Performance-Based Seismic Design in Real Life: The Good, the Bad and the Ugly

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OPENING SCENE
REMINISCING UPON DEFINITIONS
Problem statement

Izmit refinery (Kocaeli 1999)  
Japan (Tohoku 1999)

How to design critical facilities for the desired seismic performance?
What is a performance objective?

A triplet of values

\[ \lambda_{x\%} \ (D > C) \ < \lambda_o \]

1: Capacity: An EDP threshold to define LS

2: maximum allowable MAF of exceeding C

3: confidence level of meeting objective vis-à-vis epistemic uncertainty
• direct monetary losses exceeding $C = 500,000\text{€}$ with a maximum MAF of $\lambda_O = 0.0021$, or 10% in 50yrs, at a confidence of $x = 75\%$;

• downtime exceeding $C = 1$ week with $\lambda_O = 10\%$ in 10yrs, at $x = 60\%$;

• no more than $C = 20\%$ of the columns enter Damage State 3 with $\lambda_O = 5\%$ in 50yrs, at $x = 90\%$;

• maximum interstory drift less than 2% with $\lambda_O = 10\%$ in 50yrs, at $x = 75\%$. 
THE BAD:
NO PROBABILITY MEANS NO PERFORMANCE
BAD: Design code approach (EN1998)

Strength Check: $S_a(T_1)$

Stiffness Check: $0.4 - 0.5 \times S_a(T_1)$

Select: $T_1, 10\%/50\text{yr} \ S_a(T_1)$

Member sizing

Final Design (?)
Issue 1: Design spectrum ≠ Seismic hazard

Seismic hazard surface, hazard curve & UHS
Issue 2: Where is the variability?

Unfortunately, each record has its own IDA curve
Variability cannot be ignored

- Frequent lower intensity earthquakes also do damage
- MAF of damage > MAF of $S_a(T_1)$!
Uncertainty should not be ignored

- Plastic rotation capacity of beam-column connections (Lignos & Krawinkler)
- Potential realizations of dynamic response IDA curves for 9-story steel frame
Result: Inconsistent / Unknown Safety

Performance (MAF)

Target

Period, $T_1$

Actual

Unsafe

Uneconomical

Behavior factor, overstrength, nominal material properties add conservativeness
BAD: Displacement-based design

• Is Stefano Pampanin in the audience?

• Confusion dates back to SEAOC Vision 2000 … and even Priestley (2000) “Performance based seismic design”

• Saying that your objectives are expressed in terms of displacement is not the same as PBSDD

• Displacement-based design is not that bad, it is simply not PBSDD

• That does not mean it cannot be upgraded…. 
Another BAD candidate: Risk targeted spectra

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*Workshop on Update of Pacific Northwest Portion of U.S. National Seismic Hazard Maps*

"Potential Design Mapping Updates," N. Luco, USGS

March 22, 2012
RT spectra ≠ performance

- They do account for hazard and risk… … but for all structures at the same time
- They are site-specific but building-ignorant
- I like RT spectra, just not on their own and not for performance-based design
- We will take another look at them later on…
THE UGLY:
WIN SOMETHING – LOSE SOMETHING
Performance-Based Design = Iterations

- Set performance targets
- Determine preliminary design (not always easy)
- Assess performance
- Iterate to convergence
  - Redesign and reassess in each cycle!
- Expensive!
UGLY: Iterate without guidance

- Trial and error? (trust user “expertise”)
- Genetic-style optimizer (shotgun approach)
- Iterate first on pushover then on dynamics? (Dolsek and coworkers)

Sinkovic et al. 2016
UGLY: Risk-based q-factor & RT-spectra guidance

Step 5

- \( \lambda(\text{LS}) < 10\% / 50 \text{ years} \) → q-factor ✓
- \( \lambda(\text{GC}) < 1\% - 2\% / 50 \text{ years} \) → q-factor ✓

otherwise → q-factor ✗ → Iterations

Step 6

- \( \lambda(\text{LS}) < 10\% / 50 \text{ years} \) → q-factor ✓
- \( \lambda(\text{GC}) < 1\% - 2\% / 50 \text{ years} \) → q-factor ✓

acceptable but maybe non-optimal
• Iterations are done by academics, not engineers
• The more fine-grained the q-factor is, the better
• Unfortunately, can only work for hard-wired objectives
• In the end, some proper nonlinear assessment would help
THE GOOD:
ALWAYS DELIVERS
How to pick a “design invariant” proxy ($T_1$?)

- Easy with experience (usual design case)
- Difficult with novel structures or new requirements
  - Example for ELASTIC 1DOF oscillator:
    - Iterate:
      1. Select initial $T$
      2. Find $S_a(T)$ from UHS at x% in 50yrs
      3. Calculate new period $T = 2\pi \sqrt{\delta_{\text{lim}} / S_a}$
Potential proxies

• Equivalent **linear** MDOF? (Franchin et al.)
  – Not trivial. Works best with automated software

• Equivalent **nonlinear** SDOF
  – Assume constant $T_1$ per cycle (force basis)
  – Assume constant $d_y$ per cycle (yield disp. basis)

• Is Stefano Pampanin in the audience?
• Forget period, let’s do yield displacement!
• “Constant” given system mass, general dimensions & material
• Largely independent of strength (Moehle, Priestley et al, Aschheim)
• Some systems (rocking walls?) may work better with constant $T_1$
Use equivalent nonlinear SDOF with variability

**SPO2IDA: Moderate periods**
Valid for firm soil, 5% damping and moderate periods

<table>
<thead>
<tr>
<th>Segment</th>
<th>SA/SAyield</th>
<th>μ @ end</th>
<th>% in SA terms</th>
<th>μ</th>
<th>Controls</th>
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<tr>
<td>Elastic</td>
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<td>16%</td>
<td>12.00</td>
<td>Hardening μ 4</td>
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<tr>
<td>Hardening</td>
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<td>1.00</td>
<td>50%</td>
<td>12.00</td>
<td>Hardening slope 20%</td>
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<tr>
<td>Softening</td>
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<td>7.60</td>
<td>84%</td>
<td>12.00</td>
<td>Softening slope -25%</td>
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<tr>
<td>Res. Plateau</td>
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<td>12.00</td>
<td></td>
<td>11.39</td>
<td>Residual plateau 70%</td>
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<tr>
<td>Collapse</td>
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<td>12.00</td>
<td></td>
<td>7.29</td>
<td>Fracturing μ 12.0</td>
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<table>
<thead>
<tr>
<th>ISO</th>
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<th>Csr</th>
<th>Cdr</th>
<th>Cr</th>
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<tbody>
<tr>
<td>Static PO</td>
<td>IDA-50%</td>
<td>capacity</td>
<td>IDA-16%</td>
<td>IDA-84%</td>
</tr>
</tbody>
</table>

Graph showing the relationship between ductility (μ) and R = SA/SAyield.
“Invert” Performance Integral

TARGET

MAF_{L_S} = \int \text{hazard curve} \times \text{IDA curves}

Depends on

- Structural parameters: Backbone shape, Base shear coefficient, dy
- Limit state definition: MAF and ductility
- Map entire parameter space to solve
Given
- site
- backbone shape
- $\delta_y$

Get
- Base shear
- Period
How to compute?

• Numerically
  – As $S_{di}$ hazard curves (Inoue & Cornell, Jalayer & Cornell, Ruiz-Garcia & Miranda etc)
  – Dynamic analysis or R-$\mu$-T with dispersion (e.g. SPO2IDA)

• Analytically
  – Invert Cornell & Jalayer or DV’s closed-form solutions

\[
C_y = \frac{1}{g \mu_{lim}^{1/b}} \cdot \exp \left[ \frac{1}{2k_2} \left( -k_1 + \sqrt{\frac{k_1^2}{\phi'} - \frac{4k_2}{\phi'} \ln \frac{P_o}{k_0 \sqrt{\phi'}}} \right) \right]
\]
Introduce uncertainty

• Assume it adds to the total variability
  – Not perfect: Bias is also possible
  – ….. but tough to quantify

• Use “required confidence” to guard against uncertainty
  – Say 90-95% against brittle failure mechanisms
  – Only 60-75% for ductile, low-consequence failures

• Tune design to user and problem requirements
A code-compatible approach

- Invert Cornell & Jalayer equations
  - Adopt power-law fit for hazard, IM vs EDP response
  - Derive solutions given the design spectral shape

- Constant accel:
  \[
  C_y = \frac{S_{amax}}{g \mu_{lim}^{1/b}} \cdot \exp \left[ \frac{k_1}{2b^2} \beta_{T\theta}^2 \right]
  \]

- Constant vel:
  \[
  C_y = \left( \frac{S_{amax} \cdot T_c}{2\pi} \right)^2 \frac{1}{\delta_y g \mu_{lim}^2} \exp[k_1 \beta_{T\theta}^2]
  \]

- Constant disp: "Any" result is ok!
THE FINAL DUEL:
THE GOOD DOES NOT ALWAYS WIN IN REAL LIFE
Can we let the BAD win?

• Bad methods are currently dominating
  – Will continue to do so for run-of-the-mill design
  – …not everybody needs accurate performance

• Good methods are lovely and will probably get better
  – Still, this does not mean engineers or codes will adopt them

• Ugly concepts may have a better chance
  – Create automated optimization (and modeling) software?
  – “Hack” the code with RT-spectra and risk-based q-factors
What is my opinion as a cinephil?

Academics love perfection, but in real life we need to be practical. Sometimes “better” is the enemy of “good enough”

So Ugly it is going to be for quite a while

For sure though, please do not let the Bad guy win
The eternal genius and running commentary of Prof. Ulysses R. Garbaggio

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