The Tall Buildings Initiative

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ABSTRACT

Several west coast cities are seeing an upsurge in the construction of high-rise buildings. Many of these buildings feature framing systems, materials, heights, and dynamic properties not envisioned by our current building code prescriptive provisions. Rather than force these buildings to conform, many jurisdictions are allowing these new designs to proceed under the alternative procedures provision of the building code, which allows alternative lateral-force procedures using rational analyses based on well-established principles of mechanics in lieu of the prescriptive provisions. Most designs are opting for a performance-based approach in which a rational analysis demonstrates serviceability and safety equivalent to that intended by the code prescriptive provisions. Several questions arise in a performance-based design. What is equivalent performance? How should it be demonstrated? If dynamic analysis is conducted for a range of anticipated earthquake ground motions, how should the ground motions be selected and how should the design value determined? How should performance designs be reviewed?

The *Tall Buildings Initiative* is funding a range of short to intermediate-term projects in 2006-2009. The final product will be a set of written guidelines containing principles and specific criteria for tall building seismic design. The document is intended to support ongoing guidelines and code-writing activities of collaborating organizations, as well as being a stand-alone reference for designers of high-rise buildings.

KEYWORDS: Tall Building Initiatives, Pacific Earthquake Engineering Research Center.

1. INTRODUCTION

The west coast of the United States, a highly seismic region, is seeing a surge in the design and construction of tall buildings (defined here as buildings 240 feet, 73 meters, or taller). Many of these buildings use high-performance materials and framing systems that have not been commonly used for building construction or that fall outside the height limits of current buildings codes. In many cases, prescriptive provisions of governing building codes are found to be overly restrictive, creating pressure to design outside the limits of the code prescriptive provisions (e.g. SFBC, 2001). These alternative procedures allow the used of nonlinear dynamic analyses to demonstrate the seismic performance of buildings. While guidelines (FEMA 356, 2000; LATBSDC 2008; SEAONC 2007) and code requirements (ASCE 7-05, 2005; IBC, 2003; UBC, 1997) exist, there still remain many undefined aspects of nonlinear performance-based design for which additional guidance would be helpful. Recent and ongoing research is providing some of the answers, but many issues in performance-based design remain unanswered.

The Pacific Earthquake Engineering Research Center (PEER) is leading the *Tall Buildings Initiative* to fund and coordinate a range of short to intermediate-term projects in 2006-2009. The final product will be a set of written guidelines containing principles and specific criteria for tall building seismic design. The document is intended to support ongoing guidelines and code-writing activities of collaborating organizations, as well as being a stand-alone reference for designers of high-rise buildings.

2. The New Generation of Tall Buildings in the Western United States

Urban regions along the west coast of the United States are seeing a boom in tall building construction. Many of the buildings are residential or mixed-use (including residential) occupancy. Functional requirements for tall residential buildings have led to new building configurations and systems that do not meet the prescriptive definitions and requirements of current buildings codes. These include efficient framing systems whose redundancy may be reduced compared with more conventional buildings. High-strength materials and specialized products are also being proposed to help meet the unique challenges introduced by these structures.
Figure 1 illustrates one example of a 60-story building in San Francisco in which the seismic force-resisting system involves reinforced concrete core walls with buckling-restrained steel braces along one axis. The building exceeds prescriptive building code height limits for core-wall-only systems by a factor of approximately three. In this building, the gravity framing comprises unbonded post-tensioned concrete flat-plate framing. Under earthquake ground shaking, this gravity framing, while not designed as part of the primary seismic-force-resisting system, will undergo lateral displacements and will accumulate over its height significant axial forces owing to unintended outrigger action. The unintended frame action also will result in wall shears higher than those expected for a wall-only system. These effects must be considered in design. Other framing systems including moment frames, steel-plate walls, and steel gravity frames mixed with concrete walls are being considered for various buildings, each with its own special design needs.

High occupancy levels and interest in re-occupancy following an earthquake are leading to rethinking of performance objectives. As a minimum, a building must be safe for rare ground shaking demands, and must remain safe for significant aftershocks. However, there is increasing concern that serviceability for more frequent events ought to be considered as well. In view of the very long vibration periods of tall buildings, special treatment of design ground motions is needed to ensure they are representative in their damage potential, including proper duration and long-period energy content, so designs based on them will safely represent anticipated effects of future earthquakes. While equivalence to building code minimum performance requirements is likely to be the basic objective, there is no consensus on how to translate that performance objective into specific engineering demands and capacity checks in a performance-based procedure. These are some of the performance-based earthquake engineering challenges of the new generation of tall buildings.

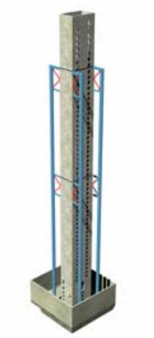


Figure 1. Schematic of seismic-force- resisting system of 60-story building in San Francisco (Magnusson – Klemencic).

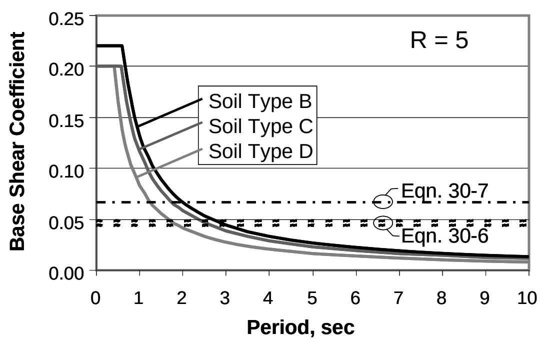


Figure 2. UBC-97 required design base shear for typical development site in San Francisco.

3. Anticipated Building Response

With the exception of special high-performance buildings and buildings with special protective systems, it usually is not economically feasible to design a building to remain fully elastic for ground motions representative of the maximum considered hazard level in regions of high seismicity. Therefore, some nonlinear behavior should be anticipated during design and analysis.
In U.S. seismic design practice, the design strength of a building satisfying the code prescriptive provisions is established based on the forces that would occur for linear seismic response divided by a force reduction factor

R. Thus, the value of R used in design provides a measure of the degree of nonlinearity expected during a design earthquake. For a tall building, the required strength commonly is controlled by minimum base-shear requirements. Consequently, the effective R value is reduced from the value specified in the building code for that framing system to a smaller value dependent on building period and other factors. Figure 2 illustrates design base shears from the Uniform Building Code (UBC, 1997) for a typical site under development in San Francisco.

The Structural Engineers Association of Northern California has issued a guideline for the performance-based seismic design of buildings designed to the “alternative provisions” clause of the San Francisco Building Code (SEAONC 2007). This document can serve as a model for other jurisdictions. A serviceability evaluation for ground motion levels having 43-year mean return period anticipates that a building may not remain fully elastic but that damage will be cosmetic and not require major repairs. Structural and nonstructural systems must be designed to be safe for ground motion levels having 475-year mean return period (10% probability of exceedance in 50 years), and the structural system is required to remain stable with maximum inter-story drifts not exceeding 0.03 for ground motions corresponding to the larger of 10% probability of exceedance in 100 years or 1.5 times median deterministic motions.

4. Ground Motions for Nonlinear Analysis

Seismic ground shaking for performance-based design of tall buildings usually is represented using site-specific seismic hazard analysis. Seismic hazard due to ground shaking should be determined considering the location of the building with respect to causative faults, the regional and local site-specific geologic characteristics, and the selected earthquake hazard level. In general, the seismic hazard should include earthquake-induced geologic site hazards in addition to ground shaking. The discussion here is limited to ground shaking hazard.

Where nonlinear dynamic analysis is used, representative ground motion records are required. The predominant current practice is to select records from actual earthquakes considering magnitude, distance, site condition, and other parameters that control the ground motion characteristics. The current practice is to use a comprehensive recorded ground motion database compiled by PEER (PEER GM, 2007). To help guide selection of ground motion records, the seismic hazard can be deaggregated for each hazard level to determine the contributions to the hazard from earthquakes of various magnitudes and distances from the site. Because magnitude strongly influences frequency content and duration of ground motion, it is desirable to use earthquake magnitudes within 0.25 magnitude units of the target magnitude (Stewart, et al., 2001). Duration can be especially important for tall buildings because of the time required to build up energy in long-period structures. For sites close to active faults, selected motions should contain an appropriate mix of forward, backward, and neutral directivity consistent with the site (Bray and Rodriguez-Marek, 2004).

Once a suite of recorded ground motions has been selected, these motions are commonly manipulated to represent a target spectrum, using either amplitude scaling or spectrum matching. Resulting motions should be compared with original motions to ensure the original character of the motion is not modified excessively. There currently is no consensus on which approach, amplitude scaling or spectrum matching, is preferable for nonlinear dynamic analyses. The advantage of scaling is that individual ground motion records retain their original character including peaks and valleys in the response spectrum. However, given the long fundamental periods characteristic of tall buildings, it can be difficult to find records with sufficient energy in the long-period range, therefore requiring relatively large scaling factors that may result in unrealistic short-period response. This procedure, therefore, if is not done appropriately, may excessively affect response of higher modes. Spectrum matching can alleviate the aforementioned problem with scaling, but matching the uniform hazard spectrum at every period also produces ground motions that are unrealistic and may be excessively demanding.

Alternative approaches to ground motion selection and scaling are being studied. PEER is coordinating a Ground Motion Selection and Modification (PEER GMSM, 2007) working group to examine various GMSM procedures for nonlinear response history analysis. Abrahamson (2006) has recommended that the ground motion selected for analysis should represent a scenario earthquake, that is, just one of the many earthquakes that contribute to the uniform hazard spectrum at the site. In this case, the selected motion is matched to the response spectrum of the scenario earthquake, which is less broadband than the uniform hazard spectrum (Figure 4). Baker (2006) and Cornell (2006) have recommended that the scenario spectrum should be modified to represent the conditional mean response spectrum, which takes into account the lack of correlation between response spectral amplitudes at different periods. This method is being implemented in a user-friendly web-based tool, "Design Ground Motion Library, DGML", supported by PEER and the California Strong-Motion Instrumentation Program. These methods imply a deaggregation of the seismic hazard to identify which earthquakes have the highest contribution to the seismic hazard at a key vibration period of the building. A problem that arises with a tall building is that different engineering demands are controlled by different periods (for example, overturning moment might be controlled by the fundamental period while link beam demands are controlled by higher "modes"). To the knowledge of the authors, this question of how to use scenario-based ground motions for tall buildings has not been completely resolved.

The *Tall Buildings Initiative* has several tasks on the subject of earthquake ground motion selection and scaling. One task is using validated broadband ground motion simulation procedures to generate ground motion records in San Francisco and Los Angeles for large-magnitude earthquakes on the major faults governing design in those regions. The records will be simulated for geographic areas of specific interest for San Francisco and Los Angeles. These broadband simulated records are to contain long-period effects such as rupture directivity effects and basin effects that are specific to the fault geometry and geological structure of the regions. A main purpose of these simulations is to define types of waveforms that result from large-magnitude earthquakes; amplitudes for design will be established by probabilistic seismic hazard analysis results. A series of review tasks also will ensure the simulation procedures are producing realistic results and are properly interpreted. Yet another task is studying how tall buildings respond to different earthquake ground motions. These studies will help define ground motion selection and scaling procedures that will result in tall building response simulations that adequately represent the range of engineering design demands on critical building components.

Another major task of the *Tall Buildings Initiative* is examining input ground motions for buildings with subterranean levels. It is well known that depth of embedment affects the input motions to a structure. Soil-foundation-structure interaction also affects building dynamic properties and effective damping associated with soil nonlinearity and radiation of energy away from the building through the surrounding soil (so-called radiation damping). Finally, dynamic soil pressures on basement walls have important effects that need to be considered in design.

5. Analysis for Tall Buildings

Performance-based seismic analysis of tall buildings in the U.S. increasingly uses nonlinear analysis of a three-dimensional model of the building. Both geometry and material nonlinearities should be accounted for during the nonlinear dynamic analyses. Components do not have significant interaction with lateral-force-resisting parts of the building may not be directly modeled. However, effective mass and P-delta effects associated with "non-participating" parts of the building must be included in the overall analytical model. Furthermore, non-participating components that support gravity loads need to be checked for performance at anticipated force and deformation demands associated with MCE loadings, including effects of unintended outrigger action, which can result in significant axial forces in gravity columns of tall buildings.

Because the behavior is nonlinear, nonlinear behavior at one hazard level cannot be scaled from nonlinear results at another hazard level. Additionally, conventional capacity design approaches can underestimate internal forces in some structural systems because lateral force profiles and deformation patterns change as the intensity of ground shaking increases (Eberhard and Sozen, 1993). Figure 5 shows moment profiles for a tall core wall building subjected to different levels of earthquake ground motion. Twenty-seven ground motion pairs for earthquakes of M7 at 10 km were factored by 1, 2, and 4, resulting in the mean core wall moments over height as shown. According to this analytical result, the wall develops its plastic moment strength at the base, as intended in design, and wall base moment remains close to the plastic moment capacity as the intensity of ground motion increases. Wall moments above the base, however, continue to increase with increasing ground motion intensity even though the base has reached its plastic moment capacity. This is because lateral deformations in various "modes" and associated internal forces continue to increase as shaking intensity increases. Design studies of very tall wall buildings suggest that this behavior can lead to formation of secondary wall plastic hinges near midheight. Only by analyzing the building for the target hazard level can these internal deformations and forces be identified. Further study is needed on this subject.

The *Tall Buildings Initiative* has embarked on a task to improve nonlinear modeling and simulation practices for tall buildings. The current focus of the work is subdivided in three main tasks. The first task is developing guidelines for good modeling and simulation practices, including subjects such as equivalent damping, component strength modeling principles, hysteresis rules, and strength-degradation modeling. The second task is developing modeling guidelines for commonly used reinforced concrete core wall buildings, including initial stiffness assumptions, strength calculations for complex geometries, deformation capacity models, and good modeling practices so the outputs from computer analyses (e.g., concrete strains) can be reliably interpreted.

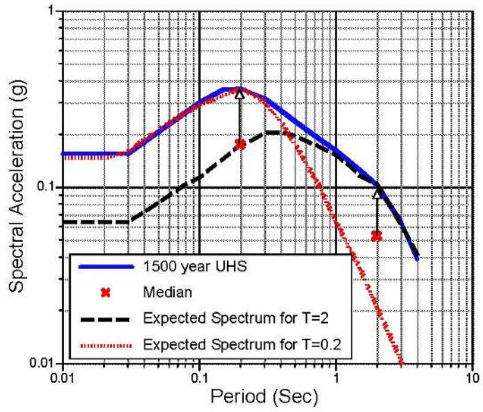


Figure 4. Uniform hazard spectrum and scenario spectra that combine to create the envelope of the uniform hazard spectrum (Abrahamson, 2006).

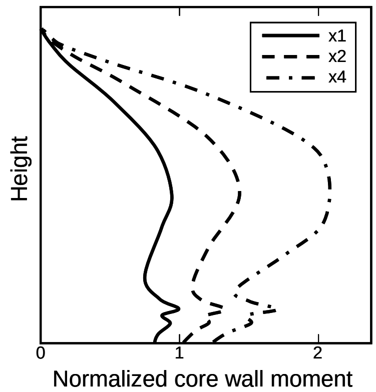
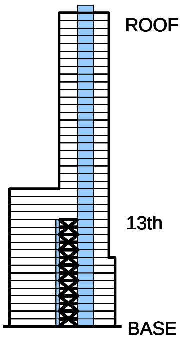


Figure 5. Variation of mean core wall moments for M7 ground motions multiplied by factors of 1, 2, and 4.

6. Design Values

For buildings designed using nonlinear dynamic analysis approaches, building codes and design guides (e.g., ASCE 7-05, 2005; LATBSDC, 2008; SEAONC, 2007) require/recommend that a building design be subjected to a series of design-level earthquake time series to determine the building design-level response. A key question, then, is how to define the design-level response when multiple design ground motions are used. The problem is illustrated in the example building results illustrated in Figure 6. This 40-story building was subjected to 14 earthquake ground motions scaled to design levels to obtain design response results (Maffei, 2005). The coefficients of variation shown in this example are not atypical of results obtained for tall buildings. If design values are taken equal to the median of the results, half the design ground motions result in responses exceeding the design value. To achieve greater conservatism, the design can be defined at some number of standard deviations above the mean or median value. In this case, taking the design shear as one standard deviation above the mean results in a 43 percent increase in design base shear. From one perspective, this is a significant increase in design demand with large cost and functionality implications, but from another perspective it anticipates a not insignificant probability of shear failure due to exceeding the design value should the design-level of ground shaking occur.

The SEAONC recommended procedure (SEAONC, 2007) recommends that demands for ductile actions be taken not less than the mean value obtained from the nonlinear response history analysis, whereas demands for low-ductility actions (e.g., axial and shear response of columns and shear response of walls) should consider the dispersion of the values. Further elaboration is provided in a commentary to the guidelines, which recommends that in typical cases the demand for low-ductility actions can be defined as the mean plus one standard deviation of the values obtained from the nonlinear response history analysis. Furthermore, it is recommended that the procedures for selecting and scaling ground motions, and for defining the demands for low-ductility actions, should be defined and agreed to early in the review process. The tentative nature of the SEAONC recommendation reflects the incomplete state of knowledge on how best to define design values. Additionally, it is not clear how reliable is the estimated "standard deviation" of the response based on seven pairs of input ground motions.



(a) Building elevation

	Roof drift, ft	Wall base shear, k	Wall moment at 13th floor, 1000 x k-ft
Minimum	2.1	7600	513
Maximum	6.7	29700	1080
Mean (m)	4.2	15500	900
m + σ	5.4	22200	1090
c.o.v.	0.23	0.43	0.21
Nonlinear static		5500	760

(b) Summary of results

Figure 6. Building elevation and summary of nonlinear dynamic and nonlinear static analysis results. Nonlinear static analysis results are for inverted triangular floor acceleration pattern.

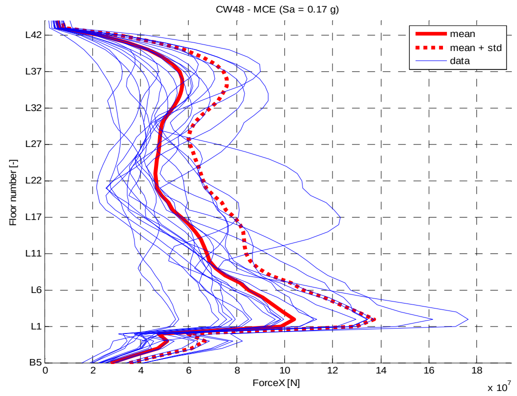


Figure 7. Story shears in a case study core-wall building, from nonlinear response history analysis, for ground motions scaled so the first-mode spectral acceleration matches the uniform hazard level value at the MCE hazard level.

One of the primary goals of the *Tall Buildings Initiative* is to establish improved understanding on how to select and scale earthquake ground motions, and how to define design values from the nonlinear response history analysis. The studies are under way at the time of this writing, so definitive recommendations cannot be given at this time. Some insights into the issue, however, are being developed through tall buildings case studies. For example, Figure 7 illustrates the distribution of story shears for a tall core-wall building with a San Francisco building site for a series of earthquake ground motions scaled so the spectral acceleration at the fundamental period matches the uniform hazard spectral ordinate at the same period for the MCE hazard level. The wide dispersion in the results is apparent.

The database of results from the same case study building can be mined to understand the probability of exceeding the design shear value for various levels of earthquake ground shaking. For example, Figure 8 illustrates over the building height (vertical axis) the probability of exceeding the design shear given that the ground shaking is at the 475-year uniform hazard level spectral acceleration value, with the design shear based on mean or mean plus one standard deviation results from earthquake ground motions scaled to DBE and MCE levels. For example, if the design shear is based on mean plus one standard deviation at the MCE level, as suggested by the SEAONC commentary (2007), the probability of exceeding the design shear for ground motions having 475-year mean return periods is approximately five percent. Whether this is an acceptable result has not been widely considered at this time.

Perhaps a more important question is whether it is sensible to express safety in terms of probabilities of failure given that ground shaking is at some predefined mean return period. It may be more sensible to define mean return periods of exceeding a safe response given the general seismic hazard to which the building is exposed (for example, the mean return period of a nonductile shear failure is 1000 years, or a 5 percent probability in 50 years). Studies to develop this approach are under way at the time of this writing.

7. Building design review

Few building departments have the expertise to understand and approve the code exceptions and alternative means proposed in a performance-based design. Questions invariably arise regarding use and performance of new materials and systems, selection of appropriate hazard levels and representative ground motions, nonlinear dynamic analysis models and results interpretations, acceptance criteria, and quality assurance in design and construction. Peer review by independent qualified experts helps assure the building official that the proposed materials and system are acceptable. The *Tall Buildings Initiative* will develop a set of written guidelines for the performance-based seismic design of tall buildings. The guidelines will include technical guidelines for the engineer and review guidelines for building departments. By clarifying design and review requirements, the overall process will be streamlined.

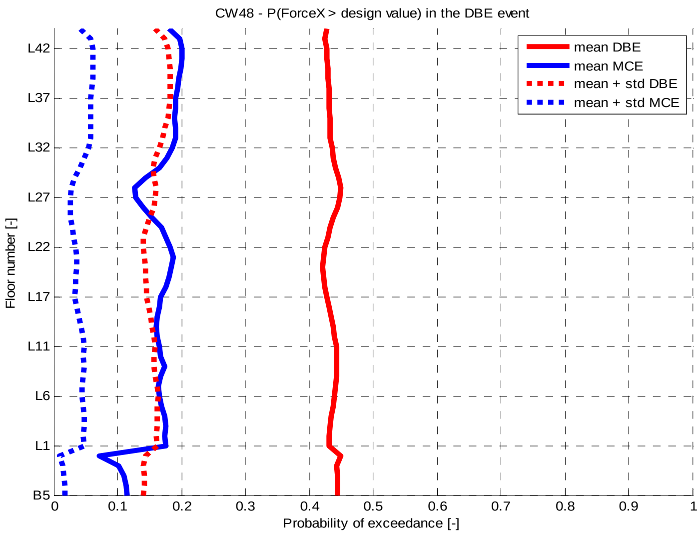


Figure 8. Probability of exceeding the design shear for ground shaking at the 475-year uniform hazard level value, for design shears based on the mean from DBE, mean from MCE, or mean plush one standard deviation for DBE and MCE.

8. Conclusions

Performance-based earthquake engineering increasingly is being used as an approach to the design of tall buildings in the U.S. Available software, research results, and experience gained through real building applications are providing a basis for effective application of nonlinear analysis procedures. Important considerations include definition of performance objectives, selection of input ground motions, construction of an appropriate nonlinear analysis model, and judicious interpretation of the results. Implemented properly, nonlinear dynamic analysis specific to the structural system and seismic environment is the best way to identify nonlinear dynamic response characteristics, including yielding mechanisms, associated internal forces, deformation demands, and detailing requirements. Proportions and details superior to those obtained using the prescriptive requirements of the building code can be determined by such analysis, leading to greater confidence in building performance characteristics including safety. Although performance-based designs already are under way and are leading to improved designs, several research needs have been identified, the study of which can further improve design practices. The *Tall Buildings Initiative* has been established to conduct problem-focused studies that will better clarify design and review requirements, thereby streamlining the overall process of performance-based seismic design of tall buildings.

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