Nonlinear Response-History Analysis for the Design of New Buildings: A Fully Revised Chapter 16 Methodology for ASCE 7-16

Project by: Large Issue Team

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Co-Founder and CEO @ Seismic Performance Prediction Program (SP3) [www.hbrisk.com]

BSSC Webinar | April 28, 2015
Reminder of the ASCE7 Process

Proposed Substantial Change to ASCE 7

Building Seismic Safety Council (2015 NEHRP Provisions)

ASCE7 Committee (for ASCE 7-16)

Final Substantial Change to ASCE 7
Issue Team Charge and Deliverables

- **Issue Team Objective:** Develop recommendations to the BSSC Committee regarding proposed improvements to Chapter 16 of ASCE7.

- **Issue Team Deliverables:**
  - Chapter 16 Code language (completely revised)
  - Chapter 16 Commentary language (completely revised)
  - Earthquake Spectra sister papers – (1&2) Development, (3) Example Applications, and (4) Evaluation
Context for Nonlinear Analysis Method

- Types of Structural Analysis Methods in ASCE 7-16:
  - Equivalent lateral force procedure (Chp. 12)
  - Response spectrum (modal) (Chp. 12)
  - Nonlinear response-history analysis (Chp. 16)
  - Now separate: Linear response-history analysis (Chp. 12)

- Other Structural Analysis Methods:
  - Nonlinear static pushover (ASCE 41)
ASCE7 Chapter 16 - Issue Team #4

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- Andy Fry, MKA
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- Ken Elwood, Univ. of British Col.
- Steve Mahin, UC Berkeley
- Graham Powell, UC Berkeley Em.
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- Nico Luco, USGS
- Mike Tong, FEMA
Current Status of Chapter 16

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Issue Team 4 on Response History Analysis
Literature Review

We had a lot to draw on (which was not the case only a few years ago)...

- Guidelines for Performance-Based Seismic Design of Tall Buildings, PEER Center, Tall Building Initiative (PEER, 2010).
- NIST GCR 11-917-15: Selecting and Scaling Earthquake Ground Motions for Performing Response-History Analyses
What is the Point? - Building Safety Goals

- The analysis approach will depend on the goal.

- **Explicit Safety Criteria:** Per ASCE 7-10 Table C.1.3.1b:

<table>
<thead>
<tr>
<th>Risk Category</th>
<th>Tolerable Probability of Collapse</th>
<th>Ground Motion Level</th>
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<tbody>
<tr>
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</tr>
<tr>
<td>IV</td>
<td>3%</td>
<td>MCE_R</td>
</tr>
</tbody>
</table>

- **Explicit Verification:** Simulate collapse capacity (to hard).
- **Implicit Verification:** Use a small number of MCE_R ground motions, use mean building response (no variability), and then satisfy acceptance criteria to show compliance.
Chapter 16: Overall Structure

- Section 16.1: General Requirements
- Section 16.2: Ground Motions
- Section 16.3: Modeling and Analysis
- Section 16.4: Analysis Results and Accept. Criteria
- Section 16.5: Design Review (not covered)
Section 16.1 (General)

The basic structure of the design approach is:

- Linear DBE-level analysis (to enforce minimum base shear, basic load cases, etc.).
- Nonlinear MCE-level response-history analysis.
Section 16.2 (Ground Motion)

- Ground motion level:
  - $MCE_R$ (to better link to what is being assessed)

- Number of ground motions:
  - 11 motions (to better estimate the mean responses)
Section 16.2 (Ground Motion)

- Target spectrum:
  - Method 1: Typical MCE$_{R}$ spectrum
  - Method 2: Multiple “scenario” spectra (typically two)
Section 16.2 (Ground Motion)

Scenario: M=7, R=10 km
(characteristic event for many CA sites)

MCE_R target for $Sa(T_1 = 1.0s)$
(at the high-end for an MCE motion at CA sites)

Figure reference: J.W. Baker – 2006 COSMOS
Section 16.2 (Ground Motion)

40 real records with $M \approx 7$ and $R \approx 10$ km

Figure reference: J.W. Baker – 2006 COSMOS
Section 16.2 (Ground Motion)

40 real records with $M \approx 7$ and $R \approx 10$ km

Observations:
- Unique “peaked” spectral shape (Sa is not large at all periods).
- These records will tend to be less damaging as the structural period elongates past 1.0s.

Figure reference: J.W. Baker – 2006 COSMOS
Section 16.2 (Ground Motion)

- Uniform hazard spectrum
- Conditional mean spectra

\[ T^* = 0.45 \text{s} \]
\[ T^* = 0.85 \text{s} \]
\[ T^* = 2.6 \text{s} \]
Section 16.2 (Ground Motion)

- Selection of motions:
  - Same general language.
  - Added: “It is also desirable for ground motion spectral shapes to be comparable to the target response spectrum of Section 16.2.2.”
  - For near-fault: Include an appropriate ratio of pulse-type motions.
Section 16.2 (Ground Motion)

- Scaling of motions:
  - Scale the maximum direction $S_a$ to the target spectrum (which is maximum direction). [*Contrast: Different from SRSS used in ASCE 7 and ASCE41.*]

- Period range for scaling:
  - Range from $0.2T_1$ to $2.0T_1$ (higher for $MCE_R$)
  - Also require 90% mass (which can control)
Section 16.2 (Ground Motion)

- Near-Fault versus Far-Field
  - BSSC Issue Team left this fairly non-prescriptive.
  - ASCE7 process added specificity (near-fault is $R < 15\text{km}$ if $M > 7.0$ and $R < 10\text{km}$ if $7.0 > M > 6.5$). As an aside/example, most of San Francisco is now “near-fault”.
    - [Contrast: Larger range than ASCE 41.]

- Orientation of Ground Motions:
  - **Near-Fault**: Apply pairs of records in FN/FP orientation
  - **Far-Field**: Apply pairs of records with “random orientation” (but ASCE7 process added a more specific +/- 10% requirement)
  - No need to rotate pairs 90 degrees
Spectral matching:

- Average matched spectra must meet a slightly higher threshold of 110% of the target spectrum.
- This is an intentional penalty for the use of spectrum matching, because studies have shown that it can lead to conservatively biased results if not done correctly.
- Only allowed for near-fault sites if it is shown that the pulse properties are maintained.
Sec. 16.3 (Modeling & Analysis)

- This section says what to do but not how to do it.
- This was intentionally not written to be a nonlinear analysis guideline.

One item to highlight – Torsion:

- Interesting topic with lots of divergent opinions!
- BSSC Issue Team: Leave this to the linear design step.
- ASCE 7: Allow the above if no Type 1a/1b irregularity exists, otherwise require 5% mass offsets in the NL model.
Section 16.4 (Accept. Criteria)

- **Big Focus:** Develop acceptance criteria more clearly tied to the ASCE7 safety goals.

<table>
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<tr>
<td>IV</td>
<td>3%</td>
<td>MCE_R</td>
</tr>
</tbody>
</table>

- **Explicit Goal:** Acceptable collapse probability.
- **Implicit Verification Approach:** Use mean structural responses (with 11 motions) to show compliance.
Section 16.4 (Accept. Criteria)

- Force-controlled (brittle) components:

<table>
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<td>MCE&lt;sub&gt;R&lt;/sub&gt;</td>
</tr>
<tr>
<td>III</td>
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</tr>
</tbody>
</table>
Proposal: Section 16.4 (Accept. Criteria)

- Force-controlled (brittle) components:

Table 4. Assumed Variability and Uncertainty Values for the Component Demand and Capacity.

(a) Demand Dispersion ($\beta_D$) and Variability in the Force Demand

<table>
<thead>
<tr>
<th>General</th>
<th>Well-Defined Mechanism</th>
<th>Variability in the Force Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>0.25</td>
<td>Record-to-record variability (for MCE_R ground motions)</td>
</tr>
<tr>
<td>0.50</td>
<td>0.25</td>
<td>$\beta_D$-TOTAL</td>
</tr>
</tbody>
</table>

(b) Capacity Dispersion ($\beta_C$) and Variabilities and Uncertainties in the Final As-Built Capacity of the Component

<table>
<thead>
<tr>
<th>General</th>
<th>Well-Defined Mechanism</th>
<th>Variabilities and Uncertainties in the Final As-Built Capacity of the Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>0.30</td>
<td>Uncertainty from estimating force demands using structural model (modeling uncert.)</td>
</tr>
<tr>
<td>0.15</td>
<td>0.08</td>
<td>Variability from estimating force demands from mean of only 11 ground motions</td>
</tr>
<tr>
<td>0.30</td>
<td>0.30</td>
<td>Typical variability in strength equation for $F_{n,e}$ (from available data)</td>
</tr>
<tr>
<td>0.10</td>
<td>0.10</td>
<td>Typical uncertainty in strength equation for $F_{n,e}$ (extrapolation beyond available data)</td>
</tr>
<tr>
<td>0.20</td>
<td>0.20</td>
<td>Uncertainty in as-built strength due to construction quality and possible errors</td>
</tr>
<tr>
<td>0.45</td>
<td>0.49</td>
<td>$\beta_C$-TOTAL</td>
</tr>
</tbody>
</table>

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Section 16.4 (Accept. Criteria)

- Force-controlled (brittle) components:

  \[2.0 \, I_e \, F_u \leq F_e\] for “critical” (same as PEER-TBI)
  \[1.5 \, I_e \, F_u \leq F_e\] for “ordinary”
  \[1.0 \, I_e \, F_u \leq F_e\] for “non-critical” (judgment)

\[F_u = \text{mean demand (from 11 motions)}\]
\[F_e = \text{expected strength}\]

Critical = failure causes immediate global collapse
Ordinary = failure causes local collapse (one bay)
Non-critical = failure does not cause collapse

Contrast: Much more stringent than the average-based approach that could be used in ASCE 41.
Section 16.4 (Accept. Criteria)

- Deformation-controlled (ductile) components:
  - Similar statistical approach used (as with force-controlled components).
  - “Pre-approved” uses of ASCE41 are also provided.
Section 16.4 (Accept. Criteria)

Drift limits:

- Mean drift ≤ 2.0*(normal limit)
- The factor of two comes from:
  - 1.5 = MCE / DBE
  - 1.25 = Approx. ratio of R / Cd
  - 1.1 = A little extra because we trust NL RHA more
Section 16.4 (Accept. Criteria)

- Treatment of “collapses” and other “unacceptable responses”:
  - **Current Treatment in ASCE7-10**: Nothing but silence….
  - **Philosophical Camp #1**:
    - Outliers are statistically meaningless.
    - Acceptance criteria should be based only on mean/median.
    - If we have 5/11 (or 3/7) “collapses”, this means nothing.
  - **Philosophical Camp #2**:
    - Outliers are statistically meaningless, but are still a concern.
    - Acceptance criteria should consider “collapses”.
    - If we have 5/11 (or 3/7) “collapses”, this is a great concern.
Section 16.4 (Accept. Criteria)

- Statistical collapse study:

<table>
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<tr>
<th>Risk Category</th>
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<tr>
<td>IV</td>
<td>3%</td>
<td>MCE_R</td>
</tr>
</tbody>
</table>
Section 16.4 (Accept. Criteria)

- Statistical collapse study:

<table>
<thead>
<tr>
<th>Number of Collapses</th>
<th>0.05</th>
<th>0.10</th>
<th>0.15</th>
<th>0.20</th>
<th>0.30</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 of 11</td>
<td>93%</td>
<td>74%</td>
<td>51%</td>
<td>30%</td>
<td>7%</td>
</tr>
<tr>
<td>1 of 11</td>
<td>7%</td>
<td>23%</td>
<td>36%</td>
<td>38%</td>
<td>21%</td>
</tr>
<tr>
<td>2 of 11</td>
<td>0%</td>
<td>3%</td>
<td>11%</td>
<td>22%</td>
<td>29%</td>
</tr>
<tr>
<td>3 of 11</td>
<td>0%</td>
<td>0%</td>
<td>2%</td>
<td>8%</td>
<td>24%</td>
</tr>
<tr>
<td>4 of 11</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>2%</td>
<td>13%</td>
</tr>
<tr>
<td>5 of 11</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>5%</td>
</tr>
</tbody>
</table>

| Number of Collapses | Likelihood if P[C|MCE\textsubscript{R}] = 10% |
|---------------------|---------------------------------------------|
| ≥ 1 of 11           | 26%                                         |
| ≥ 2 of 11           | 3%                                          |
| ≥ 3 of 11           | 0%                                          |
| ≥ 4 of 11           | 0%                                          |
| ≥ 5 of 11           | 0%                                          |
Section 16.4 (Accept. Criteria)

- Collapse study conclusions (lots of statistics):
  - Even 0/11 collapses, in no way proves that the collapse probability is < 10%. Way too much uncertainty.
  - If building is safe, there is still a 25% chance of getting a collapse (i.e. “false positive”).
  - If building is safe, it is highly unlikely (only 3% chance) that we will see 2+ collapses.

- Final Criterion:
  - Basic Case: Allow up to 1/11 “collapses” but not 2/11.
  - With Spectral Matching: Require 0/11 collapses.
  - For Risk Categories III-IV: Require 0/11 collapses.
“Collapses” are more generally called “unacceptable responses” and include:

1. True dynamic instability,
2. Analytical solution fails to converge,
3. Predicted demands on deformation-controlled elements exceed the valid range of modeling,
4. Predicted demands on critical or ordinary force-controlled elements exceed the element capacity, or
5. Predicted deformation demands on elements not explicitly modeled exceed the deformation limits at which the members are no longer able to carry their gravity loads.
Section 16.5 (Design Review)

- Typical requirements and language...
- Design review is critical!
Example Applications

- MKA Example
- SGH Example
- R&C Example

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## Example Applications

<table>
<thead>
<tr>
<th>Example</th>
<th>Location</th>
<th>Tectonic Regime</th>
<th>Fault Distance</th>
<th>Type of Region for Design Spectrum</th>
<th>Original Design</th>
<th>Site Class</th>
<th>Structural System</th>
<th>Regularity</th>
<th>Stories</th>
<th>Period Range</th>
<th>Software</th>
</tr>
</thead>
<tbody>
<tr>
<td>R+C</td>
<td>Berkeley CA</td>
<td>Shallow crustal</td>
<td>Short</td>
<td>Deterministic</td>
<td>IBC 2006</td>
<td>III</td>
<td>Equivalent Lateral Force</td>
<td>C</td>
<td>Steel SMRF &amp; BRBF</td>
<td>Regular</td>
<td>5+1</td>
</tr>
<tr>
<td>MKA</td>
<td>Seattle WA</td>
<td>Shallow crustal &amp; subduction</td>
<td>Short &amp; Long</td>
<td>Probabilistic</td>
<td>IBC 2006</td>
<td>II</td>
<td>Response Spectrum</td>
<td>C</td>
<td>RC Core</td>
<td>Narrow core &amp; torsional</td>
<td>42+3</td>
</tr>
<tr>
<td>Virginia Tech</td>
<td>-</td>
<td>Shallow crustal</td>
<td>Medium to Long</td>
<td>Probabilistic</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>D</td>
<td>Steel SMRF</td>
<td>Regular</td>
<td>2-8+0</td>
</tr>
</tbody>
</table>

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More Information: Publications

ASCE 7 Chapter 16 Project Documentation:

- Chapter 16 in the 2015 NEHRP Provisions (code and commentary)
- Chapter 16 in the ASCE 7-16 Standard (code and commentary)
- Earthquake Spectra papers in progress/review:
  1. Provisions Development (1 of 2)
  2. Provisions Development (2 of 2)
  3. Example Applications
  4. Evaluation Studies

Recent Advances in Ground Motion Selection and Scaling
Questions/Comments?

- Thanks you for your time.
- Please contact me if you would like more information/background because a short presentation is not enough!
- Contact:
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  - Website: www.hbrisk.com
  - Direct: (530) 514-8980