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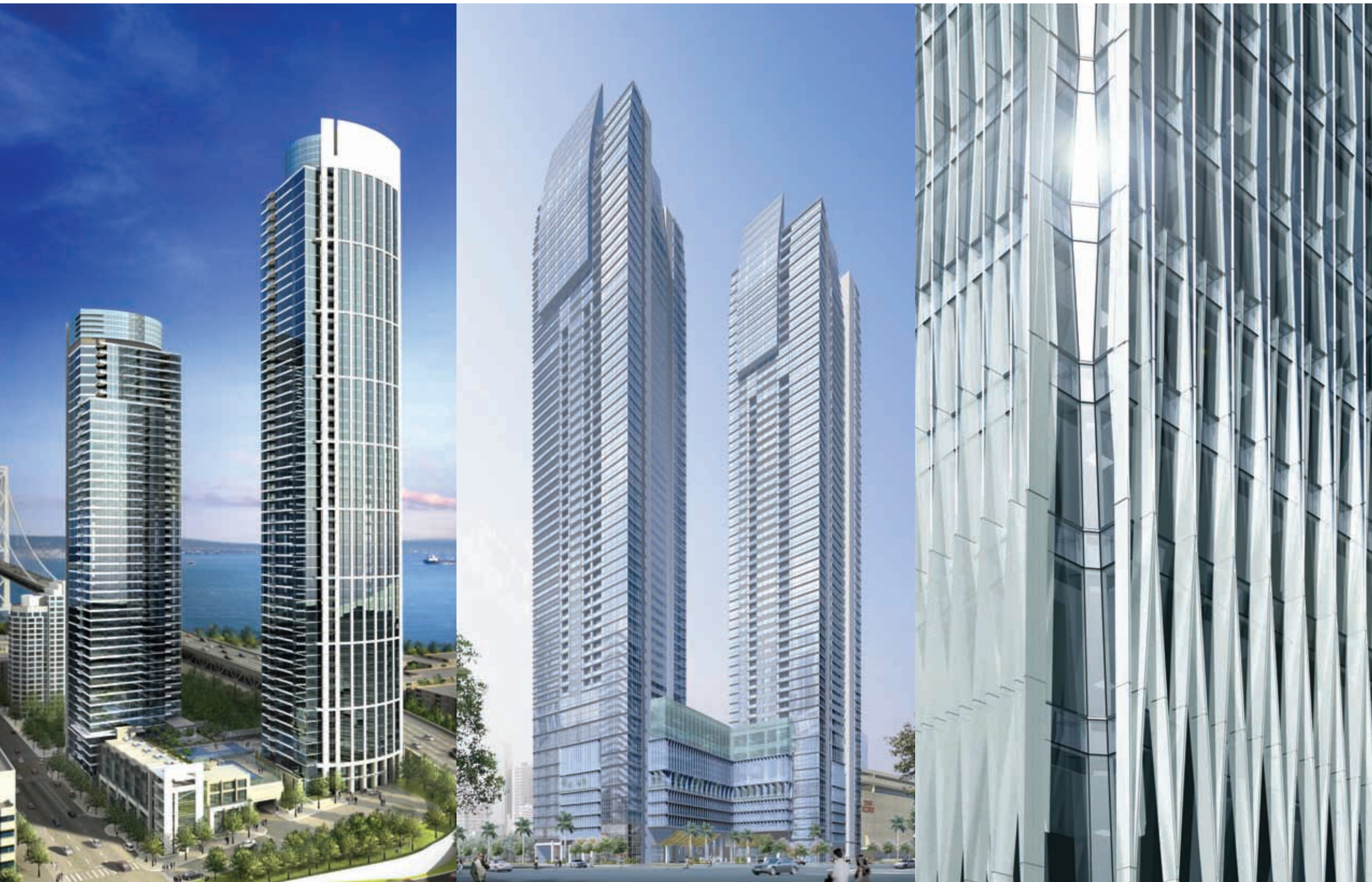
Recommendations for the **Seismic Design of High-rise** Buildings

A Consensus Document - CTBUH Seismic Working Group



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3.0 Seismic Hazard Assessment

3.1 Introduction

The conventional description of seismic hazard for design is an elastic acceleration response spectrum. It is important for the structural designer to understand how such a spectrum is derived, what it represents, and the uncertainties in the reported seismic demand.
A peer-reviewed site-specific seismic hazard assessment is recommended for all high-rise building projects, particularly in locations where the extent of previous study and codified guidance is limited. It should be borne in mind that the accuracy of code response spectra for periods of more than 3 seconds is usually uncertain, and that site specific studies are often required to characterize the seismic demand for the longer period range of interest for many tall buildings.

The following sections present recommendations for site-specific hazard studies and the selection and scaling of ground motions. For the purpose of these Recommendations, it is assumed that a) modal analysis will be conducted for the service-level assessment because the building response must be elastic or near-elastic, and b) nonlinear response-history analysis will be conducted for the collapse-level assessment for which inelastic response is expected in the building.

3.2 Acceleration Response Spectra

A site specific acceleration response spectrum represents the maximum acceleration response of a series of elastic single-degree-of-freedom oscillators of varying natural period at the site for a given intensity of shaking. The intensity of shaking can be defined using a probability of exceedance in a given period of time (typically 50 years) or to a specific scenario earthquake representing a maximum magnitude earthquake in the region. The spectrum can be developed for a point on the ground surface (free-field) or at depth in the soil column.

Site-specific spectra are generally developed for a reference site class condition by Probabilistic Seismic Hazard Analysis (PSHA). Such analysis generates a family of seismic hazard curves, which plot mean annual frequency of exceedance versus 5% damped spectral acceleration across a wide period range. At a selected mean annual frequency of exceedance (e.g., 0.00040, which corresponds to a return period of 2475 years), a plot of spectral acceleration versus period is known as a Uniform Hazard Spectrum (UHS). Every spectral ordinate in a UHS has an identical mean annual frequency of exceedance. It is highly unlikely that the spectrum for one earthquake record will match the UHS across a wide range of periods.

Deterministic Seismic Hazard Analysis (DSHA) can also be undertaken to estimate spectral demands at a site given a maximum magnitude earthquake on a known active fault at the shortest distance from the fault to the site.

The structural engineer is responsible for the safety and performance of the building, and should be cognizant of the following:

1. The seismic response of tall buildings can be influenced by multiple modes, with significant modal responses occurring in second or higher translational or torsional modes. Spectral demands at periods smaller than the fundamental period may be more critical in terms of design actions and deformations than first mode demands.

2. Site-specific spectra are developed on the basis of an understanding of the seismo-tectonic environment of the region, less than 100 years of instrumental recordings of earthquake motions, physical examination of faults by trenching (where surficial expression of faults is available), estimates of the temporal distributions of earthquake shaking on nearby faults, alternative attenuation functions, local site effects and other factors. Spectra are typically represented by mean values and dispersions, where the dispersions capture the epistemic (model) uncertainty. Depending on the tectonic setting, soil type, period and selected annual frequency of exceedance, 84th percentile spectral demands can be twice the median demand.

3. The structural engineer should exercise care in selecting an appropriate damping level consistent with the height, structural form and the likely response level of the building. The design spectrum is typically associated with 5% of critical damping, which is likely to be substantially higher than damping measured in a tall building under service loadings. (Appendix A provides information on this topic.)
The literature (e.g., ASCE 7, Eurocode 8) provides equations and tables to transform a 5% damped spectrum to a more lightly damped (e.g., 2%) spectrum.

4. The maximum accelerations of elastic single-degree-of-freedom systems of varying period will generally not result from the same earthquake event. For example, the maximum spectral demands in long period buildings will generally be associated with infrequent, large magnitude earthquakes whereas the maximum spectral demands at short periods are often associated with more frequent, smaller magnitude earthquakes close to the site.

5. PSHA, which is used to generate mean geomean horizontal shaking spectra for different annual frequencies of exceedance, utilizes ground motion attenuation functions. Most of these functions are valid in the period range of 0 to 4 seconds and only a small number have been developed for periods up to 10 seconds. Site specific spectra developed for the period range of 0 to 4 seconds are often extended to longer periods (which are of interest for the analysis and design of tall buildings) by assuming that spectral acceleration is inversely proportional to period and anchoring spectral demand at a period of 3 or 4 seconds.

6. Geomean spectral demands can be substantially smaller than maximum spectral demands and substantially greater than minimum spectral demands. The ratio of maximum to geomean demands can exceed 1.3 in the long period range (Huang et al., 2008).

7. Near source effects can have a significant impact on spectral demands in the long period range. Care must be taken to adequately account for these effects in seismic hazard studies for sites situated within 15km of known active faults. Within 3km of active faults, maximum demands are generally oriented perpendicular to the strike of the fault for large magnitude earthquakes (Huang et al., 2008).

The mean geomean spectrum that is produced by PSHA should be adjusted for the maximum direction of shaking for response spectrum analysis using the procedures to be adopted by the United States Geological Survey in the 2009 seismic hazard maps for the United States. The short- and long-period multipliers on geomean spectral demands at 1.1 and 1.3, respectively, and are based on the studies reported in (Huang et al., 2008).

The site-specific spectrum for maximum shaking, which was developed for a reference site class, must be converted to a free-field or surface spectrum. The conversion is achieved using either short or long period site class modifiers (see ASCE 41-06) or site-response analysis, which is discussed in Section 3.3. If the site-class modifiers are to be used, the reference spectral values of bedrock motion are those of the mean geomean spectrum.

3.3 Site Response

For hard and soft rock sites, with shear wave velocities in the upper 30m of 760 m/sec or greater, site amplification of bedrock motion effects are generally small and are ignored in the hazard assessment. For firm soil and soft soil sites, a more robust procedure for establishing seismic demands is to conduct a site response study, wherein bedrock motions are transmitted upwards by vertically propagating shear waves through nonlinear soil layers. More sophisticated (and computationally intensive) 3-dimensional methods simulating the entire wave propagation process from fault to site are now beginning to emerge.

For the design of high-rise buildings on softer sites with deep and massive foundations and basements, one key issue is what motions are appropriate for the design of the building, given the variation of motions with depth in the ground. This is discussed further in section 4. These so-called foundation motions may be substantially different from the free-field surface motions predicted by a seismic hazard assessment.

A site response study should also identify the potential for liquefaction at depth, slope instabilities and other geo-seismic hazards.

3.4 Selection and Modification of Earthquake Histories for Response-History Analysis

Although acceleration response spectra can be used directly for elastic design using modal analysis, nonlinear response-history analysis requires the use of sets of ground motion records. Some modification of recorded real ground motions is generally necessary to assess the performance of a tall building because the spectral content of a given earthquake record is unlikely to be similar to that of the target spectrum.

There is no consensus on the best procedures for the selection and scaling of earthquake ground motion records (time series). The topic is the subject of significant study at this time and results will vary with the degree of inelastic response in the building for the chosen level of seismic hazard. Herein, it is assumed that the degree of inelastic response is limited and is less than that assumed for low and medium rise code compliant buildings subjected to maximum earthquake shaking.

The modification process typically generates a family of ground motion records that have similar response spectra to the target UHS over a wide range of natural periods. This process is conservative because a UHS is generally composed of spectral contributions from multiple sources, earthquake magnitudes, and site-to-source distances—no single combination of source, magnitude, and distance dominates the entire spectrum in most cases. Baker and Cornell (2006) developed the conditional mean spectrum to address this issue.

Alternate procedures may be used to select and scale ground motions for response-history analysis. The selected records must capture the distribution of spectral demand across the period range of interest in each principal horizontal direction, which will generally be between the period of the fourth translational mode and 1.5 times the fundamental translational mode.

Three acceptable procedures are presented below; other robust procedures may be used. For each of these procedures it is assumed that maximum, geomean and minimum spectra have been generated for the collapse-level assessment using the procedures presented in Section 3.3

Procedure 1: Matching to the maximum spectrum

Spectrally matched ground motion records should produce the same spectral response (+10%, -5%) as the maximum spectrum for all the important translational modes of the tall building. The ground motions should be matched in the time domain from a period of 0 second to a period of 1.5 times the fundamental translational period of the building.

Energy Dissipation Components

6.0 Energy Dissipation Components

Energy dissipation components (also known as dampers) and systems can be used to mitigate the effects of earthquake shaking and wind-induced vibration.

Traditional systems for reducing wind-induced vibrations in high-rise buildings such as tuned-mass dampers and tuned liquid dampers are generally unsuitable for mitigating earthquake-induced response because they are tuning-sensitive and will not provide reliable control when the building suffers significant yielding and period elongation. In addition they generally cannot generate high levels of damping and are difficult to design to accommodate the very high responses associated with strong earthquakes.

Energy dissipation components based on the yielding of metals, developed for earthquake engineering applications, are unsuitable for mitigating wind-induced motion because the serviceability wind-induced forces on the components will be lower than their yield forces. They will therefore not dissipate energy in serviceability wind events when damping is required to satisfy occupant comfort criteria. Similar comments apply to friction dampers.

Energy dissipation components constructed using viscous fluids (e.g. fluid viscous dampers and viscous wall dampers) can be used in certain applications to mitigate both earthquake and wind effects. The advantages of such components and systems include:

1. System performance is somewhat independent of changes in the dynamic properties of the building.

2. Building response in multiple modes can be mitigated rather than just in the fundamental mode as is the case with tuned mass and liquid dampers.

3. Dampers can be constructed with large displacement capacity to mitigate the effects of severe earthquake shaking and high fatigue life to mitigate the effects of wind storms over the life of the building.

Viscoelastic solid dampers can be used in some circumstances to control wind and seismic responses. However, they present some design challenges since their properties require modification during a wind or seismic event to account for the effect of viscous heating and the consequent loss of force output for a given stroke and velocity. Damper manufacturers should be consulted for appropriate numerical models for viscoelastic dampers subject to small amplitude, large-cycle wind loading and large amplitude small-cycle earthquake loading.

Nonlinear mathematical models for metallic yielding, friction and viscoelastic dampers are available in the literature (e.g., ASCE 41-06) for earthquake applications.

Damper performance should be confirmed by full-scale testing under maximum earthquake and maximum wind loadings. Procedures for testing dampers for earthquake effects can be found in US codes, guidelines and standards (e.g., ASCE 41-06). Procedures for testing dampers for wind effects should be developed on a project-specific basis considering demands (displacement, velocity and number of cycles) associated with the response of the building to wind during its lifetime. Attention should be paid to fatigue of damper components and wear of seals under large cycle wind loading.

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About the Council

The Council on Tall Buildings and Urban Habitat, based at the Illinois Institute of Technology in Chicago, is an international organization sponsored by architecture, engineering, planning, and construction professionals, designed to facilitate exchanges among those involved in all aspects of the planning, design, construction and operation of tall buildings.

The Council's mission is to disseminate information on healthy urban environments and tall building technology, to maximize the international interaction of professionals involved in creating the built environment and to make the latest knowledge available to professionals in a useful form.

Since its founding in 1969, the Council has been active in organizing and sponsoring professional conferences on the regional, national and international levels. Symposia, workshops, seminars, and technical sessions are held periodically on topics of unique interest to the particular community.

As one of its services to the public, the Council publishes the CTBUH Journal, a journal that includes papers submitted by researchers, scholars, suppliers, and practicing professionals in the industry. The Council also operates the "High-Rise Buildings Database" which contains important data on thousands of tall buildings throughout the world.

The Council is the recognized source for information on tall buildings worldwide, focusing on their role in the urban environment. The Council provides a forum for discussing the ideas associated with providing adequate space to live and work, involving not only technological factors, but social and cultural aspects as well.

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