Performance-Based Wind Design

The Next Frontier

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With the release of the ASCE/SEI *Prestandard for Performance-Based Wind Design* (PBWD) in August 2019, the industry has taken an initial step toward implementing a structural engineering technique similar to well-established Performance-Based Seismic Design (PBSD) for the other most common building environmental hazard, wind. The Prestandard outlines an alternative and comprehensive approach to building design for wind loading, which explicitly evaluates occupant comfort, building drift, and extreme wind event behavior. The application of this approach may have the greatest significance to tall building design, particularly in high seismic hazard regions where both seismic and wind load effects control lateral demands.

While PBSD methodologies have been in use worldwide for over 25 years, the development of similar techniques for the design of buildings due to wind hazards has lagged behind. Several concerns have slowed the application to wind design, including duration and directionality of loading, element fatigue, computational methods, wind-tunnel techniques, and dynamic response. The Prestandard was created to address these concerns and chart a path forward for implementation of PBWD.

ASCE/SEI Prestandard

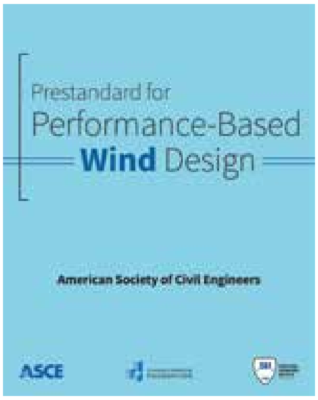
The *Prestandard for Performance-Based Wind Design* presents an alternative to the prescriptive procedures for wind design specified in the nationally adopted ASCE/SEI ASCE 7 standard. The Prestandard calls for performance objectives to be established concerning the relevant building or facility responses meaningful to the owners, occupants, and users of the building or facility. These objectives range from occupant comfort level (detection of objectionable building motion), through serviceability (drift and motion), to strength and safety levels (building strength, damage potential, stability, and reliability). The designer and building stakeholders may apply specific design techniques to determine and demonstrate acceptable building functions across the range of objectives.

The Prestandard recognizes that a detailed evaluation of building response requires a detailed understanding of the relevant wind environment. Therefore, the building analysis and design are predicated on conducting wind-tunnel testing to establish structural loads. The designer then evaluates these loads using one of three methods of linear or nonlinear response history analysis. The three methods are included to give designers a choice between modest additional analysis up to sophisticated levels of additional analysis.

Method 1

The first method requires a linear response history evaluation of wind loads. This analysis can be completed using commercially available analysis platforms. The Prestandard provides a series of element- and system-level acceptance criteria benchmarked to the linear analysis output. If the linear evaluation indicates elevated demand-to-capacity ratios, as defined in the Prestandard, the designer may be required to perform a nonlinear evaluation of the structure. In this method, the designer is restricted to limited levels of inelasticity within specific structural elements.

A storm descends on the Chicago skyline.



Prestandard for
Performance-Based
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Figure 1. ASCE/SEI Prestandard.

Method 2

The second method directly evaluates structural reliability for agreement with the target reliabilities of ASCE 7, Chapter 1. The reliability evaluation requires a nonlinear incremental dynamic evaluation of the building response as input; the analysis findings are then compared with the critical collapse initiation modes specific to the structure. The designer can then determine the resulting reliability of the structural system relative to the target reliabilities required by ASCE 7. In this method, the designer has considerable latitude to identify and demonstrate acceptable structural performance within elastic and inelastic elements.

Method 3

The third method, like Method 2, also directly evaluates a building's structural reliability but instead uses system nonlinear analysis directly coupled to the wind time-history loads and the uncertainties in structural load and resistance. The high computational demands of Method 3 can be avoided using a structure Shakedown Analysis, which has recently advanced to a point where it is ready for practical use. Shakedown Analysis directly determines reliability through Monte Carlo simulation of the structural response. Method 3 findings can then be compared to the target reliabilities required by ASCE 7. With this method, the designer has the most significant latitude to identify and demonstrate acceptable structural performance within the structure.

The Prestandard provides a series of structural element and structural system performance targets for evaluating the analysis findings for each method. If the building performance is acceptable, the resulting design may be submitted to the Authority Having Jurisdiction for Peer Review, according to the alternate design provisions of ASCE 7, Chapter 1 (*Figure 2*).

Furthermore, recognizing that the historic bulk of wind-related losses for tall buildings are due to wind-driven rain damage following breaches of the building envelope, the Prestandard provides building envelope

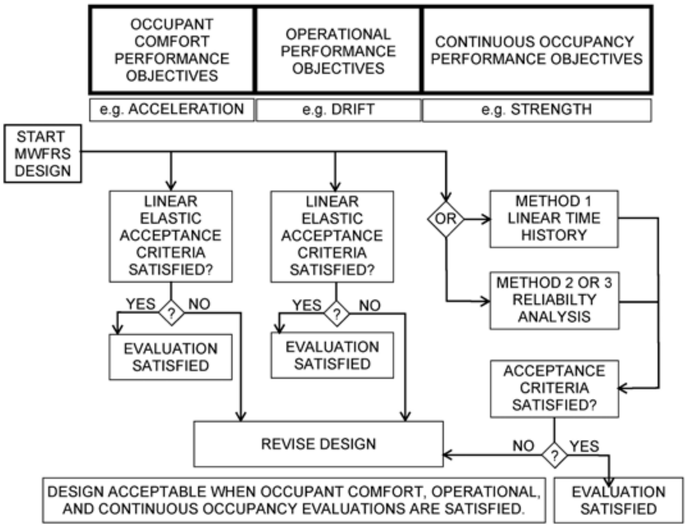


Figure 2. Outline of PBWD Main Wind Force Resisting Systems analysis and acceptance methods.

enhancements specifically intended to improve envelope performance. These enhancements include recommendations from envelope industry groups, recommended ASTM testing benchmarks, and recommendations for installation testing and construction observation.

Tall-Building Design

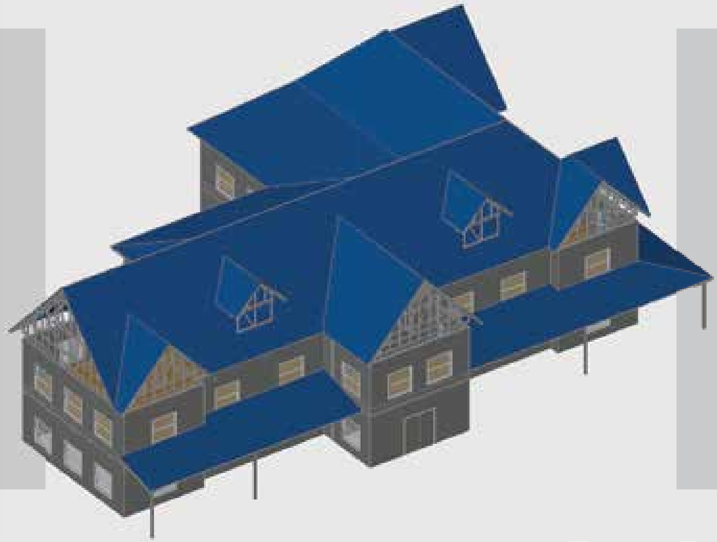
While the Prestandard applies to various building types and heights, it is considered most impactful to tall-building design, which is typically dominated by the flexural and dynamic response of the structure. The methodology can be applied to the design of a variety of Main Wind Force Resisting Systems (MWFRS) with different structural materials. With the MWFRS typically consisting of a third or more of the structural material in a tall building, the use of enhanced design techniques can optimize its material utilization.

Figure 3. Tall buildings in the high wind and seismic region of the Philippines.

The Prestandard outlines a procedure to ensure the building meets the established performance objectives in three primary areas: occupant comfort, operational performance, and building strength. While most current building codes do not require wind-tunnel testing or verification of serviceability criteria, the use of PBWD will allow designers and owners to more directly understand the behavior of the building and make adjustments to refine that behavior.

Optimization of the structure for its strength is partially achieved by taking advantage of inherent material overstrength and allowing for limited element yielding in ductile elements that can then dissipate energy and redistribute forces. The Prestandard recommends this be achieved through the use of expected material strengths and demand-to-capacity ratios (DCR) of 1.25 or 1.5, depending on the method used.

Method 1, described above, is the most straightforward and has many similarities to the methodology of PBSD, as outlined in the PEER *Tall Building Initiative Guidelines.* Method 1 follows these steps:



1) Conduct a wind-tunnel study to identify building wind-force demands
2) Classify the structural components as deformation (ductile) or force (brittle) controlled
3) Using results of the wind tunnel study, complete a preliminary design of the MWFRS, applying enhanced design criteria for deformation-controlled elements
4) Verify the structural components' response when subjected to wind time history records
5) If necessary, conduct nonlinear response history analysis to verify that components meet the acceptance criteria

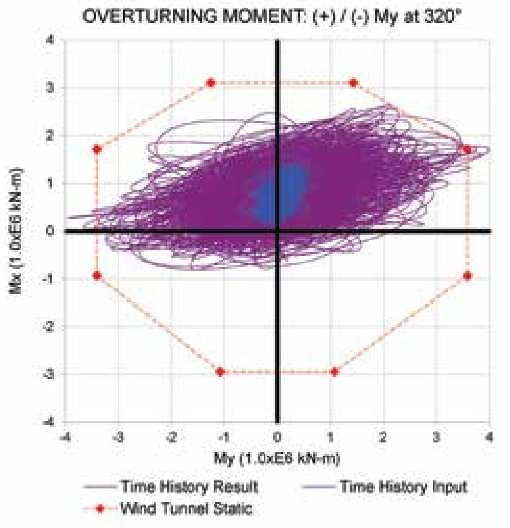


Figure 4. Example of a building base over-turning from wind response history showing dynamic response.

While the process of Method 1 is straightforward, it involves considerable additional design effort beyond conventional approaches – primarily the application of wind time histories and conducting the nonlinear response history analysis.

Traditional methods to compute the element forces in the structure involve applying a set of static wind loads distributed through the height of the building to a linear-elastic analysis model. In PBWD, the element forces are determined by applying a set of loads in a response history analysis corresponding to various wind directions. The dynamic response of the structure, considering mass and stiffness, is then directly captured in the analysis model. The global response of the building, subject to a linear response history analysis, should match the wind tunnel static loading (*Figure 4*) closely. If results are not similar, further consideration should be given to response history input and details of the analysis model.

Enough wind directions must be considered for the response history analysis to fully envelop the response of all components of the MWFRS. As a minimum, wind directions should be selected to produce peak base demands in all four quadrants of overturning (Mx+ My+, Mx+ My-, Mx- My-, Mx- My+).

When the preliminary design has been evaluated with linear response history results and components are found to exceed a DCR of 1.0, a nonlinear response history analysis is required to verify the response and acceptance criteria. The development of this more complex model requires advanced modeling techniques to capture the nonlinear behavior of any yielding elements such as coupling beams, shear wall flexure, or other deformation-controlled elements.

With a properly calibrated nonlinear model, the dynamic behavior of the building should respond to the changing stiffness as elements yield and forces redistribute. Given that the analysis directly captures the dynamic behavior, the Prestandard also allows for the more thoughtful implementation of supplemental damping systems to control building movement as well as element forces. Careful consideration of the reliability, redundancy, and damping properties of these systems is crucial to ensure that performance objectives are met.

Significant motivation in applying PBWD in tall buildings design comes in high-seismic hazard regions where the wind demands control the design of certain elements. Seismic design principles rely heavily on the concept of energy dissipation through the yielding of ductile (deformation-controlled) elements. When those elements are made stronger and stiffer due to the wind demands, they tend to dissipate less energy in an earthquake. This can cause other brittle (force-controlled) elements in the building to require more strength than they would otherwise. By implementing PBWD, this issue is improved and better aligns wind and seismic approaches.

Research

One of the most critical topics for the PBWD process is the inelastic behavior of structural elements subjected to wind demands. Because inelastic behavior has not historically been permitted, there is limited research available on this topic. To address this gap, the MKA Foundation sponsored research on conventionally detailed reinforced concrete coupling beams at UCLA (Abdullah and Wallace). The experimental program tested eight different test specimens with four different wind-loading protocols. The initial results are positive and suggest that standard concrete coupling beams can resist wind demands with more than 2,000 loading cycles and ductility demands of at least 1.5 with little to no strength degradation. The research results will be published in 2020 and will include nonlinear modeling recommendations such as effective stiffness values and backbone curves. Similar research is underway across the country to evaluate the performance of reinforced concrete shear walls, concrete-filled composite-steel-plate shear walls (CF-CPSW), and concrete-encased embedded-steel wide-flange coupling beams.

Further development is also underway for Methods 2 and 3 found in the Prestandard. This includes research sponsored by the MKA Foundation at the University of Michigan (Spence), which seeks to publish software to perform the Method 3 analysis.

Conclusions

The most significant advancements of PBWD will be the application of the methods found in the Prestandard to real building designs, an effort currently underway by the authors on several projects nearing completion. Similar to Performance-Based Seismic Design, the first several designs will require outside-the-box thinking and open collaboration between the structural engineer, wind engineer, building owner, peer reviewers, and the local jurisdiction. The publication of the *Prestandard for Performance-Based Wind Design* is only the beginning, and much more knowledge will be gained in the coming months and years regarding how tall buildings respond to wind.▪

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