Seismic Performance and Design Requirements for High-Rise Concrete Buildings

By Joe Maffei, S.E., Ph.D. & Noelle Yuen, S.E.

In recent years there has been a resurgence of high-rise construction in the major cities along the West Coast of the U.S. Unlike previous high-rise booms, most of the new and proposed tall buildings are for residential or mixed use rather than for offices. Concrete construction is often favored, and many of the new high-rises use concrete core-wall construction without supplemental moment frames in the seismic-force-resisting system.

Concrete core-wall construction can offer advantages of lower costs, faster construction, and more open and flexible architecture. Cost and schedule savings are realized because core-wall buildings withstand seismic forces and deformations without the moment frames that are used in traditional high-rise construction. By eliminating the need for moment frames, smaller framing members or flat slabs can be used for the building floors, and the framing depth of floors can be reduced.

In a core wall building, resistance to seismic forces is provided by a reinforced concrete core that surrounds the elevator banks. Stairs, restrooms, and mechanical/service uses may also be located within the core. For buildings 300 feet or taller, the concrete core usually has a minimum dimension of 30 feet in each plan direction, with walls that are 18 to 30 inches thick (*Figure 1*). Regular openings are used in the core walls, and the coupling beams above the openings are reinforced and detailed to dissipate earthquake energy.

Code Acceptance of Non-Prescriptive Designs

In high seismic zones, prescriptive provisions of U.S. building codes do not permit the core-wall structural system for buildings over 240 feet tall; however, under building code provisions that permit alternative systems, building authorities have granted approval to core-wall buildings greater than 240 feet tall using the process of Seismic Peer Review. (*See sidebar.*) The Engineer of Record is required to identify any exceptions being taken to prescriptive requirements, and to demonstrate to an expert reviewer that the building provides at least equivalent seismic performance to that implied or resulting from the prescriptive requirements of the building code.

Figure 1: Concrete core-wall building under construction, the Washington Mutual/Seattle Art Museum, Magnusson Klemencic Associates, Structural Engineers.

The task of the Engineer of Record is to show that a building satisfies the equivalent performance criteria defined in IBC Section 104.11:

104.11 Alternate materials, design and methods of construction and equipment. The provisions of this code are not intended to prevent the installation of any material or to prohibit any design or method of construction not specifically prescribed by this code, provided that any such alternative has been approved. 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 that the material, method or work offered is, for the purpose intended, at least the equivalent of that prescribed in this code in quality, strength, effectiveness, fire resistance, durability and safety.

For non-prescriptive *seismic* designs, the performance is evaluated with respect to strength, effectiveness, and safety. Alternative or non-prescriptive seismic designs are also accepted in the building code by ASCE 7-05, Section 12.1.1, paragraph 3:

Seismic force-resisting systems that are not contained in Table 12.2-1 shall be permitted if analytical and test data are submitted that establish the dynamic characteristics and demonstrate the lateral force resistance and energy dissipation capacity to be equivalent to the structural systems listed in Table 12.2-1 for equivalent response modification coefficient, R, system overstrength coefficient, Ω_o, and deflection amplification factor, Cd, values.

Although Table 12.2-1 of ASCE 7-05 lists a number of types of concrete wall seismic-force-resisting systems, none of the design rules for such systems are as stringent as the capacity-design requirements typically applied to the design of core-wall high-rise buildings. Thus, based on expected seismic performance, capacity-designed and flexure-governed concrete wall buildings can be considered a distinct type of seismic-force-resisting system. This distinction currently exists in building codes outside the US, and has been discussed as a potential change to upcoming US building codes by the American Concrete Institute and National Earthquake Hazards Reduction Program.

Capacity Design

The capacity-design approach to seismic design requires that the structural engineer:

1) Select a desirable mechanism of nonlinear lateral deformation for the structure, which identifies those structural elements and actions that are intended to undergo nonlinear response. The mechanism should not lead to concentrated nonlinear deformations such as occurs, for example, with a story mechanism.
2) Ensure that the detailing of the designated nonlinear elements provides adequate ductility capacity, i.e., allows the elements to deform well beyond yield without significant strength degradation.
3) Design all other elements and actions of the structure for elastic, or nearly elastic, response.

For a concrete core-wall building under earthquake lateral displacement, the desired mechanism consists of flexural plastic hinging near the base of the core wall and flexural yielding of coupling beams, as shown in *Figure 2*. Some core-wall buildings have coupling beams only in one plan direction, with walls in the other plan direction acting as cantilever walls, as shown in *Figure 2*. The cantilever wall is designed to develop a single plastic hinge at its base. In each plan direction, the wall flanges, typically including the entire core-wall section, contribute to global moment capacity.

The nonlinear elements of the structure – coupling beams and the base plastic hinge – are detailed for ductile response. Other elements and actions of the structure – such as wall shear, wall moment outside the hinge zone, floor and roof diaphragms, and foundations – are given sufficient strength that their behavior will be essentially elastic. *Table 1* lists structural elements and actions for a core-wall building that are typically designed for nonlinear behavior and those that are designed for elastic, "capacity-protected" behavior.

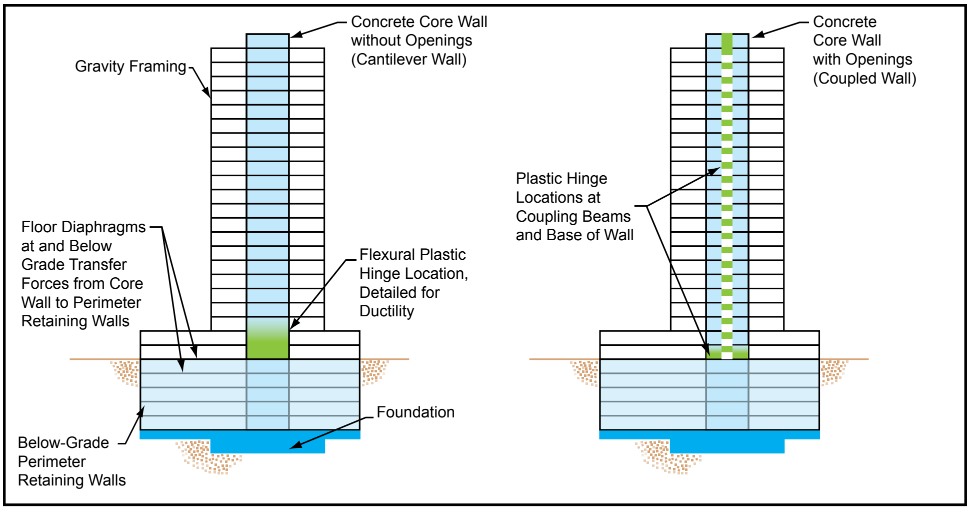

Figure 2: The typical nonlinear action for a cantilever wall (left) is a flexural plastic hinge at the base of the wall. For a coupled wall (right) nonlinear actions are flexure-yielding coupling beams and a flexural plastic hinge at the base of the wall.

Flexure-Governed Design

A critical consideration in the design of the concrete wall system is to protect against shear failure in the wall. A wall governed by flexural yielding will maintain its lateral-force resistance through large displacements and will deform in a way that distributes deformation over the height of the building. A wall shear failure, by contrast, leads to a degradation of strength and can cause a concentration of deformation and damage over a limited height (*Figure 3*). Flexure-governed response provides a greater assurance against collapse in a severe earthquake.

The seismic design process for concrete core-wall buildings is based on methods that were established in the New Zealand and Canadian building codes beginning in the 1970s. A large number of core-wall high-rises were built in Vancouver before the methodology was applied, with Seismic Peer Review, to high-rise buildings in the Seattle area and elsewhere in the U.S.

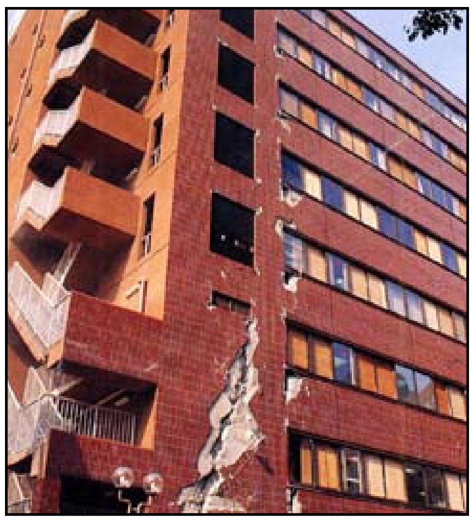

Figure 3: Concrete wall failing in shear in the 1995 Kobe earthquake. Capacity design aims to protect against such a failure mode.

Capacity Design using Nonlinear Response-History Analyses

The capacity design approach was principally developed and promoted by researchers and practicing engineers in New Zealand, at a time when computer analysis capabilities were limited. Nonlinear response-history (NLRH) analyses were only feasible on large university computers using two-dimensional models of simplified structures. Researchers used such analyses to derive detailed requirements for capacity design that could be applied to simpler static and linear analysis and design practices.

These detailed capacity-design requirements, such as dynamic shear amplification factors, are still useful, particularly for regular structures less than 20 stories and for the preliminary design of taller structures. Today, thanks to recent advances and availability in structural analysis software, the capacity design approach can be combined with building-specific NLRH analyses to design high-rise buildings and verify acceptable seismic performance.

Two-Stage Design Process

Core-wall high-rise buildings can be designed according to a two-stage process that follows the capacity-design approach and assesses seismic performance under severe earthquake ground motions.

The first stage of the process is to design the building to comply with all code provisions (except for identified exceptions such as the height limit). This means that the designated yielding elements of the building, namely the flexural design of the core-wall hinge zone and the coupling beams, are designed for code-level demands including the code *R* factor. For tall buildings with long periods, this code-level demand is typically governed by minimum base shear requirements (*Figure 4*).

The second stage is to analyze the structure using an NLRH analysis at the Maximum Considered Earthquake (MCE) level of ground motion. The MCE level is currently defined in building codes to correspond to a 975-year return period in California and about a 2500-year return period elsewhere. The purpose of this analysis is to:

1) Verify that the expected seismic behavior of the structure is governed by the intended mechanism, with nonlinear behavior occurring only in the designated structural elements.
2) Verify that all other potential mechanisms and actions remain essentially elastic. When evaluating actions designed to remain elastic, the design should consider the dispersion of the NLRH results, rather than just the average response.

Table 1: Typical nonlinear and capacity-protected elements for a core-wall building with concrete flat slabs.

Structural elements and actions designed for nonlinear behavior:	Notes
• Coupling beams (diagonally reinforced if deformation demands are high) • Base of wall plastic-hinge zone	Strength is determined from Code-Level evaluation. Elements are detailed for ductile response.
• Floor and roof slabs in out-of-plane flexure	Although considered part of the "gravity" system, slabs may yield from induced lateral displacement.
Structural elements and actions designed for elastic (capacity-protected) behavior:	**Notes**
• Wall shear and sliding shear • Wall moment outside designated hinge zone • Floor and roof diaphragms and collectors • Foundation perimeter walls • Foundations • Columns • Floor and roof slab punching shear	Strength is determined from the MCE level nonlinear response-history (NLRH) analysis. Elements are designed to remain essentially elastic.

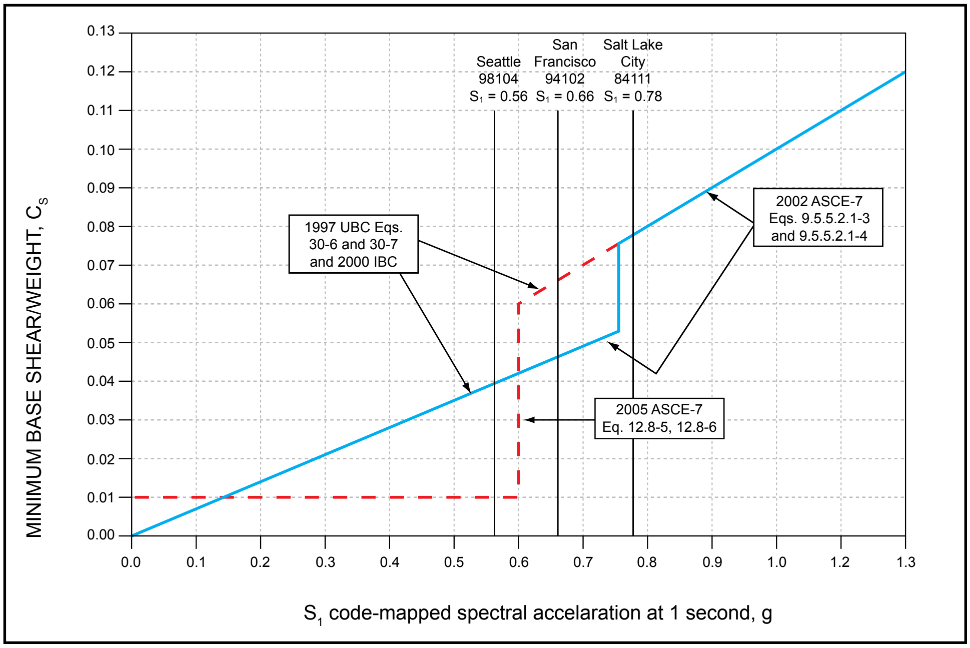

Figure 4: Minimum base shear equations for recent building codes, as a function of the ground motion parameter S1.

Properly applied, the NLRH analysis takes the place of applying the code-prescribed overstrength factor, Ω_0,to actions designed to remain elastic.

Semi-Performance-Based Design

The design approach could be considered a "semi-performance-based". The Code Level evaluation aims to have the design meet all prescriptive code requirements with which it is logical that the design comply, without evaluating seismic performance. The MCE Level evaluation explicitly considers the performance of the structure at a level for which the structure should not collapse. This evaluation uses state-of-the-art methods of analysis, and structural force and deformation capacities based on expected rather than nominal values. Story drift limitations can be checked at the Code Level, and also at the MCE Level; for example, using the average of the response-history runs and taking acceptable drift as 1.5 times that in the building code.

A performance-based evaluation of serviceability in moderate earthquake ground motions can also be added to the design approach. For core-wall buildings the serviceability evaluation could include an explicit evaluation of the level of ground motion for which coupling beam damage affects the post-earthquake occupancy of the building. A determination about the significance of various levels of coupling-beam damage, based on research results, would be necessary for such an evaluation.

Interaction with the Gravity System

In customary seismic design practice, the structural engineer designates certain elements to be part of the Seismic-Force-Resisting System. For concrete buildings, these are typically structural walls and moment frames. Gravity framing is usually not included in the lateral analysis for earthquake resistance, but is instead evaluated for its ability to sustain the imposed seismic deformations. In reality, gravity framing systems contribute to some degree to lateral-force resistance, and this contribution should be considered in the design of high-rise buildings, particularly at the MCE-level evaluation.

For core-wall buildings with concrete flat-slab floors, the gravity structural system consists of the floor slabs and supporting columns. Lateral displacement of the core wall and columns of the building induces moments and shears in the floor slabs, which act as unintentional "outriggers" that increase the building's lateral resistance. Often, the lateral displacement under MCE-level ground motions is enough to cause flexural yielding in the slabs. Yielding of the floor slabs is typically acceptable, while other failure modes such as punching shear from the induced deform-ations must be prevented (*Table 1, see page 29*).

Two other aspects of this slab-outrigger effect are important for engineers to evaluate. The first is that shear in the core wall is increased, and the second is that earthquake axial forces are generated in the "gravity" columns. These demands should be included in the shear design of the core wall and in the design of the columns.

Defining Equivalent Seismic Performance

The IBC's equivalence criterion requires that the building's seismic performance be "at least the equivalent of that prescribed in this code." In assessing seismic performance, the Engineer of Record and Peer Reviewer should consider both the intentions of the building code, and the performance that results from a code-prescriptive design with good seismic performance.

Table 2: Differences between Seismic Peer Review and Structural Plan Check

Seismic Peer Review	Structural Plan Check
Done by an engineering firm or a panel of engineers, independent of the Engineer of Record, with expertise in seismic design	Done by a jurisdiction's building authority or by a third-party consultant to the jurisdiction.
Ideally starts at schematic design	Reviews completed structural documents.
Review of seismic criteria, seismic evaluation and design concepts and methods, preliminary design, and final design	Review is for compliance with prescriptive structural requirements of the building code.
Typically covers only seismic design.	Covers gravity, wind, seismic, and any other loads.
Peer reviewer gives professional opinion (e.g., to building authority)	Jurisdiction has the authority to grant or deny building permit.
Is recommended for projects where the seismic criteria, design methods, or performance are not pre-determined or may be complex. Required for certain types of seismic systems or seismic analysis methods.	In most jurisdictions is carried out at some level of detail on all types of building projects.
Paid for by owner.	Paid for by permit fees.

A problematic issue is that the building code's intended seismic performance is defined only in general terms (SEAOC *Blue Book* Section C101.1), and it may be impossible to ever more specifically define the seismic performance intent of the building code. Part of the reason is that current design rules for different seismic systems in the building code may result in quite different levels of seismic performance from one system to another. Another part of the reason is that the assumptions used in attempting to define seismic performance – ground motion, soil and structure properties, non-linear demands, deformation capacity, etc. – all include significant uncertainty. This uncertainty is related to both the inherent variability of earthquake and material phenomena, and to the limitations in our knowledge of the best methods and assumptions to use in all the steps of predicting seismic performance.

For the reasons noted above, predicting seismic performance is complex and uncertain, and hence code intentions are defined only in general terms. Thus, if one only considers code intentions, judging whether the seismic performance of a non-prescriptive design is "equivalent to code" can be difficult. Accordingly, it can be helpful if one considers, in addition to code intentions, the seismic performance that is expected to result from the code-prescriptive design of a building similar to the non-prescriptive design being considered.

This consideration can be useful in judging equivalent performance for parts of a structural design that are not closely related to those prescriptive exceptions being taken using alternative design methods. A point to remember here is that, because building codes are not perfect, it is possible to design a high-rise building that meets all prescriptive code requirements, and yet still leads to inadequate performance in an earthquake. (For example a shear failure in a wall along with a concentration of nonlinear deformation over just a few stories.) Such a benchmark would not be accepted as equivalent performance, because it does not meet the *intent* of the code. It is not acceptable to provide equivalence to a poorly performing, yet code compliant building.▪

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Seismic Peer Review versus Structural Plan Check

For both Seismic Peer Review and Structural Plan Check, the work of the Engineer of Record is subjected to an independent and objective review by another licensed engineer. While Structural Plan Check has long been part of the permitting process for most buildings, the additional step of Seismic Peer Review has become more common in the past decade because of an increased realization that good seismic performance can depend on more than conformance to building-code prescriptions. Differences between Seismic Peer Review and Structural Plan Check are summarized in *Table 2*. The Structural Engineer Association of California has written professional practice guidelines on Peer Review.

Neither a Seismic Peer Review nor a Structural Plan Check relieves the Engineer of Record from being fully responsible for the structural design. Both Seismic Peer Review and Structural Plan Check should be carried out with the objective of providing an impartial and independent review of the Engineer of Record's work.

Seismic Peer Review should start during the early phases of a project and include an examination of basic design concepts, objectives, and criteria proposed for the project. Major decisions affecting the seismic design are reviewed throughout the project with a consideration of the expected seismic performance. Typically the Peer Reviewer's comments are documented in a comment log, along with the Engineer of Record's response, references to associated follow-up comments, and an indication whether each comment is resolved.

Seismic Peer Review can be a voluntary process that an owner chooses to employ, it can be requested by a building authority, or it can be required by the building code. The 2006 International Building Code requires Seismic Peer Review (called Design Review) when the nonlinear response-history method of structural analysis is used, or when certain design solutions, such as base-isolation or energy-dissipation devices, are used. Building authorities typically require a Seismic Peer Review when an alternative (i.e., non-prescriptive) method of seismic design is proposed.

Structural Plan Check focuses on determining if a set of construction documents conforms to the structural requirements of the governing building code. Structural Plan Check differs from Seismic Peer Review in that it covers the review of the structural design for gravity, wind, and other loads in addition to seismic effects. Structural Plan Check is typically a review of final or near-final documents, and does not focus on evaluating seismic performance, but instead on reviewing a completed design for code conformance.

A building authority can use Structural Plan Check to approve or reject a building permit application. In contrast, a Seismic Peer Reviewer does not directly have the authority to approve or reject a design. The responsibility of the Peer Reviewer is to provide their professional opinion, typically in a findings letter, to the party requesting the Peer Review.

Structural Plan Check is typically paid for by building permit fees, while Seismic Peer Review is typically an added cost to the owner. In the case where a building authority requests a peer review, the peer reviewer often contracts with the jurisdiction, which then passes on the cost to the building owner.

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