Title:	**Performance-Based Seismic Design – State of Practice 2012**
Authors:	Ron Klemencic, President, Magnusson Klemencic Associates Guo-Qiang Li, Professor, Tongji University J. Andrew Fry, Chief Operating Officer, Magnusson Klemencic Associates
Subject:	Structural Engineering
Keywords:	Code Compliance Performance Based Design Seismic
Publication Date:	2012
Original Publication:	CTBUH 2012 9th World Congress, Shanghai
Paper Type:	1. Book chapter/Part chapter 2. Journal paper 3. Conference proceeding 4. Unpublished conference paper 5. Magazine article 6. **Unpublished**

Performance-Based Seismic Design – State of Practice 2012

Summary

Ron Klemencic[1], J. Andrew Fry[2], Guo-Qiang LI[3]

[1]President, Magnusson Klemencic Associates, 1301 Fifth Avenue, Suite 3200, Seattle, Washington 98101

[2]Chief Operating Officer, Magnusson Klemencic Associates, 1301 Fifth Avenue, Suite 3200, Seattle, Washington 98101

[3]State Key Laboratory for Disaster Reduction in Civil Engineering of Tongji University, Shanghai, China

Abstract

A summary and synthesis of the Performance-Based Seismic Design (PBSD) procedures and standards around the world is presented. The summary information draws from the papers written by leading technical experts in PBSD from the various countries indicated. Many similarities in design and analysis methodologies are noted.

Keywords

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

Introduction

The history of building standards can arguably be traced back as far as the Code of Hammurabi, written more than 3,700 year ago. Building codes and standards as we know them today have existed for more than a century. These standards have served as a listing of the minimum requirements that a designer/builder must meet when designing and constructing a building. Minimum requirements by definition only provide a limited amount of guidance to designers. Code writers continually strive to improve and clarify these minimum requirements resulting in longer and longer lists of requirements and associated commentary.

Design standards around the world have developed along independent paths. However, basic requirements in the various standards have many similarities. Performance-based design has challenged code writers to think beyond prescriptive minimum requirements by demanding clarity on the target levels of building performance desired for different hazards. Performance objectives have begun to appear in many building codes. Additional provisions that allow engineers to provide designs that demonstrate that the building satisfies these performance objectives while not satisfying some of the minimum requirements, such as height limits, have also been incorporated. An example can be found in the current building code used in the United States:

> 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.

Tall buildings are unique structures that demand rigorous technical design. Building codes have been, and continue to be, developed considering the most common types of structures that will be designed and constructed in the region over which the code applies. Designers of unique structures commonly find themselves struggling to apply code provisions to buildings that were not considered when the building code language was developed. This is particularly true when designing for earthquakes, for which hazard definitions are commonly targeted at low- to mid-rise buildings which demonstrate primarily first-mode response. Thus, performance-based seismic design was born.

PBSD has been applied to tall buildings for more than 30 years. However, only in the most recent decade has PBSD become truly accepted worldwide. Technology has allowed designers to use advanced, three-dimensional, non-linear computer simulation models combined with risk-targeted seismic hazards. When used together it has become possible to analyze building behaviors under even the most extreme earthquake loading and demonstrate that performance targets are achieved.

This paper draws from a series of seven papers prepared by leading PBSD designers around the world. Each paper presents a summary of the design approaches used and includes case studies of projects that have been recently designed using PBSD. The papers illustrate that performance objectives for earthquakes are generally consistent around the world. Buildings are expected to resist frequent earthquakes with limited damage and very rare earthquakes with minimal risk of total or partial collapse.

The summary information is presented in tabular format so that comparisons can be made between the approaches used in different countries. Tables are presented for nine different critical parameters of PBSD and observations made regarding similarities and differences in approach. International best practices are noted when they are identified.

Observations

Code Requirements

A listing of the current national building codes for each country is presented. A number of the codes draw content from the codes developed in the United States. PBSD is required in China and Japan for tall and irregular buildings. The majority of countries permit PBSD as an alternate approach to allow engineers to consider building designs that do not comply with all of the stipulated requirements. Korea does not permit designers to use PBSD to avoid code provisions.

The evidence presented in the papers from the various countries indicates that PBSD is slowly gaining international acceptance. This trend is expected to continue as authorities having jurisdiction grow in their understanding of the methodologies used to demonstrate building performance under earthquake loading.

Seismic Design Levels and Performance Objectives

In PBSD it is observed to be common practice to consider multiple seismic hazard levels. The approach to defining the hazard levels differs from country to country and the names selected for each level vary. However, there is general agreement that structural designs should consider:

- A frequent or service level earthquake with a mean recurrence interval of approximately 50 years. At this demand level, structures are expected to respond with limited or no structural damage and only minor yielding of structural elements. It is generally understood that minor damage to non-structural elements may occur but expected that with limited repairs, the building will remain operational.
- An extremely rare or severe earthquake with a mean recurrence interval of between 1,000 and 2,500 years. At this demand level, the performance objective is to have minimal likelihood of total or partial collapse of the structure. It is generally understood that buildings may not be repairable after this extreme event.
- An intermediate hazard level, often called design level or rare earthquake, is commonly considered as well. The design level earthquake commonly has a mean recurrence interval of around 500 years and is

consistent with the seismic hazard considered for typical building design. The performance objective at this hazard level is defined as "life-safety". ASCE 41 provides the following definition of this performance objective:

> Life-safety performance means the post-earthquake damage state in which significant damage to the structure has occurred, but some margin against either partial or total structural collapse remains. Some structural elements and components are severely damaged, but this has not resulted in large falling debris hazards, either inside or outside the building. Injuries may occur during the earthquake; however, the overall risk of life-threatening injury as a result of structural damage is expected to be low. It should be possible to repair the structure; however, for economic reasons this may not be practical. While the damaged structure is not an imminent collapse risk, it would be prudent to implement structural repairs or install temporary bracing prior to reoccupancy.

Modeling Procedures

Before a non-linear analysis can be performed, the structure must be proportioned and designed. There is agreement that three-dimensional, linear elastic computer models are used for this initial design of the structure. One of the lower hazard levels (frequent or design level) is considered for this initial proportioning. It is common practice for the initial design to be performed in a manner consistent with as many code provisions as possible. When considering extremely rare earthquakes, a non-linear analysis is often employed. This non-linear analysis may consider static (pushover) or dynamic (earthquake record) demands. The complexity of the computer simulations varies from country to country, with a trend observed toward the use of complete, three-dimensional models of the structure.

Engineers and peer reviewers desire computer models that are as accurate as possible. Expected material properties rather than specified properties are often used to more accurately reflect the true stiffness of the structure. The stiffness of the entire structure, not just the seismic force-resisting system is sometimes evaluated with a trend observed toward analysis models including a representation of the stiffness of structural elements that are not part of the seismic force-resisting system. Non-linear component models are calibrated to correspond to physical test data where such data exists. Soil-structure interaction of the foundations is also a current hot topic. Engineers are beginning to incorporate the stiffness and damping of the soil surrounding the foundations into the computer simulations. This is an area where technical advancements are expected as more data becomes available.

Different levels of structural damping are considered at the different design levels. When responding elastically, structures commonly exhibit low levels of inherent damping. As non-linear responses increase, damping also increases. The approaches used in the various countries mimic this behavior by increasing structural damping levels from 1 or 2 percent at low demand levels to 5 percent at extreme levels.

Review Procedures

The complex analyses and unique nature of high-rise buildings mean that peer reviews by an uninvolved third party occur in all countries. The make-up of peer review panels and committees vary per local requirements but generally consist of individuals with expertise in geotechnical engineering, structural engineering of tall buildings, seismic hazard determination, and non-linear analysis. Peer reviews tend to focus on the following major topics:

- Validation of design criteria and performance objectives
- Review of proposed exceptions to the applicable building codes and standards
- Review of analysis models and anticipated building dynamic response
- Detailing of critical elements
- General conformance of the structural design to the stated performance objectives

Conclusion

Performance based seismic design is gaining worldwide acceptance for high-rise building design. This paper has presented a comparison of PBSD approaches from seven different countries noting many similarities in design approach. International best practices are noted in the paper and include:

- Designs that conform to building codes and standards to the full extent possible.
- Clear documentation of design criteria and performance objectives with any exceptions to code provisions clearly noted.
- Consideration of multiple seismic demand levels with performance objectives selected for each.
- Verification that wind demands do not control the lateral design of the building.
- Use of computer models that represent the stiffness of the structure as accurately as practical and considering:

  - Expected material properties
  - Representation of the stiffness of gravity system of the structure where appropriate
  - Soil-structure interaction effects
  - Effects of embedment and basements
- Damping selected to correspond to the level of seismic demand.
- Peer reviews performed by individuals with expertise in geotechnical engineering, structural engineering of tall buildings, seismic hazard determination, and non-linear analysis.

This paper has highlighted how designers around the world are utilizing PBSD with advanced analysis techniques to study building response to seismic hazards of various intensities and verifying that desired performance objectives are met. PBSD of tall buildings has a relatively short history but is expected to have a very bright future as international acceptance is steadily growing.

References

- ASCE 7 (2010). *Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-10),* American Society of Civil Engineers, Reston, VA.
- ASCE 41(2007). *Seismic Rehabilitation of Existing Buildings (ASCE/SEI 41/06 plus Supplement 1),* American Society of Civil Engineers, Reston, VA.
- IBC (2012). *International Building Code,* International Code Council, Washington, DC.
- Performance-Based Seismic Design – State of Practice 2012 in the United States of America, R Klemencic, JA Fry, JD Hooper, et al, CTBUH Proceedings, 2012.
- Performance-Based Seismic Design – State of Practice 2012 Japan, M Nakai, N Koshika, K Kawano, et al, CTBUH 9th World Congress Proceedings, 2012.
- State of Practice of Performance-Based Seismic Design in Korea, DH Lee, YJ Lee, DE Kang, T Kim, JH Kim, CTBUH 9th World Congress Proceedings, 2012.
- Performance-Based Seismic Design State of Practice, 2012 Manila, Philippines, JA Sy, N Anwar, T HtutAung, D Rayamajhi, CTBUH 9th World Congress Proceedings, 2012.
- Overview of Performance-Based Seismic Design of Building Structures in China, GQ Li, YB Xu, FF Sun, CTBUH 9th World Congress Proceedings, 2012.

- State of Practice of Performance-Based Seismic Design in Indonesia, D Sukamta, N Alexander, CTBUH 9th World Congress Proceedings, 2012.
- Seismic Performance of High-Rise Concrete Buildings in Chile, R Lagos, M Kupfer, J Lindenberg, et al, CTBUH 9th World Congress Proceedings, 2012.
- TBI (2010). *Guidelines for Performance-Based Seismic Design of Tall Buildings,* Pacific Earthquake Engineering Research Center, Tall Building Initiative, November 2010.

Table 1: Code Requirements

Chile	Indonesia	China	Philippines	Korea	Japan	USA
Current Code There are multiple Chilean Loading and Design Standards.	Current Code 2002 Indonesian Seismic Code, which adopted many UBC-97 provisions. New code currently in development will adopt many ASCE 7-10 provisions.	Current Code "Code for Seismic Design of Buildings" GB 50011-2010	Current Code 2010 National Structural Code of the Philippines (NSCP), developed by the Association of Structural Engineers of the Philippines. NSCP is based on IBC 2009, UBC 1997, and ASCE 7-05.	Current Code Korean Building Code 2009 (KBC 2009). KBC 2009 is based on ASCE 7-05 for design values.	Current Code The Building Standard Law of Japan	Current Code International Building Code 2012 and American Society of Civil Engineers (ASCE 7-10)
Performance-Based Design Performance-based design procedures are not included in the Chilean Seismic code for buildings.	Performance-Based Design Current code does not address. New code will have alternative non-prescriptive option, but no specific guidelines will be given.	Performance-Based Design PBSD first introduced in 1989 code. Required for tall, irregular, or important buildings. "Technical Specification for Concrete Structures of Tall Buildings" JGJ3-2010 presents the concepts and methods of performance-based seismic design adopted in Chinese codes.	Performance-Based Design Allowed as an alternative design approach but not addressed directly. General procedure follows the PEER TBI Guidelines.	Performance-Based Design Not allowed to bypass the code restriction on the location and height of the seismic force-resisting system that can be used.	Performance-Based Design Required for buildings greater than 60 meters in height.	Performance-Based Design Allowed as an alternative design approach, but not addressed directly.

Table 2: Definition of Seismic Demand Levels

Chile	Indonesia	China	Philippines	Korea	Japan	USA
The Chilean building code mentions three design earthquakes (frequent, intermediate, and extreme).	Service Level Current and new code does not define.	Minor Earthquake 10 percent probability of exceedance in 50 years.	Service Level 43-year return period (50 percent probability of exceedance in 30 years). Only required when using a PBSD.	Service Level N/A	Rare Earthquake 50-year return period	Service Level 43-year return period (50 percent probability of exceedance in 30 years). Only required when using a PBSD.
Design Level 475-year return period	Design Level Current Code: 475-year return period New Code: 2/3 MCE	Moderate Earthquake Between minor and severe earthquake – not explicitly defined in the code.	Design Level 2/3 of the MCE demand	Design Level 2/3 of MCE demand Less than 1,000-year return period		Design Level 2/3 of the MCE demand Required by certain jurisdictions
	Maximum Considered Earthquake Current Code: Not defined. New Code: 2,475-year return period.	Severe Earthquake 2 to 3 percent probability of exceedance in 50 years.	Maximum Considered Earthquake ASCE 7-10 definition expected to result in structures with 1 percent in 50-year collapse probability.	Maximum Considered Earthquake 2400-year return period	Extremely Rare Earthquake 500-year return period	Maximum Considered Earthquake ASCE 7-10 definition expected to result in structures with 1 percent in 50-year collapse probability.

Table 3: Performance Objectives

Chile	Indonesia	China	Philippines	Korea	Japan	USA
Frequent Operational	Service Level Limited Damage	Minor Earthquake No damage or usable without repair	Service Level Limited Damage	Service Level N/A	Rare Earthquake Limited Damage	Service Level Limited Damage
Design Level Life-safety Performance	Design Level No major structural damage	Moderate Earthquake Usable after normal repair		Design Level Varies from Immediate Occupancy to Collapse Prevention depending on Occupancy Category		Design Level Life-safety Performance
Extreme Collapse Prevention	Maximum Considered Earthquake Collapse Prevention	Severe Earthquake No collapse or serious damage that can create hazard to life safety	Maximum Considered Earthquake Low (10%) probability of total or partial collapse	Maximum Considered Earthquake N/A	Extremely Rare Earthquake Collapse Prevention	Maximum Considered Earthquake Low (10%) probability of total or partial collapse

Table 4: Modeling Procedures

Chile	Indonesia	China	Philippines	Korea	Japan	USA
Frequent Linear elastic model	Service Level N/A	No specific differences outlined between models for each hazard level. Elastic time history analysis for buildings not exceeding height limits and structure regularity limits. If building exceeds height/regularity limits, two independent structure analysis software packages are required. Elastic-plastic time-history analysis for buildings over 200 meters. If over 300 meters, two independent structure analysis software packages are required.	Service Level Linear elastic model using best estimate of initial element stiffness. Gravity system included if it impacts response.	Service Level N/A	Rare Earthquake Linear elastic model	Service Level Linear elastic model using best estimate of initial element stiffness. Gravity system included if it impacts response.
Design Level Linear elastic model	Design Level Linear elastic model		Design Level Linear elastic model using best estimate of cracked element stiffness. Gravity system may be included.	Design Level Linear modeling using M-factor for deformation-controlled components per ASCE 41 for preliminary design. Non-linear modeling for advanced design.		Design Level Linear elastic model using best estimate of cracked element stiffness. Gravity system may be included.
Extreme Non-linear pushover analysis may be performed	Maximum Considered Earthquake 3-D non-linear model using best estimate of element strength and stiffness.		Maximum Considered Earthquake 3-D non-linear model using best estimate of element strength and stiffness. Gravity system included if it impacts response.	Maximum Considered Earthquake N/A	Extremely Rare Earthquake Lumped mass models are used for dynamic analyses that are built from hysteresis characteristics determined from static push-over of a full 3-D component model.	Maximum Considered Earthquake 3-D non-linear model using best estimate of element strength and stiffness. Gravity system included if it impacts response.

Table 5: Foundation Interaction

Chile	Indonesia	China	Philippines	Korea	Japan	USA
Not addressed.	Not considered in the case study; the analytical model is fixed at the mat foundation.	Typically modeled with rigid base.	Soil-structure interaction is considered in the modeling of foundation, using equivalent vertical and lateral spring stiffness values.	Typically not included in lateral models. Included for severely soft soil. Spring stiffness is by soil-structure interaction analysis or geo-tech engineer recommendation.	Typically included in lateral model as springs. Occasionally included in the lumped mass model as finite-element.	Typically included in lateral models in a limited manner. Foundation supports typically assumed to be pinned rather than using soil springs and dashpots.

Table 6: Damping

Chile	Indonesia	China	Philippines	Korea	Japan	USA
	Case study utilized 2.5% damping	Frequent Earthquake 5% for concrete and masonry structures 2%-4% for steel structures depending on height	Service Level 2.5% of critical damping for response spectrum	Service Level N/A	No imposed methodologies. Typical values: 2% for steel-framed; 3% for concrete-framed. Typical methods: Frequency proportional, tangent stiffness, and Rayleigh Damping.	Service Level 2.5% of critical damping for response spectrum
Design Level 5% damping for design level earthquake		Moderate Earthquake Not specified.	Design Level 5% of critical damping for response spectrum	Design Level 5% of elastic viscous damping ratio Additional 0.2% stiffness-dependent damping ratio for higher mode motions		Design Level 5% of critical damping for response spectrum
		Rare Earthquake 5% for all structure types	Maximum Considered Earthquake 2% to 3% damping considered	Maximum Considered Earthquake N/A		Maximum Considered Earthquake Rayleigh damping included in non-linear model to limit viscous damping to 2.5% of critical in primary modes of response

Table 7: Gravity Load-Resisting Systems

Chile	Indonesia	China	Philippines	Korea	Japan	USA
Typical high-rise buildings have all shear walls or concrete moment frame columns as part of both lateral and gravity systems.	The gravity load-resisting system was not considered in the case study.	A secondary lateral system is generally required. Gravity system is often detailed to provide this.	Not addressed.	Typically not included in PBSD.	Typically designed integrally with the lateral force-resisting system.	Typically analyzed using deformation compatibility approach. Analyzed directly for calculated demands when included in lateral models.

Table 8: Non-Structural Systems

Chile	Indonesia	China	Philippines	Korea	Japan	USA
Not addressed.	Not addressed.	Weight/mass of permanent MEP components shall be included in lateral models. Stiffness of non-structural elements can be neglected. Effect of nonstructural components on structural elements supporting them shall be considered.	Not addressed.	Typically not included in PBSD.	Must be confirmed to be damage-free at Rare EQ and must not fall from building at Extremely Rare EQ.	Common to include mass of non-structural systems in the lateral models. Rarely is the stiffness of non-structural elements included in the lateral model. Performance can be assessed based on acceleration and drift demands.

Table 9: Review Procedures

Chile	Indonesia	China	Philippines	Korea	Japan	USA
Not addressed.	A peer review is required for all buildings located in Jakarta that are 8 stories or greater under the current code and the proposed new code.	For general building structures, peer review shall be conducted by a qualified drawing review firm after the design is completed. For high-rise buildings, peer review shall be conducted by the Expert Committee organized by local or national construction department.	Since the performance-based designed approach is a relatively new concept and falls outside of the prescriptive building code, the independent peer reviews have been a general practice or requirement as described in PEER (2010) methodology. Generally limited to seismic design, but can include wind and non-structural components at the building official's discretion.	The check list initiated by the committee of damping devices is frequently used in different kinds of damping practices.	Review by organization designated by national Ministry to ensure code minimum-prescribed safety requirements and criteria are met. Includes review of effects of wind, snow, earth pressure, temperature change, etc.	Peer review is required due to non-conforming design approach. Common practice involves a panel of three reviewers, including structural design and seismic hazard expertise. The authority having jurisdiction assists in determining the scope of review.