Solutions to the Short-Period Building Performance Paradox.

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The Short-Period Building Performance Paradox

Why do analytical models of code compliant designs predict high probabilities of collapse for short-period buildings contrary to damage observed in actual earthquakes and the judgement of earthquake engineers?

“Show me the bodies” Bill Holmes
Trends in the Probability of Collapse ($MCE_R$ Ground Motions)
(Collection of FEMA P-695 Collapse Results, NIST GCR 12-917-20, NIST 2012)
Importance of Short-Period Building Performance

Common. The majority of buildings in the United States are low-rise and have a short fundamental period:
- For example, approximately 90% (by number) or 75% (by square footage) of all buildings in Los Angeles County are low-rise construction.

Typical. Typical of building construction used for:
- Residences - All SFD and most MFD buildings
- Essential facilities (police, fire and EOCs)

Earthquake Risk. Dominant contributor to earthquake risk:
- Deaths, dollars (e.g., insured losses) and downtime (e.g., temporary shelter)
- Community resiliency
Overall Project Goal and Approach

**Practical Solutions.** The overall goal of the ATC-116 Project is to develop practical solutions to the problem of short-period building response and performance in earthquakes being unreliably estimated using current analytical methods. It is intended that topical studies of light-frame wood buildings and other structural systems will:

- **Understand the Paradox.** Investigate the major causes and develop practical solutions to the performance paradox of short-period buildings,

- **Improve Analysis Methods.** Improve analytical modeling methods, calibrated and validated with observed performance of buildings in recent earthquakes and full-scale shake table building tests, and

- **Improve Design Practice.** Provide the basis and develop recommendations for improving design practice and requirements in building codes and standards – *with the design and construction community*
Sources of Observed Response Behavior and Collapse Performance of Short-Period Buildings

Response Behavior (e.g., building periods)
- CSMIP Data Base – Numerous earthquake records
- CUREE Caltech Wood Project – In-situ vibration tests

Observations of Earthquake Damage and Collapse Performance

Full-Scale Shake Table Tests
- 2-story residential building - E-Defense (Miki Japan)
- 2-story residential building – NEESWood Project (Univ. of Buffalo)
Example CSMIP Earthquake Data - Templeton Hospital
(1-story irregular light-frame wood structure; 335’ x 277’ in plan; 1975 design date; SFRS – 2 x 6 studs at 16” o.c. sheathed with ½-inch plywood on one side; roof diaphragms sheathed with ½-inch plywood; concrete grade beams below shear walls and 5” concrete slab on grade)
Selected Templeton Hospital Acceleration Time Histories Recorded during the 2003 San Simeon Earthquake (CSMIP)
1994 M6.7 Northridge Earthquake
Single-Family Dwelling (SFD) Damage – Wood Frame Buildings

Post-1960 2-story home

Older 2-story home (with cripple walls)
1994 M6.7 Northridge Earthquake
Multi-Family Dwelling (MFD) Damage – Wood Frame Buildings

Northridge Meadows
Apartment Complex

Woodland Hills
Apartment Complex
1995 M6.8 Kobe Earthquake
Example Damage of Collapse of Short-Period Buildings

Collapse of a 2-story Japanese house with weak walls and a heavy clay-tile roof

Incipient collapse of a 2-story mixed-use building
## Summary and Comparison of Earthquake Losses

<table>
<thead>
<tr>
<th>1994 Northridge Earthquake</th>
<th>1995 Kobe Earthquake</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>60 fatalities</strong> (20 due to building collapse – 4 wood buildings)</td>
<td><strong>6,340 fatalities</strong> (most due to collapse of smaller buildings)</td>
</tr>
<tr>
<td>1,044 hospitalized injuries</td>
<td>25,000 serious injuries</td>
</tr>
<tr>
<td>11,088 displaced households</td>
<td>300,000 homeless</td>
</tr>
<tr>
<td>14,500 Yellow or Red tagged buildings:</td>
<td>150,000 collapsed or destroyed buildings:</td>
</tr>
<tr>
<td>Less than 1% of buildings Red Tagged in areas of strongest (MMI IX) shaking</td>
<td>✓ More than 20% of buildings collapsed within 5 km of fault rupture</td>
</tr>
<tr>
<td>$26 - $40 billion of total direct economic loss (1994 dollars)</td>
<td>$100 -$200 billion of total direct economic loss (1995 dollars)</td>
</tr>
<tr>
<td>$18.5 - $25 billion of building-related economic loss (1994 dollars)</td>
<td>$80 - $150 billion of building-related economic loss (1995 dollars)</td>
</tr>
</tbody>
</table>
Example Photos of Large Drift Displacements of Wood Buildings at Incipient Collapse

Shake table tests of modern 2-story Japanese home (E-Defense, Miki, Japan)

4-story apartment building in the San Francisco Marina District, 1989 Loma Prieta Earthquake
Observed Performance – Key Findings for Modern Light-Frame Wood Buildings

**Collapse Failure Mode.** Collapse of light-frame wood buildings in an earthquake is typically a result of $P-\Delta$ side-sway failure of the first-story (excluding collapse damage due to foundation failure). Full-scale shake table tests confirm this mode of failure.

**Large Lateral Displacements at Incipient Collapse** Observations of light-frame wood buildings severely damaged by earthquake or strongly shaken by shake table testing indicate large lateral displacements at the point of incipient collapse (e.g., mean first-story drift ratio of 10 percent, or greater).

**Low Probability of Collapse for MCE\textsubscript{R} Ground Motions.** Based on observed damage (i.e., Red-Tag data) in the 1994 Northridge earthquake, light-frame wood buildings have very low probabilities of collapse for MCE\textsubscript{R} ground motions (i.e., 0.3-second response of 1.5 g) suggesting target MCE\textsubscript{R} collapse rates for benchmarking analytical results of:

- $P[\text{Collapse} | \text{MCE\textsubscript{R}}] < 2$ percent for 1-story wood buildings, and
- $P[\text{Collapse} | \text{MCE\textsubscript{R}}] < 5$ percent for 2-story, or taller, wood buildings.

- Red Tag % - 186 Post-60 Census Tracts
- Red Tag % - 22 Equal Count Groups
- Best Fit (MLE) of Red Tag % (1st 21 Grps)
- P[Col] - 'Newer' W1 Bldgs. (FEMA P-155)

Example Statistic
Census Tract 115200
Buildings w/Red Tag 23
Total 905

Collapse Probability or Red Tag Percentage

0.3-Second Response Spectral Acceleration (g)
Summary of Short-Period Design (MCE) Ground Motions from 1976 to 2016 for Selected Sites in Southern California, Default Site Conditions

<table>
<thead>
<tr>
<th>Southern California City</th>
<th>ASCE 7 $S_{MS}$ (MCE_R)</th>
<th>ASCE 7 $S_{MS}$ (MCE)</th>
<th>1.5 x UBC (e.g., 1.5<em>2.5</em>0.44N_a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Los Angeles</td>
<td>2.36</td>
<td>2.40</td>
<td>2.16</td>
</tr>
<tr>
<td>Century City</td>
<td>2.53</td>
<td>2.16</td>
<td>1.83</td>
</tr>
<tr>
<td>Northridge</td>
<td>2.08</td>
<td>1.69</td>
<td>1.63</td>
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<tr>
<td>Long Beach</td>
<td>2.02</td>
<td>1.64</td>
<td>1.80</td>
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<td>Irvine</td>
<td>1.50</td>
<td>1.55</td>
<td>1.50</td>
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<tr>
<td>Riverside</td>
<td>1.80</td>
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<tr>
<td>San Bernardino</td>
<td>2.79</td>
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<td>San Luis Obispo</td>
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<td>1.23</td>
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<td>San Diego</td>
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<td>1.25</td>
<td>1.61</td>
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<tr>
<td>Santa Barbara</td>
<td>2.54</td>
<td>2.83</td>
<td>2.07</td>
</tr>
<tr>
<td>Ventura</td>
<td>2.42</td>
<td>2.38</td>
<td>2.46</td>
</tr>
</tbody>
</table>

ASCE 7 SMS (MCER)
Parametric Studies of Light-Frame Wood Buildings

Parametric studies investigated the response behavior and collapse performance of analytical models of light-frame wood building archetypes representing a variety of different configurations and modeling features.

- **Baseline Configurations.** In depth study of “baseline” configurations of archetypes models that incorporate “best estimate” properties of other parametric studies (e.g., nonstructural finishes).

- **Collapse Displacement Capacity** – Focused study that varied residual strength of archetype models at large post-capping displacements.

- **Nonstructural Exterior and Interior Wall Finishes** – Focused study of archetype models with and without nonstructural wall finishes.

- **Soil-Structure Interaction and Foundation Flexibility** – Focused study of archetype models with flexible foundations and nonlinear soil springs representing a range of typical site conditions.
Baseline Archetype Configurations

Occupancy Types and Height:
- **Commercial.** 1-story, 2-story and 4-story commercial (COM) buildings – 48’ x 96’ in plan
- **MFD Residential.** 1-story, 2-story and 4-story multi-family dwelling (MFD) buildings – 48’ x 96’ in plan
- **SFD Residential.** 1-story and 2-story single-family dwelling (SFD) buildings – 24’ x 48’ in plan

Design Criteria:
- **ASCE 7-10,** except:
  - **IRC** (i.e., SFD configurations also designed using prescriptive criteria)
- **Risk Category II** (all configurations)
- **Site Class D** site conditions
- Three Seismic Design Levels:
  - “High” – SDC $D_{\text{max}} - C_s = 0.154$
  - “Very High” – 1.5 x “High” - $C_s = 0.231$
  - “Moderate” – SDC $C_{\text{max}} - C_s = 0.077$
Modeling of Light-Frame Wood Building Archetypes

3-D Models - Archetype configurations modeled (and analyzed) as 3-D structures using the Timber3D program

Building Blocks – 3-D models are composed of “building blocks” that model the strength and stiffness of many different combinations of structural and nonstructural wall material and wall length.

  ◦ Key Modeling Improvement – Strength and stiffness of nonstructural wall materials were not included in models of prior studies (since nonstructural components are not part of the SFRS)

Residual-Strength – Building blocks incorporate post-capping residual strength to provide realistic lateral displacement capacity of building archetypes (e.g., collapse drift ratios of 10 percent, or greater)

  ◦ Key Modeling Improvement – De facto limit on collapse displacement of prior studies was about 3% to 4% drift ratio.

P-D Effects – Building blocks explicitly incorporate P-D effects

  ◦ Key Modeling Improvement – P-D effects were not important in models of prior studies (since not significant at small drift ratios).
Schematic Illustration of One-Story Three-Dimensional Baseline Model Configuration
Analysis of Light-Frame Wood Building Archetypes

Linear Dynamic Analysis:
- Fundamental-mode period (each direction) and mode shapes

Nonlinear Static and Dynamic Analyses:
- FEMA P-795 – Cyclic/monotonic pushover analysis of building blocks
- FEMA P-695 - Incremental dynamic analysis (IDA) of archetypes:
  - Many increments (40 typical) of ground motion intensity each requiring 44 nonlinear response history analyses (i.e., 22 earthquake records each with two orientations of X-Y components)

Response Statistics (at each increment of ground motion intensity)
- Peak values of floor acceleration, and story and roof displacements

Collapse Evaluation:
- FEMA P-695 – Probability of collapse (median collapse acceleration)
- Collapse Statistics - Number of collapses (out of 44 analyses) at each increment of ground motion intensity
- Median Collapse Displacement – Median drift ratio at the point of incipient collapse
Red markers represent the incipient collapse points of individual ground motions.
Median collapse acceleration, $S_{MT} = 1.84$ g; $P[\text{Collapse} | MCE_R] = 7.3$
Median collapse displacement (roof drift ratio at incipient collapse) = 8.17%
Example FEMA P-695 Pushover Curves
High Seismic Baseline Model of the 1-Story Commercial Building Archetype (COM1B)
Example FEMA P-695 Pushover Curves w/P-D Effect

High Seismic Models of the 2-Story Commercial Building Archetype with Different Amounts of Residual Strength – COM2B-C6 (60%), COM2B-C4 (40%), COM2B (30% - Baseline) and COM2B-C0 (0% residual strength)

- COM2B-C6 Model - $P_{[Col|MCE]} = 5.1\%$
- COM2B-C4 Model - $P_{[Col|MCE]} = 11.4\%$
- COM2B (Baseline) Model - $P_{[Col|MCE]} = 13.4\%$
- COM2B-C0 Model - $P_{[Col|MCE]} = 22.9\%$

Median 1st-Floor Drift Ratio at Incipient Collapse:
- 1st-Floor DR = 4.6\% $P_{[Col|MCE]} = 22.9\%$
- 1st-Floor DR = 14.2\% $P_{[Col|MCE]} = 5.1\%$
Summary of Key Findings of Baseline Parametric Studies

**Consistent Building Period.** Fundamental-mode periods of baseline archetype models which include nonstructural finishes are consistent with measured periods in actual buildings.

**Consistent Collapse Failure Modes.** Simulated side-sway collapse of all baseline archetype models is due to P-∆ failure of the first story consistent with observed failure collapse modes of light-frame wood building in earthquakes and on shake tables.

**Consistent Collapse Probabilities (1-Story and 2-Story SFD and MFD Buildings).** MCE$_R$ collapse probabilities calculated for one-story and two-story SFD and MFD baseline archetype models (High Seismic design) are consistent with collapse rates based on Red-Tag data of wood buildings in areas that experienced MCE$_R$ ground motions during the 1994 Northridge earthquake. Collapse probabilities of (weaker) two-story COM, and four-story MFD and COM archetype models are much greater than those based on Red-Tag data, and exceed the 10-percent probability of collapse safety objective of ASCE/SEI 7-10.
High Seismic - $MCE_R$ Collapse Probabilities of Light-Frame Wood Building Baseline Archetypes and Target Values of $MCE_R$ Collapse Probability Based on Red-Tag Data – Trends with Model Period ($T_1$)
High Seismic - $MCE_R$ Collapse Probabilities of Light-Frame Wood Building Baseline Archetypes and Target Values of $MCE_R$ Collapse Probability Based on Red-Tag Data – Trends with Strength ($V_{max}/W$)
Very High Seismic - $MCE_R$ Collapse Probabilities of Light-Frame Wood Building Baseline Archetypes and Target Values of $MCE_R$ Collapse Probability based on Red-Tag Data – Trends with Strength ($\frac{V_{\text{max}}}{W}$)

The probability of collapse of a Very High Seismic light-frame wood building archetype model is substantially greater than that of the corresponding High Seismic model, even when the SFRS is designed for proportionally greater seismic forces.
Summary of Key Findings of Baseline Parametric Studies

**Collapse Trend with Building Height – Shorter is Better.** The probability of collapse of light-frame wood building baseline archetype models increases with height, all else being equal. This trend is most likely due to differences in archetype model strength ($V_{max}/W$), which tends to decrease with height, and P-D collapse of the first story, which becomes more critical with height.

**Strength – Stronger is Better.** Collapse of light-frame wood baseline archetype models is strongly influenced by archetype model strength ($V_{max}/W$), the stronger the archetype model, the better the collapse performance, all else being equal.

**P-D Effects.** Collapse of light-frame wood building archetype models is strongly influenced by P-D effects. In general, the taller (and heavier) the archetype model, the more P-D detrimentally affects collapse performance, all else being equal.

**Very High Seismic (Near Fault) Collapse Performance– Worse than High Seismic.** The probability of collapse of a Very High Seismic archetype model is substantially greater than that of the corresponding High Seismic model, even when the SFRS is designed for proportionally greater seismic forces.
Summary and Conclusion

**Short-Period Wood Buildings** - The ATC-116 project has investigated (and resolved) the short-period building performance paradox for wood light-frame buildings.

**Paradox Resolved** - With improved modeling methods, response and collapse results of analytical models reasonably well match observed performance of wood light-frame buildings in earthquakes (and on shake tables)

**Transfer of Knowledge** – Results of the wood studies provide a basis for improving design practice and building codes and standards (e.g., values of the design period, T, and design parameters, e.g., R, $\Omega_o$ and $C_d$).

**Short-Period Masonry Buildings** – Similar effort is nearing completion for short-period reinforced-masonry shear wall buildings (to be completed in 2018).

**Short-Period Steel Buildings** - Similar effort is now underway for short-period steel concentrically braced frame buildings (to be completed in 2019).