Structural Performance

performance issues relative to extreme events

Performance-Based Seismic Design of Tall Buildings

Why & How?

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Driven by a passion for innovation and seeking freedom from prescriptive code requirements, Structural Engineers found in the Performance-Based Seismic Design (PBSD) approach a perfect tool box. PBSD is not a new idea, but its application to newly constructed towers is out-of-the-ordinary. Experiences from designs and peer reviews of high-rise buildings in active seismic zones designed over the past decade have clearly shown that the PBSD approach, in lieu of a prescriptive code, significantly enhances not only the safety but also the economics of these mega structures.

This article introduces the general concept of PBSD and answers specific questions: Why should I consider PBSD in lieu of code-based seismic design? Do building codes allow for PBSD? Are there unique features in tall buildings when it comes to earthquake response? What are the available guidelines for PBSD of tall buildings?

What is PBSD?

Performance-based seismic design allows the design team to choose and then explicitly verify a building's seismic performance under different intensities of earthquake shaking. Much of the framework for PBSD in the US can be traced to work in the 1990s, such as Vision 2000 (SEAOC, 1995), ATC 40 (ATC, 1996), FEMA 273 and FEMA 356 (currently ASCE 41-06).

To perform PBSD, you need to do the following:

1) Select return periods for earthquake intensities and corresponding performance levels;
2) Work with a geotechnical engineer to develop site-specific ground motion corresponding to selected return periods;
3) Subject the mathematical model to ground shaking and estimate structural response quantities (inter-story drift, floor accelerations, deformation demands on ductile elements, force demands on non-ductile elements, etc.) for each level of earthquake intensity;
4) Evaluate global and element performance based on acceptance criteria that reflect selected performance objectives.

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Typical performance goals for a tall building, expected from the building code but not actually evaluated, are:

(a) Minor damage under frequent earthquakes, allowing immediate occupancy after inspection
(b) Low probability of collapse under very rare earthquakes.

These objectives can be enhanced if stakeholders desire.

Why PBSD in lieu of CBSD?

- PBSD is a significant improvement over code-based seismic design (CBSD) as it provides the design team and the stakeholders with greater understanding of the building's likely performance at different levels of seismic events.
- PBSD accommodates architectural features that may not be possible with prescriptive requirements.
- PBSD allows for innovative structural systems and materials that are not codified, resulting in more cost efficient lateral systems.
- PBSD produces safer and more serviceable buildings when compared to CBSD designs.

Do Building Codes allow PBSD?

Codes have traditionally permitted the use of alternative analysis and design methods, provided that these methods follow well-established principles of mechanics and/or are backed up with test results. The following are excerpts from current and proposed building codes:

Section 104.11 of 2009 and 2012 IBC

"The provisions of this code are not intended to prevent the installation of any material or to prohibit any design or method of construction not specifically prescribed by this code, provided that any such alternative has been approved. An

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alternative material, design or method of construction shall be approved where the building official finds that the proposed design is satisfactory and complies with the intent of the provisions of this code, and that the material, method or work offered is, for the purpose intended, at least the equivalent of that prescribed in this code in quality, strength, effectiveness, fire resistance, durability and safety."

Section 12.6 of ASCE 7-05

"The structural analysis required by Chapter 12 shall consist of one of the types permitted in Table 12.6.1, based on the structure's seismic design category, structural system, dynamic properties, and regularity, or with the approval of the authority having jurisdiction, an alternative generally accepted procedure is permitted to be used."

Section 1.3 of ASCE 7-10

1.3.1 Strength and stiffness. "Buildings and other structures, and all parts thereof, shall be designed and constructed with adequate strength and stiffness to provide structural stability, protect nonstructural components and systems from unacceptable damage and meet the serviceability requirements of Section 1.3.2. Acceptable strength shall be demonstrated using one or more of the following procedures:

a. the Strength Procedures of Section 1.3.1.1
b. the Allowable Stress Procedures of Section 1.3.1.2; or
c. subject to the approval of the authority having jurisdiction for individual projects, the Performance-based Procedures of Section 1.3.1.3."

1.3.1.3 Performance-based Procedures. "Structural and nonstructural components and their connections shall be demonstrated by analysis or by a combination of analysis and testing to provide a reliability not less than that expected for similar components designed in accordance with the Strength Procedures of Section 1.3.1.1 when subject to the influence of dead, live, environmental and other loads. Consideration shall be given to uncertainties in loading and resistance."

1.3.1.3.1 Analysis. "Analysis shall employ rational methods based on accepted principles of engineering mechanics and shall consider all significant sources of deformation and resistance. Assumptions of stiffness, strength, damping and other properties of components and connections incorporated in the analysis shall be based on approved test data or referenced Standards."

PBSD for Tall Buildings Versus Low- and Medium-rise Buildings?

- Higher modes in tall building are significantly excited by ground shaking, while low- and medium-rise respond primarily in the fundamental mode.
- Inter-story drift in a high-rise is the result of two components, namely: rigid body displacement and racking (shear) deformations. In low- to medium-rise buildings, inter-story drift is dominated by shear deformations.
- Specific to tall buildings:
  - Large shear demand near the base due to significant contributions from higher modes
  - Reduced ductility due to large gravity axial demands on vertical elements
  - Minimum stiffness is often controlled by wind serviceability
  - Strength at the base may be controlled by wind survivability
  - Capacity-based design principles are less valid when forces need to be summed up over multiple elements
  - At long periods, the reliability of ground motion prediction and the availability of earthquake records are less

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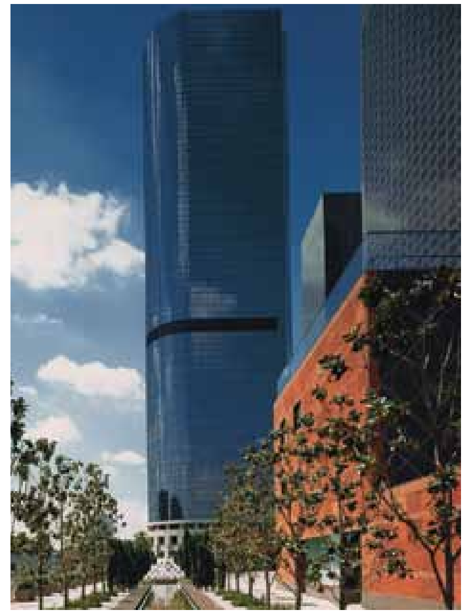

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Comparison of Current Guidelines

- **LATBSDC**: The first US consensus document was published in 2005 by the Los Angeles Tall Building Structural Design Council (LATBSDC) in response to the residential tall building boom in Southern California. This document, *An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region*, was significantly revised in 2008 and reached the current form in 2011 (3rd edition). This document strikes a good balance between completeness and conciseness.

- **AB-83**: Faced by a number of tall building designs seeking code exceptions (mainly height limits and minimum base shear), the City of San Francisco requested the Structural Engineering Association of Northern California (SEAONC) to customize the LATBSDC's first edition to suit local use. These efforts resulted in the publication of the *Recommend Administrative Bulletin on the Seismic Design & Review of Tall Buildings Using Non-Prescriptive Procedures* in April 2007. This document was adopted by the City of San Francisco as AB-83. This Bulletin is strongly tied to the Building Code with a minimum design base shear requirement.
- **PEER**: Parallel to LATBSDC and SEAONC efforts, the Pacific Earthquake Research Center (PEER) at the University of California Berkeley embarked on a four-year Tall Building Initiative that resulted in the publication of *Guidelines for Performance-Based Seismic Design of Tall Buildings* in 2010, and a number of task reports such as ATC 72 (2010).
- **CTBUH**: The Council of Tall Building and Urban Habitat summarized the best current and emerging practices worldwide in *Recommendations for the Seismic Design of High-rise Buildings* that tend to frame issues of importance and were published in 2008.

The comprehensive comparison of these four guidelines can be found on the following page.

Ten Commandments for PBSD of Tall Buildings

1) Meet with the Building Officials – the design team needs to ascertain that the local jurisdiction would accept PBSD;
2) Develop a detailed design criteria – keep it alive throughout the project;
3) Ensure the structure has enough stiffness and strength for wind serviceability and survivability – this defines lower-bounds;
4) Ground motion developed and peer reviewed as early as possible;
5) Identify seismic fuses and detail them for ductility – this is the most important commandment;
6) Design for seismic serviceability in order to size deformation-controlled actions;
7) Perform capacity based design in order to size force-controlled actions;
8) Engage the peer review panel – the sooner you get their feedback, the faster the design progresses;
9) Test design for Collapse Prevention, and plan for at least one design iteration;
10) Document the design – a key to successful PBSD.

What will the Next Generation PBSD Look Like?

- *Holistic* – not limited to structural elements but rather includes all Architectural, Mechanical, Electrical, Plumbing, etc. elements
- *Measurable in 3Ds* – damage (dollars), downtime (loss of occupancy) and death (injuries, fatalities)
- *Probabilistic* – triple integral including earthquake intensities, demand parameters and damage measures▪

PBSD Guidelines – General Comparison

	AB-83	CTBUH	PEER	LATBSDC
Year of Publication	2007	2008	2010	2011
Adoption	City of San Francisco	None	West Cost of the United States	City of Los Angeles
Applicability	Height > 160 ft	Height > 164 ft (50 m)	-Fundamental Period >> 1 second -Significant mass participation in higher modes -Significant portion of lateral drift due to axial shortening	Height > 160 ft
Performance Objectives	At least equivalent to the 2001 City of San Francisco Building Code (SFBC-01)	-Negligible damage for earthquake shaking demands having a return period of about 50 years -Collapse prevention under the largest earthquake shaking expected	Occupancy Category II buildings intended by ASCE 7 which entails: -Limited damage under Frequent Earthquakes -No significant hazard under design earthquake (2/3 MCE) - Low Probability of Collapse (~10%) under Maximum Considered Earthquake (MCE)	- Serviceable under Frequent Earthquakes - Low Probability of Collapse under Extremely Rare Earthquakes
Code Level Design	Required (exceptions allowed)	Not required	Not required	Not required
Minimum Base Shear	For Strength Only	None	None	None
Capacity Design Principals	Required	Required	Required	Required
Serviceability Evaluation	Required only when serviceability performance is less than code prescriptive design	Required	Required	Required
Collapse Prevention	Required	Required	Required	Required
Peer Review	Required	Required	Required	Required
Detailed Design Criteria	Required	Required	Required	Required
Guidance on Sizing Elements	Code-Level Force for sizing DCA	Not provided	Provided	Not provided
Wind Demands	Not mentioned	Discussed	Discussed	Not mentioned
Non-linear component Modeling & Acceptance Criteria	Applicable Documents or Laboratory tests or analyses	ASCE 41-06 or Laboratory tests Or First principles Engineering Mechanics	ASCE 41-06 or ATC 72-10	ASCE 41-06
Force-Controlled Actions (FCA)	Not provided	Not provided	Provided	Provided
Deformation-Controlled Actions (DCA)	Not provided	Not provided	Provided	Provided
Instrumentation	No requirements	Encouraged	No requirements	Required
Published Case Studies	No	No	Yes	Yes
Unique Features		-Discussion on inherent damping - Guidance on performance assessment in regions of low seismic hazard	-Detailed Modeling Guidelines (ATC-72) -Design documentation - Discussions on ground motion development	-Additional RC detailing requirements -High Strength Concrete Quality Control requirements

PBSD Guidelines – Serviceability Evaluation

		AB-83	CTBUH	PEER	LATBSDC
Performance Objective		Immediate Occupancy	Immediate Occupancy	Immediate Occupancy	Immediate Occupancy
Earthquake Shaking	**Return Period**	43 yrs	30-72 yrs	43 yrs	43 yrs
Earthquake Shaking	**Damping Level**	Not provided	1-2% for buildings between 50 & 250 m tall	2.5%	2.5% Maximum
Earthquake Shaking	**Directionality**	Not mentioned	Maximum/Minimum Rotated Component	Not mentioned	Geometric Mean
Modeling & Analysis	**Analysis Type**	Linear Response Spectrum OR Non-linear Response History Analysis	Linear Response Spectrum OR Linear Response History Analysis	Linear Response Spectrum OR Non-linear Response History Analysis	Linear Response Spectrum OR Non-linear Response History Analysis
Modeling & Analysis	**Material Properties for Stiffness**	Specified	Not mentioned	Expected	Expected
Modeling & Analysis	**Effective Stiffness**	No specific recommendation	No specific recommendation	Modifiers Provided	Modifiers Provided
Modeling & Analysis	**Modeling of Gravity Elements**	Not mentioned	Required for Reinforced Concrete Construction	Required only if significantly contribute to stiffness or experience significant stress	Required only if significantly contribute to global or local stiffness
Modeling & Analysis	**P-Delta**	Not mentioned	Required	Required	Required
Modeling & Analysis	**Response Spectrum Analysis**	Not provided	CQC with minimum 90% mass participation	CQC with minimum 90% mass participation	CQC with minimum 90% mass participation
Modeling & Analysis	**Earthquake Loading (E) – Response Spectrum Analysis**	Not provided	Using Maximum Spectra only: -100% Ex + 30% Ey -100% Ey + 30% Ex OR Using Maximum & Minimum: -Ex (Max)+Ey (Min) -Ex (Min)+Ey (Max)	-100% Ex + 30% Ey -100% Ey + 30% Ex	-100% Ex + 30% Ey -100% Ey + 30% Ex
Modeling & Analysis	**Earthquake Loading (E) – Response History Analysis**	Minimum of seven pairs scaled per Sec. 1631.6.1 of SFBC-01	Three pairs if matched to UHS or nine pairs if matched to suite of conditional mean spectra	-Minimum of three pairs (demand is maximum) -Seven pairs (demand is mean) scaled similar to MCE	-Minimum of three pairs (demand is maximum) -Seven pairs (demand is mean) scaled per Sec. 16.1.3 of ASCE 7-05
Modeling & Analysis	**Non-linear Dynamic Response Analyses**	Not provided	N/A	Use same mathematical model as Collapse Prevention	Use same mathematical model as Collapse Prevention
Modeling & Analysis	**Accidental Torsion**	Not mentioned	Not Required	Not Required	If A_x > 1.5, consider accidental torsion in Collapse Prevention Evaluation
Modeling & Analysis	**Expected Live Load (L_{exp})**	Not provided	Not mentioned	0.25 L	0.25 L
Modeling & Analysis	**Load Combinations**	D + L_{exp} + E	-For Response Spectra: Factored Gravity + E -For linear Response History: Unfactored Gravity + E	D + L_{exp} + E	D + L_{exp} + E
Soil-Structure Interaction	**Modeling**	Not mentioned	Rigid "Bathtub" model (stiffness & full mass)	-Requires modeling the subterranean structure (stiffness & partial mass)	Requires modeling the subterranean structure (stiffness only)
Soil-Structure Interaction	**Kinematic Interaction**	Not mentioned	Modified for kinematic interaction	Free field	Free field Or Modified for kinematic interaction

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PBSD Guidelines – Serviceability Evaluation. (continued from previous page).

Acceptance Criteria	**Inter-story Drift Limit**	No limit provided	No limit provided	0.5%	0.5%
	Residual Inter-story Drift Limit	No limit provided	No limit provided	0.5%	0.5%
	Acceptance Criteria-Response Spectrum Analysis	Minor yielding of ductile elements	$R_u \le R_n$	$R_u < 1.5\ \phi\ R_{n,}$ (R_n is calculated using specified material properties)	-$R_u < 1.5\ R_{n,e}$ for DCA -$R_u < 0.7\ R_{n,e}$ for FCA
	Acceptance Criteria-Response History Analysis	Minor yielding of ductile elements	Maximum $R_u \le R_n$	- $R_u < R_{n,e}$ for FCA -Laboratory Test Data OR IO limit of ASCE 41-06 for DCA	IO limit of ASCE 41-06 OR Laboratory Test Data
	Non-structural	Code Design	Racking Deformations & Floor Accelerations < limits by Architect	Code Design	Code Design

PBSD Guidelines – Maximum Considered Earthquake Evaluation

		AB-83	CTBUH	PEER	LATBSDC
Performance Objectives		Low probability of collapse	Collapse Prevention	Collapse Prevention	Collapse Prevention
Earthquake Shaking	**Return Period**	2,475 yrs	2,475 yrs	2,475 yrs	2,475 yrs
	Damping Level	5% equivalent viscous damping	1-2% for buildings between 50 & 250 m tall (slightly higher damping is permitted with lumped plasticity models)	Maximum of 2.5% modal, explicit viscous damping elements, or Rayleigh damping (ATC-72)	Maximum of 2.5% modal or Rayleigh damping
	Target Spectra	Uniform Hazard Spectra (UHS) (with deterministic cap)	-Maximum UHS or -Maximum & minimum UHS or - Suite of maximum and minimum Conditional Mean Spectra (CMS)	-UHS (with deterministic cap) or -Suite of CMS	UHS (with deterministic cap)
	Number of Records	Minimum of seven pairs	-Three pairs if matched to UHS or -Nine pairs if matched to suite of CMS	Minimum of seven pairs	Minimum of seven pairs
	Records Scaling	-Amplitude Scaling or -Spectral Matching Either should satisfy Sec. 1631.6.1 of SFBC-01	Spectral Matching	-Amplitude Scaling or -Spectral Matching	-Amplitude Scaling or -Spectral Matching Either should satisfy Sec. 16.1.3 of ASCE 7-05
	Near Source Effects	Required for sites within short distance of active fault(s)	Required for sites within 15 km of active fault	Required for sites within short distance of active fault(s)	Required for sites within short distance of active fault(s)

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PBSD Guidelines – Maximum Considered Earthquake Evaluation (continued from the previous page).

Modeling & Analysis	**Analysis Type**	Non-linear Response History Analysis	Non-linear Response History Analysis	Non-linear Response History Analysis	Non-linear Response History Analysis
	Material Properties for Stiffness	Specified	Not mentioned	Expected	Expected
	Effective Stiffness	Not provided	ASCE 41-06	ATC 72-10 or ASCE 41-06	Modifiers provided
	Sources of Hysteretic Deterioration	Not listed	Not listed	Listed	Not listed
	Cyclic Deterioration Modeling	Not mentioned	Not mentioned	Option 1 –cyclic deterioration in analytical model Option 2 –modified backbone curve based on cyclic envelope Option 3 –modified backbone curve based on factors Option 4 –no deterioration	Option 1 –cyclic deterioration in analytical model Option 2 –modified backbone curve based on cyclic envelope
	Modeling of Gravity Elements	Required if affect the dynamic response	Required for Reinforced Concrete Construction	Required only if significantly contribute to stiffness and strength	Required only if significantly contribute to global or local stiffness
	P-Delta	Required	Required	Required	Required
	Direction of Ground Motion Application	-Fault-normal /parallel, components shall be applied according fault orientation -Random orientations, components shall be applied at randomly selected orientation angles (individual ground motion pairs need not be applied in multiple orientations)	Not discussed	-Apply the pairs of accelerograms along the principal directions of response -If near-fault directionality effects dominate, accelerograms should be applied in the fault-parallel and fault-normal directions	-Fault-normal /parallel, components shall be applied according fault orientation -Random orientations, components shall be applied at randomly selected orientation angles (individual ground motion pairs need not be applied in multiple orientations)
	Accidental Torsion	Not required	Not required	Not required	Required only if flagged in serviceability check
	Expected Live Load (L_{exp})	0.1 L	Not mentioned	0.25 L	0.25 L
	Load Combinations	$D + L_{exp} + E$	Unfactored Gravity+ E	$D + L_{exp} + E$	$D + L_{exp} + E$
	Sensitivity Analyses	Not mentioned	Recommended for soil-structure-interaction	Not mentioned	Recommended
Soil-Structure Interaction	**Modeling**	Foundation strength and stiffness shall be presented	-Rigid "Bathtub" model (stiffness & full mass) or -Fully coupled nonlinear soil-foundation-structure	-Modeling subterranean structure (stiffness & partial mass) or -Rigid "Bathtub" model (stiffness & full mass)	Modeling subterranean structure (stiffness only)
	Kinematic Interaction	Not mentioned	Modified for kinematic interaction	-Free field or -Modified for kinematic interaction	-Free field or -modified for kinematic interaction

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PBSD Guidelines – Maximum Considered Earthquake Evaluation (continued from the previous page).

Acceptance Criteria	**Inter-story Drift Limit**	Mean of 3%	No limit provided	Mean of 3% Maximum of 4.5%	Mean of 3% Maximum of 4.5%
	Residual Inter-story Drift Limit	No limit provided	No limit provided	Mean of 1% Maximum of 1.5%	Mean of 1% Maximum of 1.5%
	Loss in Story Strength Limit	No limit provided	No limit provided	≤ 20% of initial strength	≤ 20% of initial strength
	Acceptance Criteria-FCA	(mean+1.0 SD) $R_u \le \phi R_{n,e}$	Maximum $R_u \le R_n$	-1.5 mean $R_u \le \phi R_{n,e}$ for Unlimited Critical Actions -(mean+1.3 SD) $R_u \le \phi R_{n,e}$ & 1.2 mean $R_u \le \phi R_{n,e}$ for limited Critical Actions -mean $R_u \le R_{n,e}$ for Noncritical Actions	-1.5 mean $R_u \le R_{n,e}$ for Critical Actions -mean $R_u \le R_{n,e}$ for Noncritical Actions
	Acceptance Criteria-DCA	Mean Deformation < Ultimate Deformation Capacity	Maximum Deformation < Ultimate Deformation Capacity	Maximum Deformation < Ultimate Deformation Capacity per ATC 41-06 OR ATC72-10	Mean Deformation < CP limits of Primary Elements per ASCE 41-06 or Experimental Data
	Acceptance Criteria-Gravity Elements	Mean Deformation < Ultimate Deformation Capacity	Maximum Deformation < Ultimate Deformation Capacity	Maximum Deformation < Ultimate Deformation Capacity per ATC 41-06 OR ATC72-10	Mean Deformation < CP limits of Secondary Elements per ASCE 41-06 or Experimental Data
	Cladding	Code Requirements	Racking Deformations & Floor Accelerations must be less than limits by Architect	Claddings and their connections must accommodate mean story drifts without failure	Claddings and their connections must accommodate mean inter-story drift in each story