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Subjects: Seismic
Structural Engineering

Keywords: Building Code
Damping
Performance Based Design
Seismic
Structure

Publication Date: 2012

Original Publication: International Journal of High-Rise Buildings Volume 1 Number 3

Paper Type:
1. Book chapter/Part chapter
2. **Journal paper**
3. Conference proceeding
4. Unpublished conference paper
5. Magazine article
6. Unpublished

International Journal of High-Rise Buildings
September 2012, Vol 1, No 3, 149-154

International Journal of
High-Rise Buildings
www.ctbuh.org

Performance Based Seismic Design – State of Practice 2012 in the United States of America

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Abstract

This paper presents a summary of the state of the practice for Performance Based Seismic Design (PBSD) in the United States. While it is not included in the prescriptive provisions of the United States' building codes, the PBSD procedure has been successfully implemented for two decades. The recent publication of the Guidelines for Performance-Based Seismic Design of Tall Buildings by the Pacific Earthquake Engineering Research Center (PEER) illustrates the fact that the engineering community has embraced this procedure and provides a thoughtful set of recommendations to building designers who intend to implement PBSD. The key parameters currently required for a PBSD also are outlined, such as seismic hazard definition, modeling procedures, and acceptance criteria. These Guidelines will serve as the basis for many PBSD projects in the coming years and as such are a common reference used throughout this paper. Finally, a brief summation of recent PBSD projects in the United States is presented.

Keywords: Seismic, Performance-Based, Tall Buildings, High-Rise

1. Introduction

In the United States, Performance Based Seismic Design (PBSD) has grown from its early childhood years to now a growing teenager with all of the optimism and promise that these years hold for any individual. Significant advances have been made in the state of the practice over the last decade, yet only a limited number of new buildings have been constructed and even fewer unique structural systems have been implemented using PBSD. However, with the lessons learned from, and the growing support for PBSD, the future holds great promise for creative applications of the basic engineering principles embodied in PBSD.

The roots of PBSD in the United States stem from the seismic rehabilitation community. Faced with the need to evaluate and rehabilitate archaic building systems and materials, an approach which enabled the evaluation of these buildings could only effectively be executed using fundamental engineering principals. Prescriptive building code provisions did not provide the means to assess nor to thoughtfully rehabilitate these older buildings. Out of these needs, PBSD was born.

In the 1990s, the analysis and evaluation techniques of PBSD that were developed for existing buildings began to be implemented in the design of new buildings. In particular, market forces demanded a more creative approach to the design of high-rise residential towers, in which views from perimeter windows and balconies command premium value. Traditional "backup" moment frames posed a significant encumbrance to the basic real estate proposition. Out of this challenge, numerous buildings were designed and constructed using concrete core wall bracing systems without the inclusion of an otherwise prescriptively required "back-up" moment frame.

These early PBSD projects spurred interest within the seismic engineering community to better define the ground motion demands, analysis techniques, and acceptance criteria for these designs to better ensure a consistent and reliable outcome.

Today, the *Guidelines for Performance-Based Seismic Design of Tall Buildings* published by the Pacific Earthquake Engineering Research Center (PEER) is recognized as the industry standard for the design of new buildings using a PBSD approach. The recommendations

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included in these Guidelines will open the door for the creative application of PBSD to many different building types and structural systems. In the next ten years, it is likely that many more new buildings will be designed using PBSD since it provides the most efficient deployment of materials to achieve a more reliable performance outcome.

2. Code Requirements

The *International Building Code* (IBC), which is published every three years, governs the design of buildings throughout most of the United States. For the majority of environmental loadings such as snow, wind and earthquake, the IBC defers to ASCE/SEI 7, *Minimum Design Loads for Buildings Other Structures,* for loading and design requirements. These requirements are prescriptively-based, requiring the loading and design to follow the provisions specified in the Standard. For earthquake loadings, the requirements are included in Chapters 11 to 23. The seismic force-resisting systems allowed are specified in Table 12.2-1, which include limitations that restrict the location and height of the seismic force-resisting systems that can be used. Because of these limitations, PBSD alternatives have been introduced in numerous designs throughout the United States to bypass these restrictions. The use of PBSD is currently considered an "alternative design approach" that must be shown to be at least equivalent to a prescriptive-based code design. However, the IBC specifically supports the use of alternative design approaches and goes so far as to state the following in Section 104.11:

> 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. Any alternative material, design or method of construction shall be approved where the building official finds 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.

In addition, the following provisions were introduced in Section 1.3.1of the latest version of ASCE/SEI 7-10, which directly support the use of PBSD and will further its use in future designs throughout the United States:

> 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.

3. Definition of Seismic Demand Levels

Seismic design of a tall building following PBSD principles requires characterization of two levels of ground shaking: the Service-Level earthquake and the Maximum Considered Earthquake (MCE). Service Level shaking is defined as an earthquake with a 43-year return period (50 percent probability of exceedance in 30 years) and is required only when using a PBSD. The MCE is defined in ASCE 7 using appropriate contemporary models for the description of regional seismic sources and ground motion prediction equations. The ASCE 7-10 definition of the MCE is intended to provide for a more uniform collapse risk for structures designed using the MCE ground motions. The MCE ground motions are now expected to result in structures with a 1 percent in 50 year collapse probability, based on the probabilistic seismic hazard at each site and a probabilistic estimate of collapse (collapse fragility curve) inherent in structures designed to the seismic provisions in the ASCE 7 standard.

In addition to the levels of ground shaking described above, local building codes may require that the building also be designed for a Design-Basis Earthquake (DBE), which is defined in ASCE 7 as two-thirds of the MCE.

Site-specific risk-targeted MCE ground motions are based on separate calculations of site-specific probabilistic and site-specific deterministic ground motions.

Probabilistic Seismic Hazard Analysis (PSHA) methods and subsequent computations of risk-targeted probabilistic ground motions based on the output of PSHA are sufficient to define MCE ground motion at all locations except those near highly active faults. The primary output of PSHA methods is a so-called "seismic hazard curve," which provides mean annual frequencies of exceeding various user-specified ground motion amplitudes. Risk-targeted probabilistic ground motions are then derived from hazard curves using one of two methods described in the ASCE 7 Commentary.

Deterministic ground motions are based on characteristic earthquakes on all known active faults in a region. The magnitude of a characteristic earthquake on a given fault should be a best estimate of the maximum magnitude capable for that fault but not less than the largest magnitude that has occurred historically on the fault. The maximum magnitude should be estimated considering all seismic-geologic evidence for the fault, including fault length and paleoseismic observations. For faults characterized as having more than a single segment, the potential for rupture of multiple segments in a single earthquake should be considered in assessing the characteristic maximum magnitude for the fault.

4. Performance Objectives

Buildings designed in accordance with PBSD principles are intended to have seismic performance capability equivalent to that intended for similar buildings designed in full conformance with the requirements of the 2012 IBC, ASCE 7-05, and ASCE 7-10. As presented in the commentary to FEMA P750 (2009), the building code is intended to provide buildings conforming to Occupancy Category II of ASCE 7-05 (Risk Category II of ASCE 7-10) with the capability to:

- Withstand MCE shaking, as defined in ASCE 7, with low probability (on the order of 10 percent) of either total or partial collapse;
- Withstand DBE shaking, having an intensity two-thirds that of MCE shaking, without generation of significant hazards to individual lives through design measures intended to assure that nonstructural components and systems remain anchored and secured to the structure and that building drifts are maintained at levels that will not create undue hazards; and
- Withstand relatively frequent, more moderate-intensity earthquake shaking with limited damage.

Performance objectives are typically measured at the Service and MCE design levels.

- At the Service Level (note that this performance objective is only directly evaluated when performing PBSD):
  - Linear, response spectrum analysis is commonly used.
  - Demand-to-capacity ratios are not permitted to exceed 1.5 times the nominal capacity of the member, using applicable phi factors.
  - Story drift at any story in the building is not permitted to exceed 0.5 percent.
- At MCE shaking:
  - All actions at individual components (forces, moments, strains, displacements, or other deformations) are evaluated either as force-controlled or deformation-controlled actions. Deformation-controlled actions are those in which reliable inelastic deformation capacity is achievable without critical strength decay. Force-controlled actions are those in which inelastic deformation capacity cannot be assured.
  - Globally, the MCE acceptance criteria is considered satisfied when the building is within peak transient drift limits and there is not an excessive loss in story strength.
  - Mean results are utilized.
  - Deformation-controlled actions are evaluated to ensure that members expected to deform into the inelastic range remain within acceptable deformation limits determined for individual element types. For example, strain in reinforcing bars may be limited to 0.02 in compression to reduce the possibility of bar buckling.
  - Force-controlled actions are typically checked to ensure strength exceeds 1.5 times the mean demand obtained from statistical evaluations of nonlinear response. Member strength is calculated using expected material properties and phi factors, determined from applicable material codes.
  - The peak transient story drift from the non-linear analysis is not permitted to exceed 3 percent.
  - In any single story, the deformation imposed is not permitted to result in a loss of total story strength that exceeds 20 percent of the initial strength.

5. Modeling Procedures

Modeling of the structure should be as realistic as possible and capture the expected properties of the materials. Elements which are not part of the main lateral force-resisting system but that influence behavior are also modeled.

At the Service Level, linear analyses are most common, using a three-dimensional mathematical model of the structure that represents the spatial distribution of mass and stiffness to an extent adequate for calculation of the significant features of the building's linear dynamic lateral response. Models include representation of the stiffness of the intended lateral-force-resisting system as well as any vertical-load-bearing elements and nonstructural components that add significant lateral stiffness or that will experience significant stress in response to Service Level shaking. Structural models incorporate realistic estimates of stiffness considering the anticipated level of excitation and damage. Expected properties, as opposed to nominal or specified properties, are typically used when computing modulus of elasticity.

At the MCE, a three-dimensional non-linear model of the structural system that represents all components and force and deformation characteristics that significantly affect the seismic demands at the MCE response level is utilized. P-Delta effects are represented in the analytical model. Elements and components that are expected to exceed their elastic capacities are commonly modeled with non-linear properties consistent with the expected deformation patterns. Elements and components that are expected to remain elastic are modeled with elastic properties.

6. Foundation Interaction

Foundation interaction is typically modeled in a limited manner. Unless necessitated by unusual conditions, fixed supports are modeled at the lowest level of the structure, and the free field ground surface motions are applied at these supports. The interaction of subterranean walls and the adjacent soil is generally neglected, since this interaction reduces the load on the structure through the basement levels. The structure below the ground surface is typically considered to be massless.

Where unusually flexible foundation conditions may significantly affect a structure's response, the structure may be supported on springs and dampers that are connected to ground motion input nodes. Subterranean wall interaction may or may not be considered.

7. Damping

Damping for Service Level analysis is 2.5 percent of critical. This is implemented through the use of a 2.5-percent-damped linear uniform hazard acceleration response spectrum.

For nonlinear analysis at the MCE, the primary source of damping is hysteretic energy dissipation in inelastic elements. Additional viscous damping is limited to 2.5percent of critical in the primary modes of response. This is generally met by using constant Rayleigh ($C = \alpha M + \beta K$) damping with coefficients α and β set to give 2.5 percent of critical damping at appropriate ratios of the fundamental building period T1 (for example, 0.4T1 and 1.1T1).

8. Gravity Load-Resisting Systems

Gravity load-resisting systems are typically analyzed using traditional methods and detailed for deformation compatibility corresponding to the level of demand that is calculated from the structural models. For elements of the gravity system that are included in the analysis models, forces and deformations can be calculated directly. The demands on critical members of the gravity load-resisting systems (typically non-participating columns) are then checked against the calculated capacities of the members.

9. Non-Structural Systems

It is common to include the mass of the non-structural systems in the analysis models, but a representation of the stiffness of these systems is rarely included.

The anticipated performance of non-structural systems can be assessed through consideration of the calculated floor acceleration, floor velocity and story drift. A committee of the Applied Technology Council (ATC-58) is currently working to assess performance of non-structural systems using these three parameters to assess their likely damage given earthquake shaking.

10. Project Examples

Special Reinforced Concrete Ductile Core Wall – The Infinity, San Francisco, California: This building was the first core-only, non-dual system, high-rise tower to be permitted and constructed in San Francisco. The 37- and 42-story towers utilized a central concrete core surrounding the basic circulation and back-of-house services without the need for a backup moment frame to satisfy the height limitations of the prescriptive building code. Performance-based and capacity-based seismic design principles were utilized to demonstrate, at a minimum, code-equivalency to the building code. Construction cycles of three days per floor were achieved with the elimination of the perimeter moment frame, saving months in the construction schedule.

Figure 1. The Infinity, San Francisco, California.

Figure 2. One Rincon Hill, San Francisco, California.

Ductile Core with Buckling-Restrained Braced Outrigger System – One Rincon Hill, San Francisco, California: At 64 stories and 590 feet, this is the tallest PBSD tower in the United States. One Rincon Hill is also the tallest high-rise to contain buckling-restrained braces (BRBs) and the first to use BRBs as outriggers. The slender tower is the first residential building in the United States to have a tuned liquid mass damper to reduce sway to acceptable comfort levels. Similar to the Infinity, a three-day-per-floor construction cycle was achieved.

Steel Plate Shear Walls – LA Live / Ritz-Carlton, Los Angeles, California: This 54-story tower utilized a performance-based design steel plate shear wall central core which increased usable square footage inside the building and eliminated the need for a perimeter backup

Figure 3. Providence Medical Center, Everett, Washington.

moment frame. With the resulting lighter building, the design team was able to add four stories to the project and shave months off the construction schedule compared to a typical dual system approach.

Steel Buckling-Restrained Braced (BRB) Frames – Providence Medical Center, Everett, Washington: This 10-story, 730,000-square-foot critical care tower utilized PBSD and nonlinear time-history analyses to quantify from analyses the maximum demands of the BRBs to the beams, columns, and foundations rather than having to rely on code-prescriptive over-strength assumptions. This approach led to consumptive quantity reductions when compared to prescriptive-code design, with the steel for beams and columns reduced by 200 tons, the total length of drilled shafts reduced by 480 feet, the volume of concrete in drilled shafts reduced by 1,200 cubic yards, and the total core area of BRBs reduced by 15 percent. In addition to material reductions, the nonlinear analysis was able to reduce the seismic joint sizes by 25 percent, reduce the story drift criteria (which cladding must be designed to accommodate) by 25 percent, and reduce the design forces for non-structural components (which are extensive in a hospital) by approximately 30 percent.

11. Other Items of Interest

As is common around the globe, goals of sustainability and efficient use of resources weigh heavily on decisions made regarding tall buildings in the United States. As this effort continues to mature, the use of PBSD principles will become more prevalent. Only with the advanced analysis associated with this design technique can engineers confidently verify that elements of the lateral force-resisting system are effectively positioned.

Accompanying the growth in the use of PBSD is continued growth in research related to building materials and components. This research is essential to allow more accurate computer models to be developed. Universities and design firms across the country are more commonly developing research programs to study new methods and systems.

12. Review Procedures

Because of the complexity of the analyses used to demonstrate building performance, most building departments in the United States have initiated a requirement for independent peer review when designs are submitted for permit under the alternative means and methods clause of the IBC. This requirement also is included in ASCE 7. The composition of the peer review panel is typically jointly determined by the owner/design team and the building department. In some cities, a single reviewer (or firm) is deemed sufficient. Many building departments prefer to have a panel that has a combination of practicing engineers and members of academia. Reviewers commonly have a specialty in either seismic design of buildings or seismic hazard determination. The need for both of these proficiencies is why a peer review panel of multiple individuals is often chosen. Having multiple reviewers is also an advantage when differences of opinion between the reviewer and the design engineer arise.

It is common to initiate the peer review process very early in the design process. Early agreement and discussion of the fundamental design decisions, assumptions, and approaches often help to avoid re-work later in the design process. Early engagement of the peer reviewers also helps to establish a good working relationship between them and the design team.

The building official typically defines the minimum acceptable scope of the peer review. In most cases, the review is limited to the seismic design, even though design for wind forces and deformations (specifically drift limits for serviceability and occupant comfort) may control the design. The design of gravity load-resisting elements is typically excluded as well, except for evaluation of deformation compatibility issues. Nonstructural elements that can create hazards to life safety are often included to ensure that proper anchorage and/or deformation accommodation has been provided.

13. Conclusion

This paper presents a summary of the state of the practice for Performance Based Seismic Design (PBSD) in the United States. While it is not included in the prescriptive provisions of the United States' building codes, the PBSD procedure has been successfully implemented for two decades. Significant advances have been made in the state of the practice over the last decade, yet only a limited number of new buildings have been constructed and even fewer unique structural systems have been implemented using PBSD. However, with the lessons learned from and growing support for PBSD, the future holds great promise for creative applications of the basic engineering principles embodied in PBSD. The recent publication of the *Guidelines for Performance-*

Based Seismic Design of Tall Buildings by the Pacific Earthquake Engineering Research Center (PEER) illustrates the fact that the engineering community has embraced this procedure and provides a thoughtful set of recommendations to building designers who intend to implement PBSD.

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The following references are commonly used when PBSD is employed in the United States:

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