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PERFORMANCE-BASED SEISMIC DESIGN OF TALL BUILDINGS IN THE U.S.

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ABSTRACT :
Building codes in the United States contain prescriptive requirements for seismic design as well as an option for use of alternative provisions. Increasingly these alternative provisions are being applied for the performance-based seismic design of tall buildings. Application of performance-based procedures requires: An understanding of the relation between performance and nonlinear response; selection and manipulation of ground motions appropriate to the seismic hazard; selection of appropriate nonlinear models and analysis procedures; interpretation of results to determine design quantities based on nonlinear dynamic analysis procedures; appropriate structural details; and peer review by independent qualified experts to help assure the building official that the proposed materials and system are acceptable. Both practice- and research-oriented aspects of performance-based seismic design of tall buildings are presented.

KEYWORDS:
buildings, design, performance, ground motion, nonlinear analysis

1. INTRODUCTION

The west coast of the United States, a highly seismic region, is seeing a resurgence 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 are not 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, leading to designs that are outside the limits of the code prescriptive provisions. This is allowable through the alternative provisions clause of building codes. For example, the International Building Code [ICC, 2006], which governs construction in much of the U.S. writes "An alternative material, design, or method of construction shall be approved where the building official finds that the proposed design is satisfactory and complies with the intent of the provisions of this code and … is at least the equivalent of that prescribed in this code in quality, strength, effectiveness, fire resistance, durability, and safety."

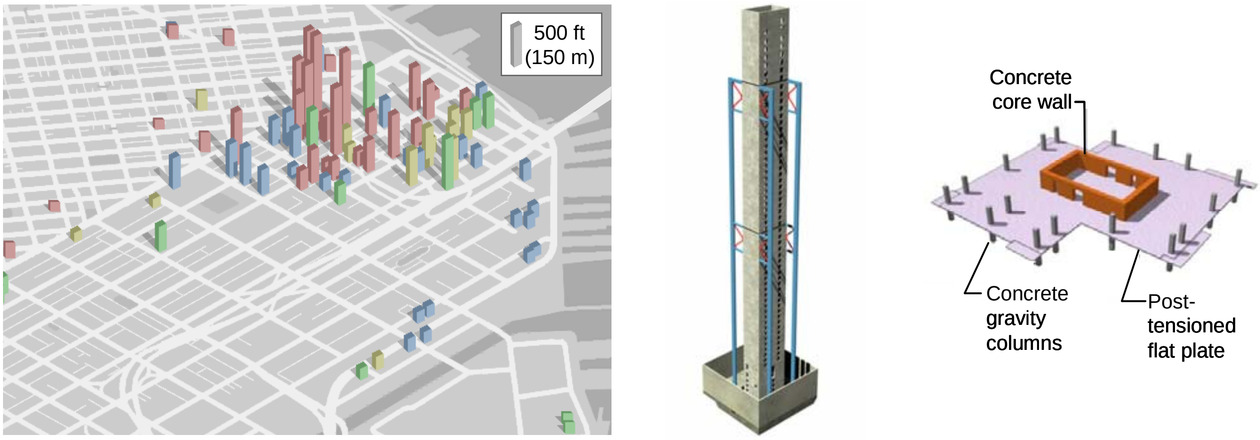
When the alternative provisions clause is invoked, this normally leads to a performance-based design involving development of a design-specific criteria, site-specific seismic hazard analysis, selection and modification of ground motions, development of a nonlinear computer analysis model of the building, performance verification analyses, development of building-specific details, and peer review by tall buildings design experts. Experience gained in the application of this approach has found its way into written guidelines [e.g., SEAONC, 2007; CTBUH, 2008; LATBSDC, 2008]. These documents generally define what needs to be considered, but leave considerable latitude in their implementation so that the designer is not overly constrained. This paper reviews the currently accepted approaches to performance-based seismic design of tall buildings in the U.S., presents examples, and describes relevant research findings and needs.

2. THE NEW GENERATION OF TALL BUILDINGS IN THE WESTERN U.S.

Urban regions along the west coast of the United States are seeing a boom in tall building construction. Figure

1a illustrates recent developments and plans in San Francisco, where buildings as tall as 1200 ft (370 m) are under study. Many of the buildings are residential or mixed-use (including residential) occupancy, though economic changes may lead to alternative functions including office occupancies.

To meet functional and economic requirements, many of the new buildings are using specialized materials and lateral-force-resisting systems that do not meet the prescriptive definitions and requirements of current building codes. Figure 1b and c illustrate the framing system of a 60-story building in San Francisco. The seismic force-resisting system is reinforced concrete core walls with buckling-restrained steel outrigger braces along one axis. The designated gravity framing comprises an unbonded post-tensioned flat-plate system. As the building responds to anticipated earthquake ground shaking, the flat plate and its supporting columns will undergo deformations and develop internal forces that must be considered as part of the design. In addition to the core wall system shown in Figure 1, other framing systems including moment frames, steel-plate walls, and other innovative systems are being considered for various buildings, each with its own special design needs.



(a) San Francisco skyline projection (b) Core wall elevation (c) Floor framing perspective

Figure 1 – (a) San Francisco developments (since 1999) and current plans (after Steve Borland) and (b and c) example framing system (after Magnusson Klemencic Associates)

3. DESIGN CRITERIA

A design criteria document generally is developed by the designer to clearly and concisely communicate to the design team, the building official, and the peer reviewers the intent and the process of the building structural design. A well prepared document will likely include data and discussion regarding the building and its location; the seismic and wind force-resisting systems; sample conceptual drawings; codes and references that the design incorporates in part or full; exceptions to aforementioned code prescriptive provisions; performance objectives; gravity, seismic, and wind loading criteria; load combinations; materials; methods of analysis including software and modeling procedures; acceptance criteria; and test data to support use of new components. The document is prepared early for approval by the building official and peer reviewers, and may be modified as the design advances and the building is better understood.

The design criteria document must define how the design is intended to meet or exceed the performance expectations inherent in the building code. A common lay-person perspective on tall buildings is that their performance should exceed the performance of “ordinary” buildings. This perspective derives from perceptions of high occupancy, emergency response challenges, and the effects on regional image in the event of damage to an iconic building. Another perspective is that mandating special performance objectives for one class of building would be precedent-setting with little technical basis but with important (usually negative) economic consequences. These clearly are public policy issues that should be publicly debated either on a national scale (through the model/national building codes) or at a local scale (through an ordinance in local government). However, given that the primary purpose of building codes is protection of life safety and public welfare, characteristics of tall buildings that present higher risks than normal buildings could be considered for enhanced performance. Examples that fall into this category are cladding and its anchorage, and emergency ingress and egress [Holmes et al., 2008].

Apart from these special characteristics, performance expectations for design of most tall buildings in the U.S. are set equal to those for ordinary buildings. This of course, is open to interpretation, as the building codes are not explicit about performance objectives. A common interpretation is that the building structural and nonstructural systems and components must be serviceable when subjected to frequent earthquakes (50% probability of exceedance in 30 years, or 50%/30yr) and the building must be stable (that is, not collapse) when subjected to extremely rare shaking (generally taken as 2%/50yr exceedance level, but not more than 1.5 times median deterministic motions). The assumed level of damping will strongly affect the design for the serviceability check; the 50%/30yr shaking level is commonly used with 5% of critical damping. If lower damping values are used (which some believe to be appropriate for tall buildings [CTBUH, 2008]), either the typical design must be adjusted or the criteria relaxed.

4. SEISMIC HAZARD ANALYSIS AND DESIGN GROUND MOTIONS

Seismic ground shaking generally is determined using site-specific seismic hazard analysis considering the location of the building with respect to causative faults, the regional and local site-specific geologic characteristics, and the selected earthquake hazard levels. The analysis produces a uniform hazard response spectrum defining linear spectral acceleration values for different periods and hazard levels. It also identifies which hypothetical earthquakes dominate the seismic hazard at the site. From this, a set of (almost always seven) ground motion pairs consistent with the site conditions and with the magnitude, distance, and mechanism of the dominant earthquakes is selected for use in nonlinear dynamic analysis of an analytical model of the building. Because magnitude strongly influences frequency content and duration of ground motion, it is desirable to use records from earthquakes 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].

The selected ground motions generally are manipulated to better fit the target linear response spectrum using either *scaling* or *spectrum matching*. *Scaling* involves applying a constant factor to individual pairs of horizontal ground motion records to make their response more closely match the design spectrum over a range of periods [ASCE 7-05, 2005]. *Spectrum matching* is a process whereby individual ground motion records are manipulated (usually in the time domain by addition of wave packets) to adjust the linear response spectrum of the motion so it matches the target design response spectrum. Resulting motions should be compared with original motions to ensure the original character of the motions is not modified excessively.

There currently is no consensus on which approach, scaling or spectrum matching, is preferable for nonlinear dynamic analysis, and both procedures are in use. 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 (up to 10 sec), 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. Spectrum matching can alleviate the aforementioned problem with scaling, though there are concerns that these uniformly matched motions will mask the inherent record-to-record variability of building response. On the other hand, given that the number of ground motion pairs is almost universally limited to seven in tall buildings designs, it is doubtful that any scaling procedure will result in motions that accurately reproduce the true dispersion in building dynamic response.

The uniform hazard spectrum is a composite of the peak response spectral ordinates for many different hypothetical earthquakes that could affect a site; in general, no single earthquake will have a response spectrum matching the uniform hazard spectrum. Recognizing this, Abrahamson [2006] recommends that each of the ground motions used to excite the building model should represent a scenario earthquake, that is, just one of the many earthquakes that contribute to the uniform hazard spectrum. In this case, the selected motion is scaled to the response spectrum of the scenario earthquake, which is less broadband than the uniform hazard spectrum. Baker and Cornell [2006] have recommended that the scenario spectrum should be modified to represent the conditional mean response spectrum, which takes into account the correlation between response spectral amplitudes at different periods. A complication that arises with a tall building is that different engineering demands are controlled by different periods, requiring ground motion sets scaled to several different scenario spectra. There currently is no established way to combine the results from different conditional mean spectra, other than to take the envelope, a result that is likely to be conservative though less so than the uniform hazard spectrum.

Figure 2 presents results of a study of the use of ground motions scaled to different response spectra. DBE refers to the design basis earthquake response spectrum of ICC (2006), which is roughly equivalent to a uniform hazard spectrum, and CMS refers to the conditional mean spectrum conditioned on a single period; three such spectra are shown corresponding to each of the first three translational modes of vibration (in one plane) of a tall core wall building model. The conditional mean spectra match the DBE spectral acceleration at the target period, but generally have lower response ordinates for periods away from the target. Several ground motion records were selected to approximately match the DBE and CMS spectra, and then were used to excite a nonlinear analytical model of the building. Figure 2b shows results of nonlinear dynamic analyses; for shears the results are the mean plus one standard deviation of the peak story shears and for moments the results are the mean of the peak story moments (these statistical measures commonly are used in current design practice). It can be observed that the envelope of the CMS results is nearly as large as the DBE results, and in this example there are locations where the CMS values are higher (attributed to ground motion variations and problem nonlinearities). Generally, little benefit is obtained from the CMS results for response quantities dominated by a single mode, and only marginal benefit is obtained from response quantities with contributions from more than one mode. Given the high expense of developing the spectra, the ground motions, and the building responses, scenario-based ground motions currently are not used for tall building designs.

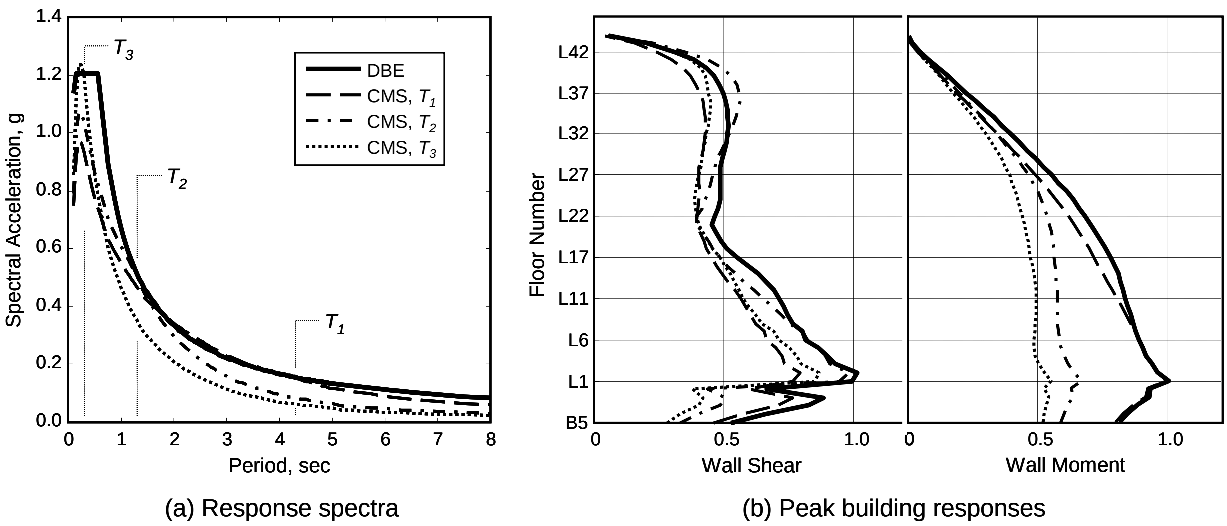


Figure 2 – (a) Design Basis Earthquake and Conditional Mean Spectra and (b) calculated wall shears and moments (mean plus one standard deviation of peak values for shear and mean of peak values for moment)

5. NONLINEAR DYNAMIC ANALYSIS AND PERFORMANCE VERIFICATION

Performance-based seismic analysis of tall buildings in the U.S. increasingly uses nonlinear analysis of a three-dimensional model of the building. Lateral-force-resisting components of the building are modeled as discrete elements with lumped plasticity or fiber models that represent material nonlinearity and integrate it across the component section and length. Gravity framing elements (those components usually not designated as part of the lateral-force-resisting system) increasingly are being included in the nonlinear models so that effects of building deformations on the gravity framing (imposed deformations and the accumulation of overturning forces over the building height) as well as effects of the gravity framing on the seismic system (for example, increased stiffness and core-wall shears) may be represented directly.

Because the behavior is nonlinear, behavior at one hazard level cannot be scaled from nonlinear results at another hazard level. Furthermore, conventional capacity design approaches can underestimate internal forces in some structural systems (and overestimate them in others) because lateral force profiles and deformation patterns change as the intensity of ground shaking increases [Kabeyasawa, 1993; Eberhard and Sozen, 1993]. Figure 3a shows statistics of story shear profiles for a tall core-wall building subjected to different levels of earthquake ground motion. (Twenty-seven records from earthquakes having ~M7 at ~10km were scaled to the first-mode spectral acceleration of the uniform hazard spectrum for 475-year (DBE) and 2475-yr (MCE) mean return periods.) The story shear has considerable dispersion for any level of ground shaking, and the shear increases as the intensity of shaking increases even though total overturning moment is limited by the wall yielding mechanism. Similar patterns can be observed for upper-story wall moments and other design parameters.

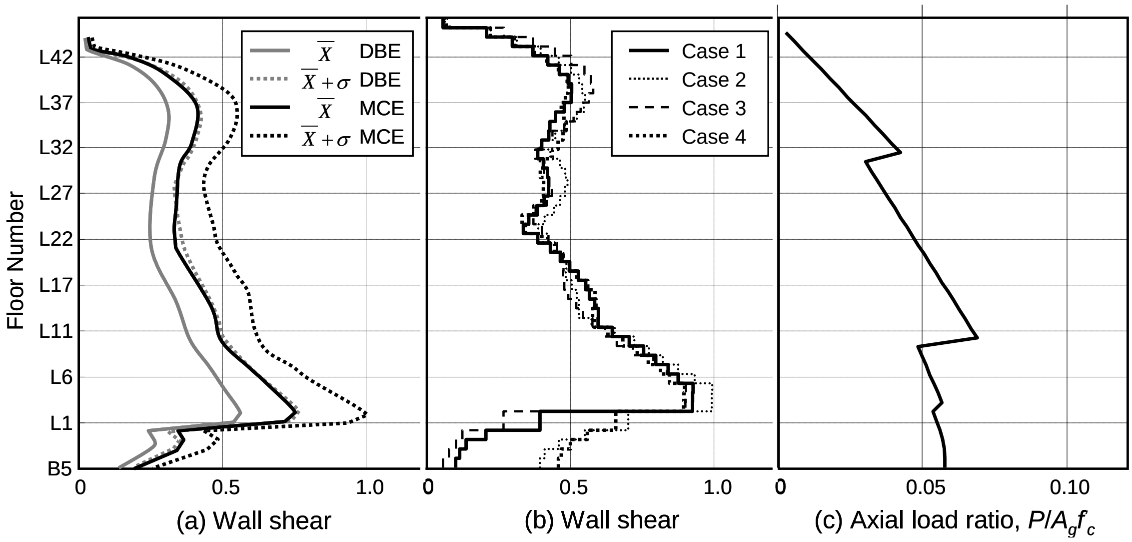


Figure 3 – Selected results from nonlinear analysis of a core wall building: (a) Mean and mean plus one standard deviation results of core wall shear for ground motions scaled to Design Basis Earthquake and to Maximum Considered Earthquake levels; (b) Effect of wall and podium diaphragm modeling assumptions on calculated core

Results of nonlinear dynamic analysis are sensitive to modeling assumptions. In reinforced concrete construction, component effective stiffnesses should consider effects of cracking on stiffness and slip of reinforcement from anchorage zones. Some guidance is available in the literature, but the level of guidance is incomplete and commonly aimed at buildings of moderate or lower height. Usual practice is to base nonlinear component strengths on expected material properties and to include reinforcement strain-hardening effects. By so doing, the computer model response is likely to be closer to best-estimate response and internal actions (e.g., axial forces, shears, and moments) on components expected to remain elastic will be more conservatively estimated. Some results are particularly sensitive to stiffness assumptions, so bounding analyses are not uncommon. Figure 3b illustrates variation in calculated wall shears for different shear stiffness assumptions of walls and podium diaphragms. The effect on shear below the main transfer slab is especially prominent.

The gravity framing system (that part designed mainly to support gravity loads and not seismic forces) typically is included in the analytical models to estimate deformation demands and forces acting on the gravity framing. Figure 3c shows results for a core wall building with post-tensioned flat plate floors subjected to a nonlinear static analysis. Analysis results can show axial stresses as high as $0.1A_g f'_c$, where A_g is the gross cross-sectional area of the column and f'_c is the concrete compressive strength. In U.S. design practice, columns are proportioned for multiple load combinations, including 1.2D + 1.6L and 1.2D + 0.5L + E, where D, L, and E are effects from dead, live, and earthquake, respectively. Given these load combinations and typical values for D, L, and E, the overturning on gravity columns may control their design.

Damping conventionally has been set around five percent of critical damping for the periods (vibration modes) likely to dominate response. A trend is to adopt lower damping values for tall buildings, in the range of two to three percent of critical damping, but this has not been well established in practice at this time.

A nearly universal practice is to use seven ground motion pairs (horizontal components only) to excite a nonlinear model of the building [ASCE 7-05, 2005; LATB, 2008; SEAONC, 2007]. A key question, then, is how to define the design-level response when each of the multiple design ground motions produces its own distinct results. In one study, a core wall building was subjected to 100 different sets of seven pairs of ground motions to identify typical response statistics. On average, the standard deviation of the wall shear demand was approximately 0.3. Thus, the choice of design value (for example, mean, median, or one standard deviation higher) has a significant impact on final design quantities.

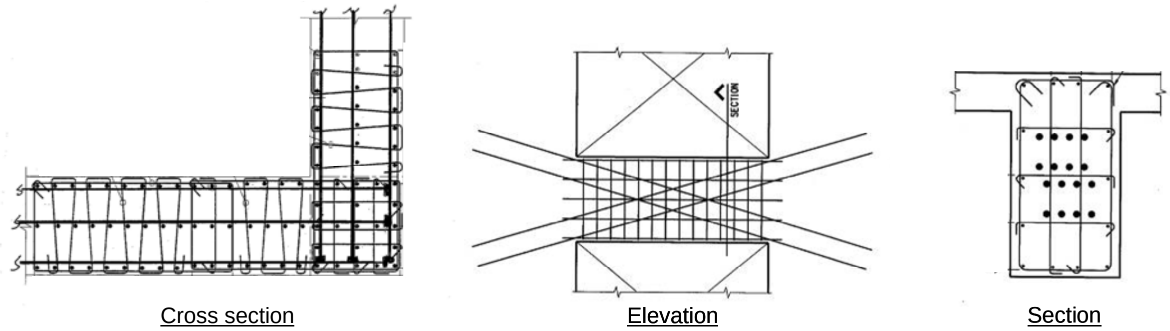
Equally important is the selection of the design strength or resistance. Lacking written guidance, designers have proposed design strengths ranging from (a) the nominal strength reduced by a strength reduction factor from the building code to (b) expected strength (based on expected materials properties) with strength reduction factor equal to 1.0. For typical shear wall configurations, and for the code strength reduction factor of 0.75, the difference between these two values is in the range of 1:1.5.

To promote more consistent design approaches, 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 (for example, shear response of walls) should consider the dispersion of the values. The commentary to the SEAONC guidelines notes that in typical cases design actions for low-ductility actions can be defined as the mean plus one standard deviation of the values obtained from the nonlinear response history analysis. SEAONC also recommends that design strengths for low-ductility actions be defined based on the product of the nominal strength (considering specified material properties) and the strength reduction factor from the building code. Simplified analyses of this approach, considering the statistics of seismic demands and resistances, suggest the probability of shear failure is approximately one fifth of the probability of reaching flexural deformation capacities. Additional development is required to formalize these findings and their adoption in practice.

6. STRUCTURAL PROPORTIONING AND DETAILING

A significant percentage of recent high-rise building construction in the western U.S. has been for residential and mixed-use occupancies. Thus, much of it has been of reinforced concrete, and the majority of those have used reinforced concrete core walls. Some concrete and steel framing, and some steel walls, also are used.

Under design-level earthquake ground motions, the core wall may undergo inelastic deformations near the base (and elsewhere) in the presence of high shear. Ductile performance requires an effectively continuous tension chord, adequately confined compression zone, and adequate proportions and details for shear resistance. In locations where yielding is anticipated, splices (either mechanical or lapped) must be capable of developing forces approaching the bar strength. Furthermore, longitudinal reinforcement is to be extended a distance $0.8l_w$ past the point where it is no longer required for flexure based on conventional section flexural analysis, where l_w is the (horizontal) wall length. Walls generally are fully confined at the base and extending into subterranean levels. Confinement above the base may be reduced (perhaps by half) where analysis shows reduced strains, though strains calculated by nonlinear analysis software generally should be viewed skeptically as they are strongly dependent on modeling assumptions (modeling procedures should be validated by the engineer of record against strains measured in laboratory tests). The reduced confinement usually continues up the wall



(a) Wall (b) Coupling beam

Figure 4 – Typical wall and link beam details.

height until calculated demands under maximum expected loadings are well below spalling levels. Transverse reinforcement for wall shear generally is developed to the far face of the confined boundary zone; otherwise, the full length of the wall is not effective in resisting shear. Figure 4a shows an example detail for boundary element confinement and anchorage of shear reinforcement using headed bars. Another accepted detail is to lap the horizontal shear reinforcement with an equal area of hoops or U-bars inserted into the boundary. Hooks on the horizontal reinforcement may not be feasible given the large diameter of the horizontal bars.

Coupled core walls require ductile link beams that can undergo large inelastic rotations. In typical cases, the small aspect ratio and high nominal shear stress dictate use of diagonally reinforced coupling beams. To facilitate construction, link beams are now constructed using full cross section confinement rather than individual diagonal confinement (Figure 4b).

Away from the core walls, gravity loads commonly are supported by post-tensioned floor slabs supported by columns. Slab-column connections are designed considering the effect of lateral drifts on the shear punching tendency of the connection. In most cases, stud rails or other systems are used to reduce the likelihood of punching around the columns. For post-tensioned slabs, which are most common, at least two of the strands in each direction must pass through the column cage to provide post-punching resistance.

7. PEER 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 peer review generally starts early in the process, starting with review of the project design criteria, and follows through to final verification of analysis and design details.

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 serviceability and 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.

9. ACKNOWLEDGMENTS

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