Performance Based Seismic Design – Rising

By Ron Klemencic, P.E., S.E.

San Francisco's 57-story One Rincon Hill (right) and the two towers of The Infinity (left, by crane), three of the more than two dozen buildings designed using a performance-based approach. (©Mark Defeo)

The recent boom in high-rise construction has offered structural engineers the opportunity to advance the state of the art in seismic engineering. While the concept of performance-based design (PBD) is not new, its application to the design of newly constructed high-rise buildings in regions of high seismicity is relatively recent. As evidenced by the dozens of tall PBD buildings currently under construction, the merits of this approach are clearly being recognized.

Something Old as New

Historically, the New York World Trade Center Towers, Chicago's John Hancock Building, and Sears Tower all used a PBD approach. In the 1960s, when these buildings were designed, wind engineering was in its infancy. The definition of suitable demand levels and commensurate acceptance criteria were developed from scratch. Definitions of "recurrence intervals" for wind events and thresholds of "occupant comfort" were studied and generally agreed upon by leading industry experts.

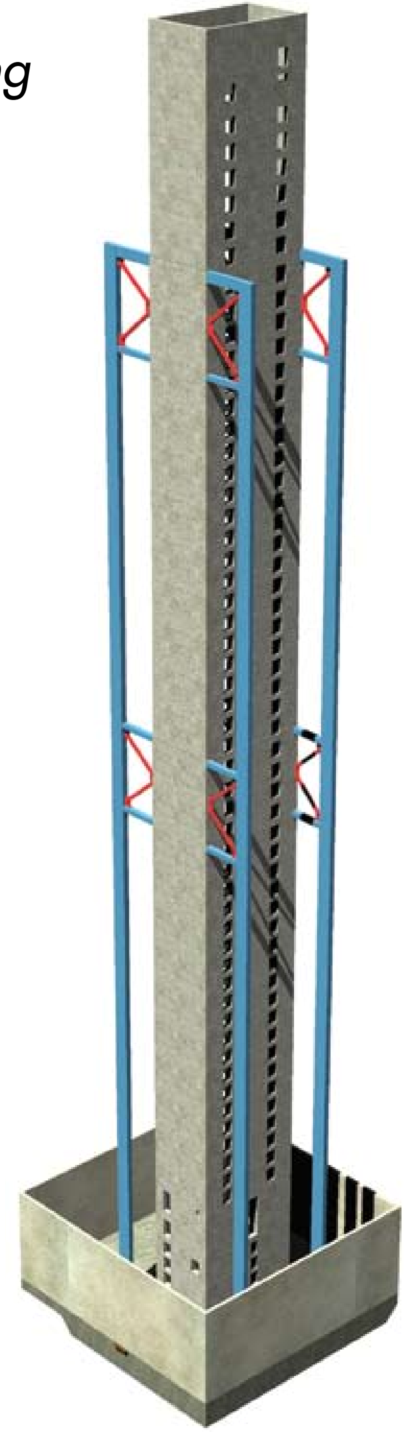
While the approach to design of tall buildings for wind effects has been refined over the years, the basic framework stems from these early pioneering designs. Today, wind engineering of high-rise buildings remains largely "performance based." Outside of minimum strength requirements, the building code provides little in the form of prescriptive requirements.

Performance-based *seismic* design dates to the 1980s, when documents such as ATC-33 and SEAOC's Vision 2000 were developed, targeting evaluation and enhancement of existing buildings. It was recognized that the structural systems present in many existing buildings did not fall within, nor meet, the prescriptive language of modern building codes. A methodology to guide structural engineers in the appropriate upgrade of these buildings was an important development.

Similar to wind engineering for high-rise buildings, site-specific demand levels were defined, and performance of the existing structural systems, as well as any upgrades, were assessed based on sound engineering principles and benchmarked against the growing body of research results. Over the last several years, this performance-based "framework" has extended to the design of newly constructed high-rise buildings.

Prescriptive- Versus Performance-Based Designs

While still legally "allowed" by the building code, there is a growing body of evidence suggesting that prescriptively designed tall buildings may not perform as well as those designed using more rigorous PBD methods. Further, arbitrary limitations imposed by the building code on structural systems (*sidebar*) do not necessarily recognize framing systems which are efficient or consistent with modern high-rise construction. The unique characteristics of tall buildings are not considered in current code provisions, and this may lead to less-than-desirable results.



Primary lateral load-resisting system of One Rincon Hill, with concrete core and outriggers comprising buckling restrained braces.

Performance-based design provides the structural engineer with the opportunity to understand the response of a particular building relative to site-specific conditions. A design can be directly "tuned" and optimized, resulting in more efficient and reliable buildings. With no specific limitations on building form, framing systems, or construction materials, greater design freedom is afforded.

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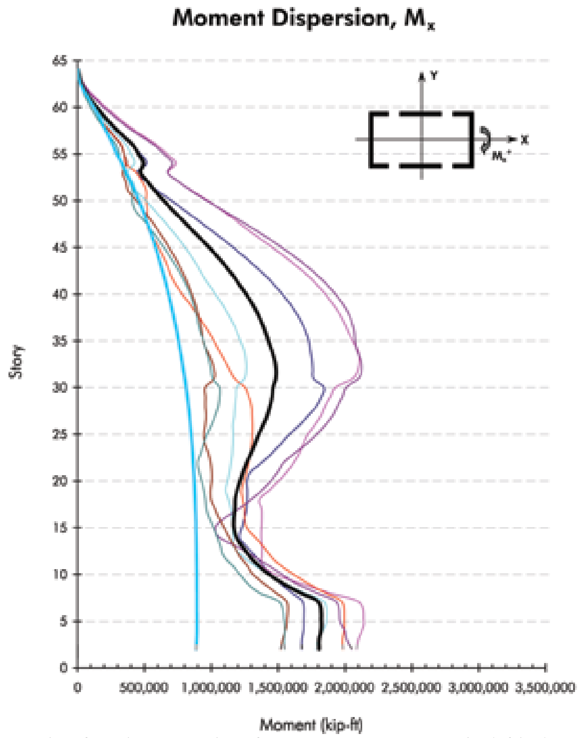


Results of nonlinear analysis for seven seismic events (thick black line – average of the seven events; thick blue line = Building Code demand level)

Technical Challenges

After completing more than two dozen tall buildings using PBD, several challenges are readily apparent. A few of the more significant include:

- Response Modification Factors, R
- Higher mode effects
- Peer reviews

Response Modification Factors, R

The "first generation" of PBD high-rise buildings largely adopted a traditional approach to establishing minimum required design strength. A design basis earthquake (DBE) was defined for the specific site, then reduced somewhat arbitrarily by a traditionally prescribed response modification factor, R. This approach was intended to provide some form of consistency with traditional prescriptive designs. However, these factors were not developed considering unique response characteristics or framing systems common to modern high-rise buildings. In addition, the approach conflicts directly with the premise of PBD: rather than defining demands and directly evaluating building performance, "artificial" modifications to demand levels lead to a design based on something not much better than a numbers game.

A more sophisticated approach, growing in acceptance, aims at directly defining a "serviceability event," which will replace any arbitrary, prescriptive strength requirement. A high-rise building subject to this level of ground shaking should respond with little damage and remain "essentially elastic." While this more direct route to establishing strength and performance has obvious merits, debates rage concerning the definitions of "serviceability event" and "essentially elastic" performance. On-going research is focused on gaining consensus in these areas.

Higher Modes Effects

It is common for the response of a tall building to be heavily influenced by higher modes of vibration when subjected to strong ground shaking. However, traditional engineering practice has focused on only the first translational mode when setting strength requirements and lateral force distributions. For tall buildings, the second or even third mode of vibration can be equally, if not more, important to the overall design.

The influence of these higher modes of vibration can result in significantly higher flexural demands, well above a building's base, as well as shear demands three to four times greater than those anticipated by a typical prescriptive design. Failing to recognize and incorporate these demands into a tower's design can lead to undesirable performance.

Peer Review

The complexities of high-rise design, coupled with evaluation by advanced mathematical modeling, have led building officials to require detailed peer reviews of these projects. These reviews are an integral part of the successful implementation of a PBD, as they ensure appropriate consideration of important design parameters.

However, these same reviews can vary widely in their focus and thoughtfulness. It is imperative that selected peer reviewers have experience in design of tall buildings. It is further important that reviews be led by senior staff members and not delegated to those less experienced. While there is great rigor to the numerical side of PBD, interpretation of analytical results remains an art form, requiring thoughtful consideration.

A Changing Landscape

There is a tremendous amount of momentum building for wide-spread application of PBD. Numerous groups have all recently published or are working on documents in support of PBD of tall buildings:

- *An Alternate Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region*, Los Angeles Tall Buildings Structural Design Council
- *Recommended Administrative Bulletin on the Seismic Design and Review of Tall Buildings Using Non-Prescriptive Procedures*, Structural Engineers Association of Northern California

Height Limitations and Code Folklore

While the absoluteness of code-prescriptive height limits suggests some "step function" in structural performance, the reality is that these limits were arbitrarily set without scientific basis:

Late 1940s – Effort begun to study the effects of earthquakes on buildings and propose specific code language to guide design.

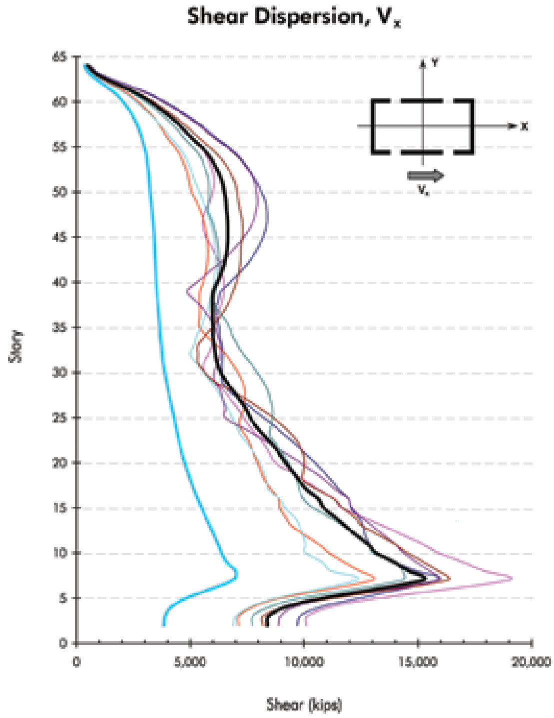
April 1951 – ASCE publishes *Lateral Forces of Earthquake and Wind*, one of the first documents to address seismic design of high-rise buildings. The document's recommendation for moment-resisting frames for buildings taller than 135 feet was anecdotal ("buildings with moment-resisting frames…have had a very good record") rather than scientifically justified.

1959 – Los Angeles removes zoning height limit of 13 stories and 150 feet. The limit, set in the early 1920s by the city council, was intended keep buildings short and encourage spread-out development.

1960 – SEAOC publishes first commentary to *Recommended Lateral Force Requirements*, stating "The limitations of 13 stories and 160 ft. have been established arbitrarily and are subject to further study." [Reportedly, the 160-foot limit mentioned in the 1960 SEAOC publication was a typographical error and was originally intended to be consistent with L.A.'s earlier limitation of 150 feet.]

1961 – *Uniform Building Code* (UBC) incorporates new height limitation for structural systems, stating "Buildings more than 13 stories or one hundred and sixty feet (160') in height shall have a complete moment resisting space frame…"

1988 – UBC extends allowable height for shear wall building frame systems to 240 feet. No specific technical justification for this increase can be found.



Results of nonlinear analysis for seven seismic events (thick black line = average of the seven events; thick blue line = Building Code demand level)

- *Administrative Bulletin AB-083, Seismic Design and Review Procedures for New Tall Buildings*, San Francisco Department of Building Inspection
- *Interim Guidelines on Modeling and Acceptance Criteria for Seismic Design and Analysis of Tall Buildings*, Applied Technology Council, ATC-72-1 PEER Tall Buildings Initiative (yet to be published)
- *Recommendations for the Seismic Design of High-Rise Buildings*, Council on Tall Buildings and Urban Habitat (yet to be published)

While these largely volunteer efforts are encouraging, one somewhat troubling undercurrent is the tendency of these groups to write prescriptive language to "guide" structural engineers in implementing PBD. Ironically, avoiding prescriptive constraints is one of the most significant virtues of PBD.

The Road Ahead

While many recently constructed buildings include reinforced concrete core walls, planning has begun for even taller buildings (1000 feet or more) which will likely include more exotic structural systems. Composite construction, passive damping systems, and ultra-high-strength concrete and steel will be employed to address the growing complexities in architectural forms. PBD methodology provides structural engineers with the framework to pursue these exciting new frontiers.▪

A False Sense of Security?

One of the most significant and alarming discoveries that has held consistent through the design of more than two dozen tall buildings relates to the predicted shear demands. A design which follows the prescriptive provisions of the building code will likely result in a shear capacity that falls well short of the likely demands the structure will experience during a significant seismic event. As shear failure of a structural wall is typically viewed as a nonductile, undesirable response, this outcome raises serious concerns about the likely performance of these buildings.

In part, this phenomenon is fueled by the prescriptive response modification factors, R. According to ASCE 7-05, a shear wall building is assigned an R value of 5 or 6, while a dual system combining shear walls and frames is assigned a higher R value of 8. In the case of a shear wall building, predicted shears considering site-specific ground motions are consistently 3 to 4 times greater than the values required by the building code. Dual-system buildings subjected to the same set of site-specific ground motions fall even shorter in their shear capacity, with demands 4 to 5 times the capacities required by the building code.

Compounding shear demands is the traditional consideration of a first-mode dynamic response of a building, with the resulting effective moment of inertia forces assumed at two-thirds the building's height. In tall buildings, higher modes of dynamic response often dominate the resulting demands on the tower. It is common to calculate the effective moment of inertia forces for a tower at one-quarter to one-third the building's height. This alone can double or triple the shear demands at the tower's base.

Future versions of the building code must either address these deficiencies with new provisions or, better yet, acknowledge that a prescriptive design methodology for tall buildings is inappropriate.

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