ATC-63

FEMA P-695 Quantification of Building Seismic Performance Factors

LATBSDC Annual Meeting
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Applied Technology Council
Director of Projects
Outline

- Project Context
- Background/Scope/Basis of Methodology
- Methodology Overview
- Example Application to Concrete Moment Frame Systems
- General Findings and Observations
ATC-63 Project Context
ATC-63  Quantification of Building System Performance and Response Parameters

- FEMA funded project
- Multi-year effort beginning in 2004
- FEMA P695 Quantification of Building Seismic Performance Factors (FEMA, 2009)
- Genesis is rooted in R-factors
  - But Seismic Performance Factors ($\Omega_0$, $C_d$) and design requirements are covered
ATC-63 Project Context

- R-factors were first introduced in 1978
  ✓ ATC 3-06 Tentative Provisions for the Development of Seismic Regulations for New Buildings
- 1988 NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings
- 1988 Uniform Building Code (UBC)
- 1985 UBC and earlier utilized K-factors
**ATC-63 Project Context**

- **K-factors** – there were essentially 4
  (frame, box, dual system, ductile moment frame)
- **ATC 3-06 R-factors** – there were 21
- **1988 NEHRP Provisions** – there were 30
- **Today in ASCE/SEI 7-05** – there are 83
- **Critically important to seismic design**
  - Set seismic design base shear
  - Account for system ductility and damping during inelastic response
ATC-63 Project Context

• But how were they determined?
That was then, this is now
Advent of Performance Based Seismic Design
More than a decade of maturation and development of advanced analytical procedures
We are now attempting to quantify the seismic performance of buildings
ATC-63 Project Context

• And asking the question: What performance goals do our building codes achieve?

• Objective - replace the smoke with science
Background, Scope, and Basis
Project Organization

ATC Management
Chris Rojahn (PED)
Jon Heintz (PQC)
William Holmes (PTM)

PMC Members
Charles Kircher (Chair)
Greg Deierlein – Stanford
M. Constantinou – Buffalo
John Hooper - MKA
James Harris – HA
Allan Porush - URS

FEMA
Michael Mahoney
Robert Hanson

PRP Members
Maryann Phipps (Chair)
Amr Elnashai - MAE
S.K. Ghosh - SKGA
Ramon Gilsanz - GMS
Ron Hamburger - SGH
Jack Hayes - NIST
Bill Holmes – R&C
Richard Klingner - UT
Phil Line - AFPA
Bonnie Manley - AISI
Andre Reinhorn - UB
Chris Rojahn - ATC
Rafael Sabelli - WPM

ATC Management Committee
Project Executive Director (Chair)
Project Technical Monitor
Project Quality Control Monitor

ATC-63 Project Management Committee
Project Technical Director (Chair)
Five Members

Project Review Panel
Twelve Members

Working Groups
Technical Consultants

Working Groups
Stanford – NDA
Krawinkler – AAC
SUNY – NSA/NCA
Filiatrault – Wood

ATC Staff
Technical Support
Administration

ATC-63 Quantification of Building System Performance and Response Parameters
ATC-63 Project Objectives

• Primary – Create a methodology for determining Seismic Performance Factors (SPF’s) “that, when properly implemented in the design process, will result in the equivalent earthquake performance for buildings different lateral-force-resisting systems”

• Secondary – Evaluate a sufficient number of different lateral-force-resisting systems to provide a basis for Seismic Code committees (e.g., BSSC PUC) to develop a simpler set of lateral-force-resisting systems and more rational SPF’s (and related design criteria) that would more reliably achieve the inherent earthquake safety performance objectives of building codes
Scope and Basis of the Methodology

- **New Buildings** – Methodology applies to the seismic-force-resisting system of new buildings and may not be appropriate for non-building structures and does not apply to nonstructural systems.

- **NEHRP Provisions (ASCE 7-05)** – Methodology is based on design criteria, detailing requirements, etc. of the NEHRP Provisions (i.e., ASCE 7-05 as adopted by the BSSC for future NEHRP Provisions development) and, by reference, applicable design standards.

- **Life Safety** – Methodology is based on life safety performance (only) and does not address damage protection and functionality issues (e.g., I = 1.0 will be assumed).

- **Structure Collapse** – Life safety performance is achieved by providing an acceptably low probability of partial collapse and global instability of the seismic-force-resisting system for MCE ground motions.

- **MCE Ground Motions** – MCE ground motions are based on the spectral response parameters of the NEHRP Provisions (ASCE 7-05), including site class effects.
**Ground Motion Record Set**

- **Far-Field Record Set:**
  \( R > 10 \text{ km} \)
- **Large Magnitude Events:**
  Moment magnitude, \( M > 6.5 \)
- **Equal Weighting of Events:** \( \leq 2 \) records per event
- **Strong Ground Shaking:** \( \text{PGA} > 0.2g / \text{PGV} > 15 \text{ cm/sec} \)
- **Source Type:** Both Strike-Slip and Thrust Fault Sources
- **Site Conditions:** Rock or Stiff Soil Sites, \( \text{Vs} > 180 \text{ m/s} \)
Technical Approach of the Methodology

- Conceptual Framework – Methodology incorporates cutting edge (nonlinear/probabilistic) performance-based analysis methods while remaining true to the basic concepts and definitions of seismic performance factors of ASCE 7-05 and the NEHRP Provisions (e.g., global pushover concept as described in the Commentary of FEMA 450)

\[ V = C_s W \]

ASCE 7-05/NEHRP Design Provisions (e.g., base shear)

Performance-Based Analysis Methods
- Probabilistic Collapse Fragility
- Nonlinear (Incremental) Dynamic Analysis
Overview of the Methodology
**Notional Flowchart of Process**

1. **Develop Test Data**
2. **Develop Design Rules**
3. **Define Archetypes**
4. **Develop Archetype Models**
5. **Analyze Archetype Models**
6. **Evaluate System Performance**
   - **P[Collapse] < Limit**
     - **Yes**
       - **Review and Documentation**
     - **No**
       - **Yes**
         - **Trial value of the \( R \) factor acceptable?**
       - **No**
         - **Peer Review applies to total process**

**Notes**
- "Homework" phase
- Characterize System Behavior
- Design archetypes (w/trial of \( R \) Factor)
- Perform Pushover and NDA
- Evaluate CMR values (and overstrength)
Notional Collapse Fragility – One Data Point

Evaluation of an individual structure (one configuration/set of performance properties) to failure using one ground motion record scaled to effect incipient collapse.
Robust analytical models of building configuration/performance properties evaluated with representative earthquake records
Notional Collapse Fragility

36 records

Sa_g.m. (T=1.0s)[g] vs. Maximum Interstory Drift Ratio
Notional Collapse Fragility

- Order collapse data from least to greatest
- Plot as a cumulative distribution function
  - Probability versus collapse intensity
Notional Collapse Fragility Curve

- 50% probability of collapse at $S_{CT} = 1.6g$
- 10% probability of collapse at $S_{CT} = 0.9g$ ($S_{MT}$)
- Acceptably low probability of collapse given MCE spectral acceleration

Collapse Margin Ratio

$CMR = 1.6g / 0.9g$
Performance Evaluation

• Simply…
  ✓ Verify that calculated \( CMR < \) acceptable \( CMR \)

• But…
  ✓ What is an acceptable probability of collapse?
  ✓ How many data points are enough?
  ✓ What is an appropriate analytical model?
  ✓ How do we address uncertainty?
    • Ground motion, Design, Modeling, Testing
Illustrative Example
Example – RC SMF System

- Develop Test Data
- Develop Design Rules
- Define Archetypes
- Develop Archetype Models
- Analyze Archetype Models
- Evaluate System Performance

- P[Collapse] < Limit
- Yes

- Review and Documentation

- Reinforced Concrete Special Moment Frame System
System Conception

Typical Frame Members
- Beams: 32” to 40” deep
- Columns: 24”x28” to 30”x40”

Governing Design Parameters
- Beams: minimum strength
- Column size: joint strength
- Column strength: SCWB
- Drift: just meets limit

- Office occupancy
- Frame System
- High seismic regions
- Design Code: IBC / ACI / ASCE 7
System Configuration

Space Frame

Perimeter Frame

Bay Width (e.g., 20 or 30 feet)
System Design Space

Number of Stories

Story Height

1-story
3 bays @ 20'

2-story
3 bays @ 20'

4-story
3 bays @ 20'

8-story
3 bays @ 20'

12-story
3 bays @ 20'

20-story
3 bays @ 20'

13' (typ.)

15'
### Performance Groups Summary

<table>
<thead>
<tr>
<th>Group No.</th>
<th>Basic Configuration</th>
<th>Design Load Level</th>
<th>Period Domain</th>
<th>Number of Archetypes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Gravity</td>
<td>Seismic</td>
<td></td>
</tr>
<tr>
<td>PG-1</td>
<td>Basic</td>
<td>Max SDC</td>
<td>Short</td>
<td>≥ 3</td>
</tr>
<tr>
<td>PG-2</td>
<td>Basic</td>
<td>Max SDC</td>
<td>Long</td>
<td>≥ 3</td>
</tr>
<tr>
<td>PG-3</td>
<td>Type 1</td>
<td>High</td>
<td>Short</td>
<td>≥ 3</td>
</tr>
<tr>
<td>PG-4</td>
<td>Type 1</td>
<td>Min SDC</td>
<td>Short</td>
<td>≥ 3</td>
</tr>
<tr>
<td>PG-5</td>
<td>Type 1</td>
<td>Max SDC</td>
<td>Short</td>
<td>≥ 3</td>
</tr>
<tr>
<td>PG-6</td>
<td></td>
<td>Min SDC</td>
<td>Long</td>
<td>≥ 3</td>
</tr>
<tr>
<td>PG-7</td>
<td></td>
<td>Min SDC</td>
<td>Short</td>
<td>≥ 3</td>
</tr>
<tr>
<td>PG-8</td>
<td></td>
<td>Min SDC</td>
<td>Long</td>
<td>≥ 3</td>
</tr>
</tbody>
</table>

20-foot bays | Space frame | High seismic design

Repeat for 30-foot bays | Perimeter frame | Low seismic design
Deterioration Modes and Collapse Scenarios

1. Deterioration Modes of RC Elements
   - Shear, flexure, joint degradation

2. Building System Collapse Scenarios
   - Sidesway Collapse (SC)
   - Loss in Vertical Load Carrying Capacity (LVCC)

3. Likelihood of Collapse Scenarios
Deterioration Modes

A Flexural hinging of beam-column elements
B Column compressive failure
C Beam-column shear failure
D Joint shear failure
E Pull-out and bond-slip of rebar at connections
F Slab-column connection punching shear
Nonlinear Analysis Models

Joints with both bond-slip springs and shear springs

Column bond-slip springs

Lumped plasticity beam-columns

2D multistory model to capture likely sidesway collapse scenarios and component behavior
Concrete Hinge Model Calibration

Identify and Test Key Parameters:
- strength
- initial stiffness
- post-yield stiffness
- plastic rotation (capping) capacity
- post-capping slope
- cyclic deterioration rate

Example Data Set:
- 250+ columns (PEER database)
- flexure & flexure-shear dominant
- calibrated to median (characteristic) values
Simulation Results

36 records

Maximum Interstory Drift Ratio

\( S_{a_{g.m.}} (T=1.0s)[g] \)
Simulation Results: Collapse Modes

**Predicted by Static Pushover**

Incremental Dynamic Analysis
Simulation Results: Collapse Data

Capacity Stats.:
Median = 2.2\,g
\sigma_{LN} = 0.36

Median_{col} = 2.2\,g

MCE = 0.8 \,g
Effect of Uncertainties

FOUR CONTRIBUTORS:

1. Record-to-Record Variability ($\beta_{RTR} = 0.4$)
2. Design Requirements
3. Quality of Test Data
4. Quality of Analytical Model

$$\beta_{TOT} = \sqrt{\beta_{RTR}^2 + \beta_{DR}^2 + \beta_{TD}^2 + \beta_{MDL}^2}$$

Greater uncertainties will require larger median collapse margins to satisfy maximum collapse probability at MCE.
## Quality Ratings

### Table 3-1 Quality Rating for Design Requirements

<table>
<thead>
<tr>
<th>Completeness and Robustness</th>
<th>Confidence in Basis of Design Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
</tr>
<tr>
<td>High. Extensive safeguards against poor behavior. All important design and quality assurance issues are addressed.</td>
<td>(A) Superior</td>
</tr>
<tr>
<td>Medium. Reasonable safeguards against poor behavior. Most of the important design and quality assurance issues are addressed.</td>
<td>(B) Good</td>
</tr>
<tr>
<td>Low. Questionable safeguards against poor behavior. Many important design and quality assurance issues are not addressed.</td>
<td>(C) Fair</td>
</tr>
</tbody>
</table>
Total Collapse Uncertainty

- Design Requirements: A-Superior
- Test Data: B-Good
- Nonlinear Model: A-Superior

<table>
<thead>
<tr>
<th>Uncertainty - Quality of Test Data</th>
<th>Uncertainty - Quality of Design Requirements</th>
<th>A - Superior</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - Superior</td>
<td>A - Superior 0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>B - Good</td>
<td></td>
<td>0.65 0.80</td>
</tr>
<tr>
<td>C - Fair</td>
<td></td>
<td>0.70 0.85</td>
</tr>
<tr>
<td>D - Poor</td>
<td></td>
<td>0.80 1.00</td>
</tr>
</tbody>
</table>
Adjusted Collapse Fragility Curve

Incremental Dynamic Analysis Results

Maximum Interstory Drift Ratio

Sa,g.m. (T=1.0s) [g]

Cummulative Probability of Collapse

Empirical CDF
Lognormal CDF (RTR Var.)
Lognormal CDF (RTR + Modeling Var.)

Median = 2.2g
σ_{LN, Total} = 0.36

MCE = 0.8g

CMR = ??
<table>
<thead>
<tr>
<th>Total System Collapse Uncertainty</th>
<th>5%</th>
<th>10% (ACMR_{10%})</th>
<th>15%</th>
<th>20% (ACMR_{20%})</th>
<th>25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.275</td>
<td>1.57</td>
<td>1.42</td>
<td>1.33</td>
<td>1.26</td>
<td>1.20</td>
</tr>
<tr>
<td>0.300</td>
<td>1.64</td>
<td>1.47</td>
<td>1.36</td>
<td>1.29</td>
<td>1.22</td>
</tr>
<tr>
<td>0.500</td>
<td>2.28</td>
<td>1.90</td>
<td>1.68</td>
<td>1.52</td>
<td>1.40</td>
</tr>
<tr>
<td>0.525</td>
<td>2.37</td>
<td>1.96</td>
<td>1.72</td>
<td>1.56</td>
<td>1.42</td>
</tr>
<tr>
<td>0.550</td>
<td>2.47</td>
<td>2.02</td>
<td>1.77</td>
<td>1.59</td>
<td>1.45</td>
</tr>
<tr>
<td>0.575</td>
<td>2.57</td>
<td>2.09</td>
<td>1.81</td>
<td>1.62</td>
<td>1.47</td>
</tr>
</tbody>
</table>

On average per performance group

For any one archetype

ATC-63 Quantification of Building System Performance and Response Parameters
### Example Results – RC SMF System

<table>
<thead>
<tr>
<th>Design Configuration</th>
<th>Computed Collapse Margin</th>
<th>Acceptance Check</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Static $\Omega$</td>
<td>$CMR$</td>
</tr>
<tr>
<td>2069</td>
<td>1.6</td>
<td>1.18</td>
</tr>
<tr>
<td>2064</td>
<td>1.8</td>
<td>1.50</td>
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<tr>
<td>1003</td>
<td>1.6</td>
<td>1.61</td>
</tr>
<tr>
<td>1011</td>
<td>1.6</td>
<td>1.25</td>
</tr>
<tr>
<td>1013</td>
<td>1.7</td>
<td>1.45</td>
</tr>
<tr>
<td>1020</td>
<td>1.6</td>
<td>1.66</td>
</tr>
<tr>
<td>Mean/Acceptable:</td>
<td>1.7</td>
<td>--</td>
</tr>
</tbody>
</table>

### Maximum Seismic ($D_{max}$) and Low Gravity (Perimeter Frame) Designs, 20’ Bay Width

<table>
<thead>
<tr>
<th>Design Configuration</th>
<th>Computed Collapse Margin</th>
<th>Acceptance Check</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Static $\Omega$</td>
<td>$CMR$</td>
</tr>
<tr>
<td>2061</td>
<td>4.0</td>
<td>1.96</td>
</tr>
<tr>
<td>1001</td>
<td>3.5</td>
<td>2.06</td>
</tr>
<tr>
<td>1008</td>
<td>2.7</td>
<td>1.78</td>
</tr>
<tr>
<td>1012</td>
<td>2.3</td>
<td>1.63</td>
</tr>
<tr>
<td>1014</td>
<td>2.1</td>
<td>1.59</td>
</tr>
<tr>
<td>1021</td>
<td>2.0</td>
<td>1.98</td>
</tr>
<tr>
<td>Mean/Acceptable:</td>
<td>2.8</td>
<td>--</td>
</tr>
</tbody>
</table>

### Maximum Seismic ($D_{max}$) and High Gravity (Space Frame) Designs, 20’ Bay Width
RC SMF Example - Conclusions

- A value of R=8 provides an acceptable level of collapse safety
- The Methodology is reasonably well-calibrated to current design provisions
  - RC SMF systems didn’t fail miserably
  - RC SMF systems didn’t pass easily
- This was true of all systems tested
**Peer Review Considerations**

- Implementation involves:
  - Uncertainty
  - Judgment
  - Potential for variation
- Peer Review is critical for:
  - Testing
  - Archetype development
  - Analytical modeling
  - Quality rating assessment
Observations and Findings
Observations and Findings

• Methodology was developed considering:
  ✔ special concrete moment frames
  ✔ ordinary concrete moment frames
  ✔ special steel moment frames
  ✔ wood shear walls

• Some trends in our current design process have become apparent…
Observations and Findings

- Performance assessment is a difficult challenge fraught with much uncertainty.
- Buildings located in the near-field have higher collapse probabilities.
- Short period buildings have higher collapse probabilities.
- Collapse performance varies by Seismic Design Category.
- Secondary systems influence collapse capacity.
- There is no practical difference in performance between $R=6$ and $R=6.5$. 
Summary

- Recommended Methodology provides a rational basis for establishing global seismic performance factors (e.g., $R$ factors)
- Intended to support and improve Seismic Codes:
  - Adoption of new systems that must be assigned values of seismic performance factors
  - Improvement of current values of seismic performance factors of existing systems
  - Collapse evaluation of a specific building designed using alternative “performance-based” methods (App. F)
- FEMA P-695 is now available online and in print
Thank you!