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GUIDELINES FOR SEISMIC DESIGN OF TALL BUILDINGS

R. O. Hamburger[1] and J. P. Moehle[2]

ABSTRACT

Performance-based seismic design methods in the United States originated as a practical and effective means to mitigate the seismic risks posed by existing buildings and were later extended to permit development of new buildings capable of superior seismic performance. These methods were quickly adapted to justify design of new buildings that do not conform to building code requirements, and which are intended only to provide equivalent performance to buildings conforming to code criteria. This practice has become particularly prevalent in the design of very tall buildings in the Western United States. The Pacific Earthquake Engineering Research Center, working with the tall building design community, has developed a performance-based seismic design methodology for tall buildings that encompasses and improves upon the procedures developed during the past 10 years of practice.

Introduction

Initial development of performance-based seismic design procedures in the United States occurred in response to societal reactions to the nearly annual occurrence of damaging earthquakes in the Western United States during the period 1979-1994. These earthquakes provided many illustrations of both the strengths and weaknesses of seismic provisions in U.S. building codes and spurred substantial evolution and improvement of these provisions. Most buildings designed to the code provisions achieved the life-safety intent of the building code, but several experienced extensive damage resulting in large economic loss. These earthquakes also provided frequent reminders that the inventory of existing buildings included many older structures that were susceptible to life-threatening damage and which posed unacceptable seismic risks.

Some corporations and institutions became interested in voluntary seismic upgrades. Engineers working on their behalf quickly found that decision-makers in these organizations wanted to know how their buildings would perform, in terms meaningful to them, before they would commit to retrofit. Often these decision-makers wanted to tailor retrofit programs to

[1]Senior Principal, Simpson Gumpertz & Heger Inc., San Francisco, CA
[2]Professor , Department of Civil and Environmental Engineering, University of California at Berkeley, Berkeley, California

optimize their costs and benefits. These same decision-makers quickly became interested in seismic performance issues in the design of new buildings as well, to assure that their important facilities would adequately protect their business and operational needs and that they did not encumber unacceptable future economic losses.

Many owners of hazardous buildings were not interested in seismic upgrades, prompting governments to adopt mandatory upgrade programs. To justify adopting such programs, it was necessary to contrast the likely performance of hazardous buildings and the consequences if no action were taken. Performance-based seismic engineering was developed to enable engineers to respond to the need to reliably assess the probable performance of new and existing buildings under a variety of design scenarios

The Federal Emergency Management Agency (FEMA) provided the primary financial support for development of performance-based seismic engineering procedures. FEMA funded the Applied Technology Council's (ATC) development of a series of performance-based engineering criteria and guidelines including FEMA-273/274(ATC, 1997a, b) that form the basis for present generation performance-based seismic engineering practice. The American Society of Civil Engineers subsequently converted these documents into the ASCE-31(ASCE, 2002) and ASCE-41(ASCE, 2006) standards that could be adopted by building codes.

These first-generation procedures experienced widespread acceptance and application, both in their intended use, evaluation and upgrade of existing buildings; and also for application to the new building design. However, for new building design, the primary application of these procedures is to demonstrate that nonconforming designs have equivalent performance capability as that intended by the building code, allowing development of buildings at lower cost or with other attributes attractive to developers. This practice became particularly popular in design of very tall buildings, contributing to the development of many of these structures in the period 2003-2008 in Los Angeles, Seattle, San Francisco and other western cities with significant seismic hazards.

Many of these structures are tall residential buildings, having post-tensioned concrete flat slabs supported by a ring of perimeter reinforced concrete columns and tubular bearing walls surrounding the central core. Prescriptive U.S. code provisions prohibit such construction in excess of 50 meters tall, without provision of a dual special moment-resisting frame capable of resisting at least 25% of specified seismic design forces. By using performance-based procedures, engineers were able to eliminate the moment-resisting frame, saving cost, and more importantly permitting exterior designs that accommodated floor to ceiling windows and reduced story heights in buildings extending to 200 meters tall.

Building Code Compliance

Western U.S. cities generally adopt and rigorously enforce building regulations based on the *International Building Code* (ICC, 2006). These codes adopt prescriptive seismic design provisions through reference to the *ASCE 7*(ASCE, 2005) standard, which is based on the *NEHRP Recommended Provisions for Buildings and Other Structures* [BSSC, 2003]. The *International Building Code* also includes permissive language that enables the use of alternative procedures demonstrated to provide performance equivalent to the prescriptive requirements. The design professional must demonstrate equivalence to the satisfaction of the building official. Many, but not all building officials have proven amenable to the use of these procedures.

The code does not limit the procedures that can be used to demonstrate equivalence, nor does the code state, in other than generic and qualitative terms, what performance is acceptable. Most engineers and building officials adopt target performance based on the commentary to the *NEHRP Recommended Provisions*. This commentary states that for ordinary structures the objective is to provide a low conditional probability of collapse, given the occurrence of Maximum Considered Earthquake shaking, and to preclude, to the extent practicable, economic losses associated with more frequent and moderate events. The recently published *FEMA P695* [ATC, 2009a] and *FEMA P750* [BSSC, 2009] reports clarify that the acceptable conditional collapse probability is 10% and specify rigorous analytical and statistical methods for collapse probability quantification. However, these methods are complex and have not yet been adopted into general practice. Instead, engineers have adapted procedures based on ASCE-41.

Engineers have typically performed preliminary design in general conformance with the prescriptive code requirements, but taking a limited number of well-defined exceptions. The resulting near conformance to the code requirements provides both building officials and engineers a foundation level of comfort with the designs. Nonlinear response history analysis is used to demonstrate adequate collapse resistance. Performance is evaluated on an element by element basis using acceptance criteria contained in the ASCE-41 standard, sometimes supplemented with project-specific criteria derived from available laboratory testing to demonstrate acceptable behavior. Since analysis tools used in most design offices are incapable of reliably predicting response of structures nearing collapse, acceptance criteria are often conservatively selected to assure response within the range of analysis reliability.

Many building officials lack the technical expertise to review complex analyses or interpret laboratory test reports and have required independent third party review as a condition of acceptance of performance-based designs. Though procedures vary, third party reviews are typically performed by teams including a practicing engineer with expertise in tall building design and seismic technology, a researcher with particular knowledge of the types of structural systems to be employed (e.g., reinforced concrete walls, steel frames, etc.) and a geotechnical engineer. Reviews can be rigorous and include consideration of the design criteria, ground motion selection and scaling, analytical modeling and results, and structural detailing. The review process can be lengthy and can have significant effect on the design.

First-Generation Procedures

Initially engineers adopted ad hoc procedures for performance-based design of tall buildings. Later, documents produced by engineers in Northern California (SEAOC, 2007) and Southern California (LATBC, 2006) formalized these procedures. Generally, designs conform to the prescriptive code provisions with limited exceptions. These exceptions may include exceedance of code-specified height limits, violation of code requirements with regard to redundancy, and occasional use of materials, e.g., high strength steel and detailing procedures not specifically recognized by the code. Given the general similarity of these buildings to code-prescriptive designs, the procedures that developed typically included: development and approval of a formal criteria document, preliminary design, code-level analysis; and verification of adequacy for Maximum Considered Earthquake shaking.

Design criteria development and approval is an important first step. The formal criteria document includes a description of the overall structure and its intended load-resisting mechanisms; identification of any exceptions to the building code requirements and the justification for these exceptions; and identification of analytical procedures, load combinations, design ground motions, material properties, and detailing. The intent is to identify all substantive issues before the designer has expended large effort in actually performing the design. In theory, if all procedures and assumptions are agreed to at project inception, approval of the finished design should be straightforward and attainable without controversy. In practice, however, it is rarely possible to foresee all issues that will arise during the design development, and many substantive criteria issues are resolved through cooperative efforts of the designers and reviewers throughout the project.

The preliminary design provides the basis for succeeding steps. Capacity-based design procedures, wherein a preferred yield mechanism is identified and other elements of the structure are proportioned to remain elastic, or essentially so, are typically used. Initial sizing of elements is often controlled by considerations of dead, live, and wind loads. In many structures, lateral design for wind forces controls even the final sizing of many elements.

The-code level design is used to confirm the adequacy of preliminary sizing and also to provide building officials with confidence, at a primary level, that the structure is comparable to one designed to conform to the code in all respects. In this step, the engineer typically performs the code-prescribed analyses, and evaluates all relevant code-prescribed strength, deformation, and detailing requirements, except those which were specifically exempted in the formal design criteria. Since the building systems used in these structures are not strictly code-compliant, *R*-coefficients and other factors required in the code procedures are typically selected jointly by the designers and reviewers based on judgment.

Verification of behavior in MCE-level shaking is performed using three-dimensional nonlinear response history analyses. Typically, suites of seven horizontal ground motion pairs are used. Ductile behaviors including wall, slab, and beam flexure are evaluated using the mean of the maxima for relevant demand parameters (flexural strain, plastic rotation, etc.). Brittle behaviors, and those with a potential to result in catastrophic failure, including wall shear, column axial force, slab punching shear, etc. are typically evaluated using either maximum demands obtained from the suites of analyses or mean demands that have been amplified by an estimated value of the standard deviation with the intent to provide a low probability of failure. Following procedures contained in *ASCE-41,* models and acceptance criteria for ductile behaviors are typically constructed using expected (mean) values of material properties, considering potential variability and strain hardening effects. Acceptance criteria for brittle and catastrophic behaviors are typically developed using lower bound material properties and sometimes using resistance factors to account for potential dimensional variability and construction quality issues.

The Tall Buildings Initiative

The PEER Tall Buildings Initiative is a cooperative program of research and development undertaken by researchers at the Pacific Earthquake Engineering Research Center and practicing structural and geotechnical engineers experienced in tall building design. Spurred by the rapid growth in the use of performance-based seismic design methodologies for the design of tall buildings, the goal of this initiative is to provide a sound and reliable basis for these procedures and to help assure appropriate seismic performance of the resulting new generation of tall buildings.

The program, initiated in 2006, encompasses a range of tasks intended to investigate: the dynamic characteristics of tall buildings; the performance capability of buildings designed using alternative procedures; societal preferences for tall building performance; alternative means of developing ground motions for design; soil-foundation-structure interaction effects, modeling, and analysis procedures; and development of design guidelines. An important companion report on modeling, analysis, and acceptance criteria for tall buildings [ATC, 2009b] is available from the Applied Technology Council. Reports on other task activities can be obtained at http://peer.berkeley.edu/tbi/index.html.

Design Guidelines

The PEER Guidelines for Seismic Design of Tall buildings represents an evolutionary step in the practice of performance-based seismic design of tall buildings. The guidelines embrace the same analytical technologies adopted by engineers following the San Francisco AB-083 and Los Angeles Tall Buildings Council criteria but provide more guidance on structural modeling, acceptance criteria, and ground motion selection and scaling. There are two important departures from prior practice. First, the guidelines do not require a code-level analysis in that it is anticipated that the procedures may be applied to structural systems for which the code response modification coefficients will not be defined, leaving the code analysis with questionable value. Second, the guidelines use more advanced procedures for evaluating structural performance, anticipating the availability of software that can reliably assess the response of structures in a near-collapse state.

The guidelines focus evaluation procedures on verification that the design performance objectives can be achieved, rather than verification that the building mostly complies with prescriptive criteria. The design performance objectives are those most commonly adopted by leading earthquake professionals today as the intent of the building code, that is, serviceability with minimal repair for frequent earthquake shaking levels and safety for rare earthquake shaking levels. With the exception of exterior cladding systems, the failure of which could cause numerous casualties in a crowded city, the guidelines address structural performance only. The procedures presume that nonstructural components and systems will be designed to conform to the prescriptive code criteria, but do caution that if a building's response characteristics are substantially different from that of typical code-conforming buildings, additional precautions may be required. The guidelines are written in a "recommendation" and commentary format. Recommendations are written in mandatory language, while commentary explains the basis for the recommendations and warns of significant design issues that may not be adequately covered by the recommendations.

As with the AB-083 and Los Angeles Tall Buildings Council criteria, designers must prepare a formal, project-specific design criteria document. The guidelines recommend independent third party review of the criteria, the analyses, and the design. The guidelines employ two levels of analysis: a Service level and a Maximum Considered level.

Service-Level Evaluation

The purpose of the Service-level check is to assure that the buildings will not experience significant damage from frequent earthquakes. Much controversy surrounded the selection of a Service-level shaking intensity. The 2008 edition of the Los Angeles Tall Buildings Council guidelines[LATBC, 2008] specified service-level shaking with a 50% exceedance probability in 30 years (43-year mean recurrence interval), but permitted Service-level analyses to use 5% viscous damping. Studies conducted by the Applied Technology Council as part of the TBI effort, and summarized in the ATC-72 (ATC, 2009b) report, suggest that 5% viscous damping is excessive for tall buildings. Instead, 2.5% equivalent viscous damping is more justifiable and, in keeping with this, some participants argued for use of a Service-level event with a 25-year mean recurrence, arguing that the response spectrum for such an event, when used with 2.5% damping, would be comparable to the 5%-damped 50%-30 year spectrum. Other participants believed that a 25-year recurrence for onset of damage to these buildings was not an appropriate design objective. Eventually consensus support was achieved for the use of a 2.5% damped, 50%-30 year spectrum as the Service-level loading.

The stated performance goal for the Service-level loading is to avoid onset of damage that would reduce the building's ability to withstand Maximum Considered-level shaking or which would require repair that would necessitate removing the building from service. It is expected that some repair of structural elements may be necessary to restore cosmetic appearance, and fire and weather resistance. Nonstructural damage is anticipated to be minor, but is not specifically evaluated.

The guidelines recommend an elastic, three-dimensional response spectrum analysis for the Service-level because the desired behavior is intended to be essentially elastic and also because it is desired to assure that an elastic analysis is available to benchmark and evaluate nonlinear models used in the Maximum Considered-level evaluation. Analytical models must extend to the structure's true base, which for most tall buildings is located several levels below grade. Soil-foundation-structure interaction effects need not be explicitly modeled, though it is permitted to do so. Based on analytical studies of typical buildings conducted under the Tall Buildings Initiative, when soil-foundation-structure interaction effects are not modeled explicitly, mass of subgrade levels is permitted to be neglected.

Acceptance criteria include both strength and deformation. Strength is evaluated by comparing computed strength demands against expected strength. Expected strength is computed using the strength formula contained in the design specifications referenced by the building code; however, mean estimates of material properties are permitted to be used in place of minimum specified values. For example, the design engineer can propose using concrete and reinforcing steel strengths equal to 1.25 times specified values, and structural steel strengths ranging from 1.1 to 1.3 times specified values depending on the grade of steel used. Resistance factors are not used in determining element strength for this evaluation. Computed demand to capacity ratios may be as large as 1.5 for ductile elements and must be less than unity for other elements. Story drift at any level is not permitted to exceed 0.5% of the story height.

If some computed demand to capacity ratios exceed a value of 1.5, designers are permitted to use three-dimensional nonlinear response history analysis to demonstrate acceptable Service-level performance. When such analyses are performed, a suite of not less than three horizontal ground motion pairs must be selected and modified to be compatible with the Service-level spectrum previously discussed. Either amplitude scaling or spectral matching may be used to achieve spectrum compatibility following procedures presented in the guidelines. Acceptance criteria must be developed based on suitable laboratory test data. Mean values of response parameters obtained from the suite of analyses cannot exceed demand levels at which the test data suggest the onset of strength degradation or damage, the appearance or repair of which would result in occupancy loss.

The Service-level event does not provide an effective floor for a structure's base shear strength. Although in some highly active seismic regions such as Los Angeles and San Francisco the 2.5% damped 50%-30 year spectrum will result in strength demand comparable to that obtained following the prescriptive code criteria, in regions of lower seismicity such as Portland, Oregon, and Salt Lake City, Utah, the Service-level spectrum will result in substantially less strength than would be required for a code-conforming building. Commentary warns designers in these regions that additional strength may be required to provide adequate margin against collapse at the Maximum Considered level.

Maximum Considered-Level Evaluation

MCE-level evaluations are performed for the same level of shaking specified by the building code for this hazard level. The intent of the MCE evaluation is to demonstrate that the structure is capable of surviving this level of shaking with low probability of collapse. However, since the procedure does not include either explicit collapse or statistical analyses as does the *FEMA P-695* procedure, building adequacy is implied through limiting nonlinear response to levels at which significant margin would seem to remain. MCE evaluations are performed using nonlinear response history analysis and at least seven pairs of motions that are modified, either amplitude scaled or spectrally matched, to be compatible with the MCE spectrum.

The guidelines provide extensive discussion of structural modeling techniques and assumptions. The subject of strength degradation, in particular, receives extensive discussion. Where strength degradation is explicitly modeled in a manner that reasonably predicts the hysteretic behavior obtained from testing using varied loading protocols, permissible levels of nonlinear response are relaxed relative to analyses conducted with models that have less explicit incorporation of cyclic strength degradation. Specifically, there are no limitations on the acceptability of nonlinear deformation demand for ductile elements, so long as element response remains within levels at which the hysteretic models employed are valid and loss of gravity load carrying capacity does not occur. The guidelines suggest limitations on deformation demand when analytical models are used that do not properly account for element strength and stiffness degradation effects.

As with Service-level evaluations, models must extend to the structure's true base level. Modeling of soil-foundation-structure interaction is not required but can be performed. Models are based on mean material properties. Acceptance criteria include both strength and deformation considerations.

Actions that are not ductile are evaluated using demand obtained from the equation:

$$Q = D + L_{\exp} + F_E \tag{3}$$

where D is the dead load and L_{exp} is the expected live load, taken as 25% of the code-specified load. The earthquake effect, F_E, is taken either as 150% of the mean earthquake demand $\bar{E}$ computed for the suite of analyses or, for actions with strength demand limited by yielding of other elements, F_E may be taken as $\bar{E} + 1.3\sigma \geq 1.2\bar{E}$, where σ is the standard deviation of the response parameter as obtained from the suite of analyses. It is widely recognized that the true dispersion of responses cannot be adequately gauged using only seven earthquake ground motion pairs. The factor 1.5 applied to the mean response is intended to produce a low probability (around 10%) of exceeding the reliable strength in any one earthquake ground motion at the MCE level. It would be applicable, for example, to wall shear strength. The alternative equation is applicable, for example, to shear in an outrigger beam designed by capacity design methods to be limited by flexural strength. Strength capacities are computed using expected material properties and a resistance factor. The resistance factor may be taken as unity where failure of the element would not result in catastrophic failure and must be taken in accordance with the building code otherwise.

The mean story drift from the suite of analyses in any story is not permitted to exceed 3% and the story drift for any single analysis is not permitted to exceed 4.5%. These limits were selected somewhat arbitrarily based on the guideline writers' comfort with the ability of present analytical methods to predict response at very large deformation. In addition to limits on maximum transient story drift, the guidelines also limit maximum residual drift. The mean value of residual drift from the suite of analyses cannot exceed 1% of story height in any story and the maximum residual drift in any story from any analysis cannot exceed 1.5% of story height.

Conclusions

The PEER Tall Buildings Initiative has been a successful collaboration of earthquake engineering researchers, practicing structural and geotechnical engineers, and building code officials to address the need for appropriate consensus criteria for performance-based design of tall buildings in the Western U.S. Though evolutionary rather than revolutionary in nature, the PEER Tall Building Design Guidelines introduce significant improvements to practice in the design of these buildings. Of particular note is the provision of modeling guidelines that more realistically account for the nonlinear behavior of buildings than approaches previously used by the profession, together with incorporation of more rational acceptance criteria. The authors believe that the new guidelines will permit the development of tall buildings that are more likely to meet the intended performance objectives embedded in the building code, either than buildings designed to the prescriptive code provisions, or buildings that have been recently designed using performance-based approaches. Future development in this area should include further guidance on selection and scaling of ground motions, direct consideration of nonstructural behaviors, and incorporation of explicit collapse margin investigations.

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