Overall Procedure of Performance-based Design

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Performance-based Structural Design of Tall Buildings
Designing for Safer Infrastructure
Innovative design that goes beyond the codes

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PERFORMANCE BASED-SEISMIC DESIGN

- More common in design of high-rise buildings in western United States.
- To substantiate exceptions to specific prescribed code requirements.
- To demonstrate higher performance levels for a structure.
- An integral component is nonlinear response history analysis.
- Involves significantly more effort in the analysis and design stages.
- Use of seismic force-resisting systems and Innovative designs not prescribed by code.
REQUIRED INFORMATION

**Basis of design**
- Description of building, structural system
- Codes, standards and references
- Loading criteria
- Materials
- Modeling, analysis and design procedures
- Performance objectives and acceptance criteria

**Geotechnical investigation**
- SPT values
- Soil stratification and properties
- Soil type for seismic loading
- Allowable bearing capacity
- Sub-grade modulus
- Liquefaction potential
- Basement wall pressure

**Site-specific probabilistic seismic assessment**
- Earthquake hazard determination
- Ground motion characterizations
- Recommended spectra (SLE, DBE, and MCE)

**Wind tunnel test**
- 10-year return period wind load
- 50-year or 700-year return period wind load
- Floor accelerations (1-year, 5-year return periods)
- Rotational velocity (1-year return period)
- Natural frequency sensitivity study
PERFORMANCE-BASED DESIGN PROCEDURE

- Preliminary design
- Wind tunnel test
- Detailed code-based design
- SLE Evaluation
- MCE Evaluation
- Peer review

• Geotechnical investigation
• Probabilistic seismic hazard assessment
## Performance Objectives

<table>
<thead>
<tr>
<th>Level of Earthquake</th>
<th>Seismic Performance Objective</th>
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<tbody>
<tr>
<td><strong>Service Level Earthquake</strong> <em>(SLE)</em>: 50% probability of exceedance in 30 years (43-year return period), 2.5% of structural damping</td>
<td><strong>Serviceability</strong>: Structure to remain essentially elastic with minor yielding of structural elements, minor cracking of concrete, and minor damage to non-structural elements.</td>
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<tr>
<td><strong>Maximum Considered Earthquake</strong> <em>(MCE)</em>: 2% probability of exceedance in 50 years (2475-year return period)</td>
<td><strong>Collapse Prevention</strong>: Structure has a low probability of collapse which will be demonstrated implicitly through analyses that indicate the structure has stable, predictable response to MCE\textsubscript{R} shaking at response levels which do not result in loss of gravity load carrying capacity or substantial degradation of lateral resistance. Extensive structural damage may occur; repairs to structural and non-structural systems are required and may not be economically feasible.</td>
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Preliminary design

**Structural system development**
- Bearing wall system
- Dual system
- Special moment resisting frame
- Intermediate moment resisting frame

**Finite element modeling**
- Linear analysis models
- Different stiffness assumptions for seismic and wind loadings

**Check overall response**
- **Modal analysis**
  - Natural period, mode shapes, modal participating mass ratios
- **Gravity load response**
  - Building weight per floor area
  - Deflections
- **Lateral load response (DBE, Wind)**
  - Base shear, story drift, displacement

**Preliminary member sizing**
- Structural density ratios
- Slab thickness
- Shear wall thickness
- Coupling beam sizes
- Column sizes
Modeling

- Either nominal or expected material properties are used based on strength and service level design
- Different cracked section properties for wind and seismic models
- P-delta effects
- Rigid zones and end-length offsets

Wind design

- Apply wind loads from wind tunnel test in mathematical model
- Ultimate strength design
  - 50-year return period wind load x Load factor
  - 700-year return period wind load
- Serviceability check
  - Story drift $\leq 0.4\%$
  - Lateral displacement $\leq H/400$ (10-year return period wind load)
- Floor acceleration (1-year and 5-year return period wind load)

Seismic design

- Use recommended design spectra of DBE from PSHA
- Apply seismic load in principal directions of the building
- Scaling of base shear from response spectrum analysis
- Consider accidental torsion, directional and orthogonal effects
- 5% of critical damping is used for un-modeled energy dissipation
- Design and detail reinforcement
## Expected Material Strengths

<table>
<thead>
<tr>
<th>Material</th>
<th>Expected Yield Strength, $f_{ye}$, ksi</th>
<th>Expected Ultimate Strength, $f_{ue}$, ksi</th>
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<tbody>
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<td><strong>Reinforcing Steel</strong></td>
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<tr>
<td>A615 Grade 60</td>
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<td>A615 Grade 75</td>
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<td>A706 Grade 60</td>
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<td><strong>Structural Steel</strong>*</td>
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<tr>
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<td>$1.2 f_u^{**}$</td>
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<tr>
<td>ASTM A913/A913M Grade 50, 60, 65 or 70</td>
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<td><strong>Plates</strong></td>
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<tr>
<td>$f'_{ce}$</td>
<td>$1.3 f'_{c}$</td>
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Source: LATBSDC 2017
<table>
<thead>
<tr>
<th>Component</th>
<th>SLE/Wind (Strength)</th>
<th>SLE/Wind (Service)</th>
<th>DBE</th>
<th>MCE</th>
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<tbody>
<tr>
<td>Structural walls (in-plane)</td>
<td>Flexural – 0.75 $E_c I_g$</td>
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<td>Flexural – 0.07(l/h)($E_c I_g$) $\leq 0.3E_c I_g$</td>
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<tr>
<td>Non-PT transfer diaphragms</td>
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<td>Shear – 1.0 $G_c A_g$</td>
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<td>PT slab (out-of-plane)</td>
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<td>Girders</td>
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<td>Flexural – 0.35 $E_c I_g$</td>
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</table>
DAMPING

Fraction of Critical Damping, $\zeta_{critical}$

$\zeta_{critical} = \frac{0.36}{\sqrt{H}} \leq 0.05$, $H$ in ft

Height of Roof Above Grade (ft)

Height of Roof Above Grade (m)

Source: TBI Ver. 2.03
Deformation-controlled Actions

• Behavior is ductile and reliable inelastic deformations can be reached with no substantial strength loss.
• Results are checked for mean value of demand from seven sets of ground motion records.

Source: ASCE/SEI 41-17
- Behavior is more brittle and reliable inelastic deformations cannot be reached.
  - **Critical action**
    - Failure of which is likely to lead to partial or total structural collapse.
  - **Ordinary action**
    - Failure of which is either unlikely to lead to structural collapse or might lead to local collapse comprising not more than one bay in a single story.

**Force-deformation relationship for force-controlled actions**

Source: ASCE/SEI 41-17
<table>
<thead>
<tr>
<th>Component</th>
<th>Action</th>
<th>Classification</th>
<th>Criticality</th>
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</thead>
<tbody>
<tr>
<td>Shear walls</td>
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<td>Coupling beams (Conventional)</td>
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<td>Coupling beams (Diagonal)</td>
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<td>Force-controlled</td>
<td>Critical</td>
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</tbody>
</table>
Acceptance Criteria

- Member strength
  - $D/C \leq 1.5$ (Deformation-controlled)
  - $D/C \leq 0.7$ (Force-controlled)
- Strength calculation
  - Use nominal material properties
  - Strength reduction factor = 1
- Story drift $\leq 0.5\%$

Modeling and Analysis

- Use linear model and response spectrum analysis.
- Accidental eccentricities are not considered in serviceability evaluation.
- 2.5% of critical damping
- Load combinations
  - $1.0D + L_{exp} \pm 1.0ESLEX \pm 0.3ESLEY$
  - $1.0D + L_{exp} \pm 0.3ESLEX \pm 1.0ESLEY$
  - $L_{exp} = $ Expected service live load which is 25% of unreduced live load
- $R$, $\Omega_0$, $\rho$, and $C_d$ are all taken as unity.

SERVICE LEVEL EARTHQUAKE EVALUATION
12.8.4.3 Amplification of Accidental Torsional Moment. Structures assigned to Seismic Design Category C, D, E, or F, where Type 1a or 1b torsional irregularity exists as defined in Table 12.3-1 shall have the effects accounted for by multiplying $M_{1a}$ at each level by a torsional amplification factor ($A_x$) as illustrated in Fig. 12.8-1 and determined from the following equation:

$$A_x = \left(\frac{\delta_{\text{max}}}{1.2\delta_{\text{avg}}}\right)^2$$  \hfill (12.8-14)

where

$\delta_{\text{max}}$ = maximum displacement at level $x$ computed assuming $A_x = 1$ [in. (mm)], and

$\delta_{\text{avg}}$ = average of the displacements at the extreme points of the structure at level $x$ computed assuming $A_x = 1$ [in. (mm)].

The torsional amplification factor ($A_x$) shall not be less than 1 and is not required to exceed 3.0. The more severe loading for each element shall be considered for design.
3.5.4. Evaluation of Effects of Accidental Torsion [LATBSDC 2017]

Accidental eccentricities need not be considered for serviceability evaluation. However, regardless of the analysis method used for serviceability evaluation, the torsional amplification factor, $A_X$, as defined in Section 12.8.4.3 of ASCE 7 shall be calculated for each floor, $x$. If the value of $A_X$ exceeds 1.50 for any floor, then accidental eccentricity shall be considered during Collapse Prevention evaluations.

6.2.2 Torsion Sensitivity Check [TBI Ver. 2.03]

Conduct analysis of a linear model of the building to check susceptibility of the building to accidental torsion effects. For this purpose, the following steps are recommended:

- Establish a linear structural analysis model in accordance with the recommendations of Section 4.3 of these Guidelines.
- Conduct analysis in accordance with the Equivalent Lateral Force Procedure or the Modal Response Spectrum Procedure of ASCE 7 Chapter 12 using seismic shaking demands as represented by the SLE evaluation response spectrum.
- Calculate floor level displacements considering inherent torsional moment, $M_t$, and, separately, including inherent torsional moment plus accidental torsional moment, $M_{t+a}$, caused by assumed displacement of the center of mass each way from its actual location by a distance equal to 5% of the dimension of the structure perpendicular to the direction of the applied forces. Where earthquake forces are applied concurrently in two orthogonal directions, the required 5% displacement of the center-of-mass need not be applied in both of the orthogonal directions at the same time, but shall be applied in the direction that produces the greater effect.
- Calculate a twisting index $A_t^x = (\delta_{max,t}/\delta_{max})$ where $\delta_{max,t}$ = the maximum displacement at Level $x$ computed considering inherent torsion, and $\delta_{max,fa}$ = the maximum displacement at Level $x$ computed considering inherent plus accidental torsion.
- Where the calculated value of $A_t^x$ exceeds 1.2 at any level, consider effects of accidental torsion in nonlinear dynamic analyses carried out as part of the MCER evaluation.
MCE Evaluation

• Use nonlinear model and nonlinear response history analysis.
• Eleven pairs of site-specific ground motions are used.
• Generally, 2.5% of constant modal damping is used with small fraction of Rayleigh damping for un-modeled energy dissipation.
• Average of demands from eleven ground motions approach is used.
• Capacities are calculated using expected material properties and strength reduction factor of 1.0 for deformation-controlled actions.
MATERIAL NONLINEARITY

Concrete stress-strain curves

- Unconfined
- Fully confined
Unacceptable Response to MCE Evaluation

• Analytical solution fails to converge.
• Predicted demands on deformation-controlled or force-controlled elements exceed the valid range of modeling.
• 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.
Acceptance Criteria (Force-controlled Actions)

Critical Actions

\[ 1.0 I_e Q_{NS} + 1.3 I_e (Q_T - Q_{NS}) \leq \phi_s BR_n \]  
(a)

\[ 1.0 I_e Q_{NS} + 1.5 I_e (Q_T - Q_{NS}) \leq \phi_s BR_{nem} \]  
(b)

Ordinary Actions

\[ 1.0 I_e Q_{NS} + 0.9 I_e (Q_T - Q_{NS}) \leq \phi_s BR_n \]  
(c)

\[ 1.0 I_e Q_{NS} + 1.0 I_e (Q_T - Q_{NS}) \leq \phi_s BR_{nem} \]  
(d)
Acceptance Criteria (Force-controlled Actions)

$I_e = \text{Seismic importance factor appropriate to the Risk Category as defined in ASCE 7}$

$Q_T = \text{Mean of the maximum values of the action calculated for each ground motion}$

$Q_{NS} = \text{Non-seismic portion of } Q_T$

$B = \text{Factor to account for conservatism in nominal resistance } R_n, \text{ normally taken as having a value of 1.0. Alternatively, it can be taken as } 0.9 \left(\frac{R_{ne}}{R_n}\right) \text{ for Eq. 4a and 4c and } \left(\frac{R_{ne}}{R_{nem}}\right) \text{ for Eq. 4b and 4d.}$

$R_n = \text{Nominal strength of the force-controlled action, in accordance with the applicable material standard}$

$\varnothing_s = \text{Resistance factor}$

$R_{nem} = \text{Nominal strength for the action, determined in accordance with the applicable material standard using expected material properties}$

$R_{ne} = \text{Expected value of component resistance determined from test results using expected material properties}$
<table>
<thead>
<tr>
<th>Action Type</th>
<th>$\phi_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical force-controlled element</td>
<td>$\phi$ as specified in the applicable material standard</td>
</tr>
<tr>
<td>Ordinary force-controlled element</td>
<td>0.9</td>
</tr>
<tr>
<td>Item</td>
<td>Value</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------</td>
</tr>
<tr>
<td>Peak transient drift</td>
<td>Maximum of mean values shall not exceed 3%.</td>
</tr>
<tr>
<td></td>
<td>Maximum drift shall not exceed 4.5%.</td>
</tr>
<tr>
<td>Residual drift</td>
<td>Maximum of mean values shall not exceed 1%.</td>
</tr>
<tr>
<td></td>
<td>Maximum drift shall not exceed 1.5%.</td>
</tr>
<tr>
<td>Coupling beam inelastic rotation</td>
<td>$\leq$ASCE 41-17 limits</td>
</tr>
<tr>
<td>Column (Axial-flexural interaction and shear)</td>
<td>Flexural rotation $\leq$ASCE 41-17 limits</td>
</tr>
<tr>
<td></td>
<td>Remain elastic for shear response.</td>
</tr>
<tr>
<td>Shear wall reinforcement axial strain</td>
<td>$\leq$0.05 in tension and $\leq$0.02 in compression</td>
</tr>
<tr>
<td>Shear wall concrete axial compressive strain</td>
<td>Unconfined concrete $\leq$ 0.003</td>
</tr>
<tr>
<td></td>
<td>Intermediately confined concrete $\leq$ 0.004 + 0.1 $\rho \left( \frac{f_y}{f'_c} \right)$</td>
</tr>
<tr>
<td></td>
<td>Fully confined concrete $\leq$ 0.015</td>
</tr>
<tr>
<td>Shear wall shear</td>
<td>Remain elastic</td>
</tr>
<tr>
<td>Girder inelastic rotation</td>
<td>$\leq$ASCE 41-17 limits</td>
</tr>
<tr>
<td>Girders shear</td>
<td>Remain elastic</td>
</tr>
<tr>
<td>Mat foundation (Flexure and shear)</td>
<td>Remain elastic</td>
</tr>
<tr>
<td>Diaphragm (In-plane response)</td>
<td>Remain elastic</td>
</tr>
<tr>
<td>Piles (Axial-flexural interaction and shear)</td>
<td>Remain elastic</td>
</tr>
</tbody>
</table>
BOUNDING THE RESULTS
Upper bound stiffness modifier = 0.35
Lower bound stiffness modifier = 0.1
Evaluation of Analysis Results

• Results extraction, processing and converting them into presentable form takes additional time.

• Results interpretation i.e. converting “numbers we have already crunched” into “meaningful outcome for decision-making”.
Base Shear

![Chart showing base shear values for different scenarios.](chart.png)
Transient Drift

Story level

Drift ratio
Lateral Displacement

Story level vs. Lateral displacement (m)
Floor Acceleration

Absolute acceleration (g)

Story level
Energy Dissipation

- Total dissipated energy
- Dissipated energy from shear walls
- Dissipated energy from conventional reinforced coupling beams
- Total dissipated energy
- Dissipated energy from diagonal reinforced coupling beams
Shear Walls

- Flexure deformation
- Axial strain
- Shear capacity
Coupling Beams

- Conventional reinforced coupling beams
  - Flexural rotation (Deformation-controlled)
  - Shear (Critical force-controlled)
- Diagonal reinforced coupling beams
  - Shear deformation (Deformation-controlled)
Moment Frames

• Beams
  • Flexural rotation
  • Shear capacity

• Columns
  • Axial capacity
  • Axial-flexure rotation (Deformation-controlled)
  • Shear capacity
Flat Slab (Slab-column connections)

- Flexural rotation
- Punching shear
Diaphragms

- Collector, shear friction
- Chord
- Axial, shear
Mat Foundation

- Bearing capacity
- Flexure capacity
- Shear capacity
Basement Walls

- Flexure capacity
- Shear capacity
  - In-plane
  - Out-of-plane
Peer Review

• Helps develop confidence in design and encourages knowledge-sharing between peer reviewer and EOR.
• Exchange of ideas has led to a significant enhancement in the body of knowledge for firms practicing PBD.
• Involve as early in the structural design phase
• Establish the frequency and timing of peer review milestones
Peer Review Scope

• Earthquake hazard determination
• Ground motion characterizations
• Seismic design methodology
• Seismic performance goals
• Acceptance criteria
• Mathematical modeling and simulation
• Seismic design and results, drawings and specifications
Peer Review

• Peer reviewer provides written comments to EOR
• EOR shall provide written responses
• Peer review maintains the log that summarizes reviewer’s comments, EOR responses to comments, and resolution of comments
• At the conclusion of the review, peer reviewer shall submit the references the scope of the review, includes the comment log, and indicates the professional opinions of the peer reviewer regarding the design’s general conformance to the requirements and guidelines in this document
Thank you.