity loads,” and called for “a profession-wide debate” over whether wind and seismic loads ought to have similar reliability as for gravity loads.
A way forward?

• In 2008 discussion over setting the goal for new design to be 10% collapse probability in 2500-year shaking, one participant was “Shocked that there was literally no debate” over whether the goal was reasonable or the right measure.

• In discussions in BSSC Project ‘07 (reassessment of seismic design procedures), there “May have been a little discussion” about measuring societal impacts, but no formal discussion.
A way forward?

• New tools to express catastrophe risk implicit in code objectives
  – New knowledge of what the public is interested in and capable of understanding
  – Physics-based models of “big ones”
  – FEMA P-695

• Can assess scenarios in light of design maps through DDR and impairment rate
A way forward

• Could similarly assess catastrophe risk
  – In Memphis, Salt Lake City, Charleston, ...
  – Under “as-is” and “what-if” code objectives
  – Difference is the benefit of a stricter code

• Let’s assess the cost of greater seismic resilience (the challenge of ATC 3-06)

• Let’s use DDR, impairment maps, costs and benefits in a nationwide conversation about code objectives
Conclusions
Conclusions

• Code’s performance metric is an accident of history
• Goals never deliberately chosen
• We called for but never had a debate
• We never involved the public
• Code protects our lives, not our cities
Conclusions

- Public is capable of discussing tolerable seismic risk
- Public thinks about earthquake risk very differently than do building professionals
- Public is willing to pay for greater seismic resilience
- Better performance may be very affordable
Conclusions

We need a societal conversation about costs & benefits of design requirements, reflecting

• More-frequent earthquakes
• Community level impacts
• Significant damage (e.g., red & yellow tags)
• Post-earthquake usability
• Fatalities and nonfatal injuries ...
Conclusions

ASCE 7 won’t lead this conversation
- 80% Subcomm. on Seismic Loads are PE or SE
- 90% of the main committee are PE or SE
- Few if any owners and tenants

The ICC won’t either
- Only code officials vote
- Subject to intense pressure from contractors

Who will?
Thanks

keith.porter@colorado.edu
626-233-9758