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A New Paradigm for Wind Design

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Abstract For taller buildings with unconventional architecture, refined structural systems or in geographical areas with high wind conditions, performance-based design can be seen as an enhanced design process and is either a supplement to, or alternative to a prescriptive code-based design. The ultimate goal of Performance-Based Wind Design (PBWD) is to result in a building that better addresses key goals of performance over the buildings full life cycle. Major innovations around the use of a PBWD approach include nonlinear dynamic analysis for wind design, limited inelasticity in the main wind force resisting system elements, and system-based performance criteria. This paper discusses potential considerations and benefits made when using a performance-based approach, in addition to the general practicality of use, for the structural design on a few key tall buildings.

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1. Introduction

For taller buildings with unconventional architecture, refined structural systems or in geographical areas with high wind conditions, our standard code approaches to design may be uneconomical or inappropriate. For structures such as these described, performance-based design (PBD) should be seen as a better approach that enables a more sustainable design through efficient use of materials. Supertall towers, unconventional structures, and older buildings designed using outdated codes, materials and details all can benefit from PBD.

Performance based design can be seen as an enhanced design process and is either a supplement to, or alternative to, a prescriptive code-based design. The approach establishes certain performance criteria which the building should achieve, and often requires more sophisticated design and analysis techniques to validate performance. PBD has been widely used in seismic engineering circles for more than a decade. Using a PBD approach for tall buildings subject to extreme winds is a paradigm shift in how we design and creates an opportunity for building efficient structural systems that are wholly considerate to the varying and dynamic nature of wind environments globally. Several features of PBWD include the evaluation of a building at various return periods (intensities), enhanced façade design, non-linear response history analysis, wind tunnel testing and site-specific wind climate assessments. This paper discusses some considerations made when using a performance-based approach for the structural design on a few key tall buildings.

The ultimate goal of PBWD is to result in a building that better addresses key goals of performance over the building's full life cycle. Two major innovations around the use of a PBWD approach over a prescriptive code-based method include limited inelasticity in the main wind force resisting system elements, and system-based performance criteria. PBWD naturally creates a greater level of resilience in our buildings as if often results in the ability to improve levels of robustness, enhance building safety and can sometimes result in a speedier return to operation after an event, relative to a typical design. A

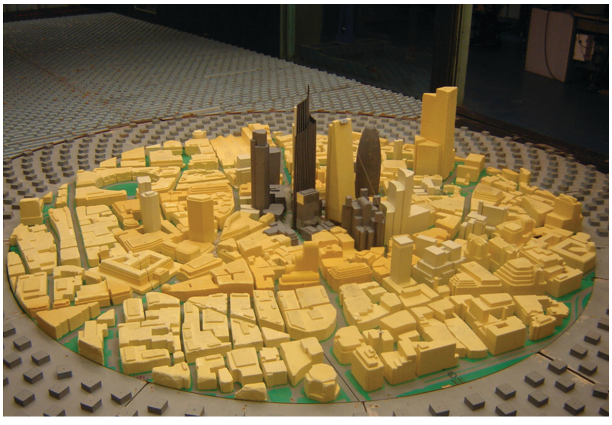


Figure 1. Wind tunnel testing model of a City.

performance-based approach to design should also result in a more focused use of materiality in structures in the places where it is needed most to resist environmental loading.

2. The Wind Environment

There are a number of wind circulation mechanisms common to our planet: monsoons (driven by synoptic circulations), sea breezes, thunderstorms, tropical cyclones (including hurricanes and typhoons), downslope winds, and winds that are particular to rather localized areas of the globe, e.g. Shamals in the Middle East.

Hurricanes, typhoons, and tropical cyclones typically form over large bodies of warm water in the middle latitudes. They are 3D structures with a low-pressure center called the 'eye' surrounded by rapidly rotating winds. These types of storms have the potential to generate some of the strongest winds experienced on the globe. Cyclonic activity is increasingly being shown to be affected by the changing climate. The general synoptic circulations that cause monsoon type winds in nearly all parts of the globe are large pressure systems that can last for days, and sometimes even up to a week. Strength of these types of winds varies seasonally and can consist of summer and winter trends separated by transition periods. These synoptic circulations are also drivers of some of the planet's most extreme winds.

Traditional design has repeatedly shown a lack of resilience in the face of wind and storm events. Year after year, storms result in many billions of dollars of losses to building stock and massive disruption in their aftermath. This damage stretches from individual buildings to entire communities and often includes systemic factors that extend beyond the design of any individual building.

Dynamically sensitive structures such as high-rise buildings or slender towers may exhibit large or prolonged deflections and accelerations in reaction to aerodynamic forces and aeroelastic interactions (e.g. vortex-induced vibrations, galloping and flutter instability) with the wind environment described above. These responses may lead to serviceability issues; for example, the halting of elevators due to excessive floor accelerations or people on the top floor perceiving the motion. Seismic engineering has employed enhanced design techniques for some time which seek to provide desired performance at various event intensities. Moving to a performance-based approach for wind explicitly forces the designer to be considerate about a buildings behavior in a storm that could occur this year, next year, in one hundred years from now and in all years in between.

3. Market Implications

As urban centers run out of large lots ripe for development, towers have grown taller and ever more slender. Aspect ratios of 15 to 1 once pushed the technical limits and financial feasibility of tower development. New supertall tower developments have exceeded aspect ratios of 20 to 1. This slenderness, coupled with climate change, results in vortex shedding effects driving tower motion at lower wind speeds and more frequent recurrence intervals.

The performance of the structural system of these towers, as a result of non-linear behavior and second order effects, becomes critical and a necessary focal point of the design. This behavior and effect can drastically magnify loads, affect dynamic wind interaction, and alter load paths in the structure. Traditional methods to estimate



Figure 2. Tropical cyclone.

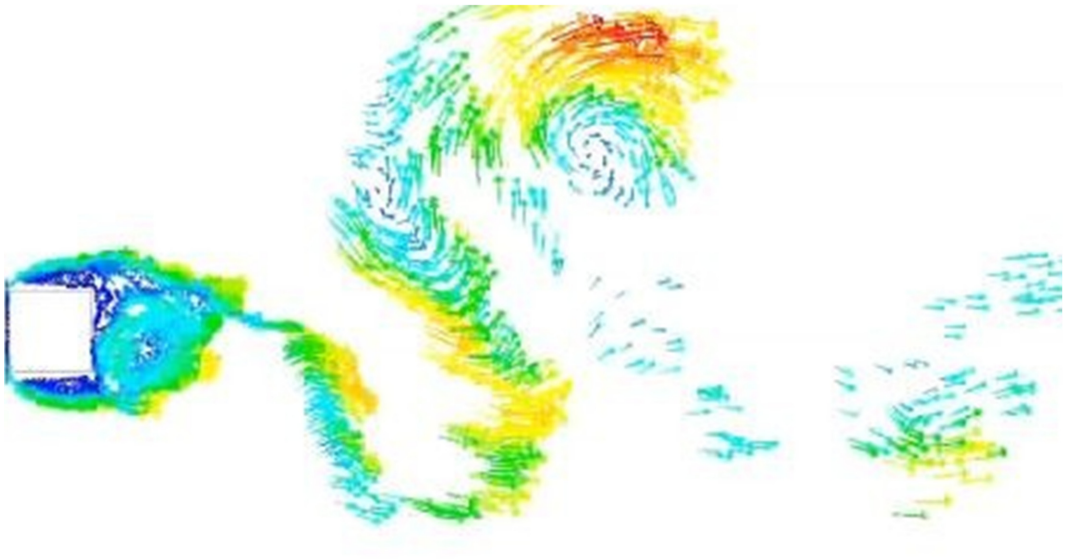


Figure 3. Vortices shedding from a building in plan.

structural performance can be more of an art than science and require significant judgement on the part of the engineer. Advances in nonlinear modelling capabilities combined with digital automation of workflows between linear and nonlinear modelling software has opened up opportunities to tackle age old tall building design problems in efficient and clear ways. This combined with a performance-based approach to wind design has the potential to move the design of these buildings into a realm of greater efficiency and with a greater level of appropriateness. Ultimately PBD results in a building that better addresses key goals of performance.

The Prestandard for PBWD, funded by the Charles Pankow Foundation, presents a recommended alternative to the prescriptive procedures for wind design of buildings contained in traditional design codes of practice. A series of case studies following the performance-based approach are given below where a review of the full building life cycle has been made. These case studies highlight some nuances of consideration around the approach and identify times when a cautious approach around integrating PBD is necessary.

4. Case Studies

Arup has investigated how PBWD can be embedded into our design processes in a series of early trial cases as given below. Arup has extensive experience carrying out



Figure 4. Arup's history of tall building design.

complex non-linear analyses for PBD, predominantly related to seismic loading. Relevant software, knowledge and expertise from this existing practice in conjunction with deep expertise in wind engineering and dynamic loading of structures has been applied to the developing field of PBWD.

4.1. Industry Collaboration

As a part of an American Society of Civil Engineers (ASCE) working group consisting of multiple practicing engineering firms, the University of Michigan, and CPP Wind Engineering Consultants, the application of PBWD has been applied over a suite of archetype buildings for both a New York City and Miami wind climate. This suite included both square and rectangular footprint high-rises (~180 m tall), representative of a typical residential or office tower in a city, and a low-rise structure, representative of a typical suburban type community, commercial or residential building. Each of these unique structures was carried through the methodology outlined in the Prestandard for Performance-Based Wind Design, hereby referred to as the "Prestandard". Further analysis, as described herein, was completed by Arup on two of these structures, as shown in Figure 5 below.

Nonlinear dynamic time history analysis was conducted using the floor-by-floor wind loads determined from wind tunnel testing carried out by CPP Wind Engineering Consultants. The Prestandard allows for inelasticity in select elements, including the brace elements that span the height of the structure in Tower #1 and in the shear walls and link beams in Tower #2. Limited inelasticity is allowed in columns in tension and beams. On a system level, similar to prescriptive design methods, limits are defined for the peak transient drifts (i.e. relative lateral deflections) the structure can undergo. Differing from the prescriptive approach, a peak residual drift is also specified due to the allowed inelasticity in the structure. The combination of these two drift limits ensures the nonlinearity is well distributed within the structure and limited permanent deformation is sustained.

The results of these case studies highlighted the potential benefits of utilizing non-linearity in the megabrace elements / link beams and core wall systems of the lateral system to both dissipate energy and limit demands in force-controlled elements of the structure. In addition, it did highlight some potential adverse effects that need to be considered. This is discussed further in the next section.

4.2 PBWD in Practice

In addition to carrying out studies on the archetype buildings described above, Arup has also looked into the application of the methodology in the Prestandard in practice. The first building reviewed included a steel tower in Mexico, the second is a tall slender tower in the USA.

Applying the performance-based approach in practice confirmed the level of effort needed to apply the methodology in the project landscape while reviewing if the findings from the archetype buildings investigations were reinforced here.

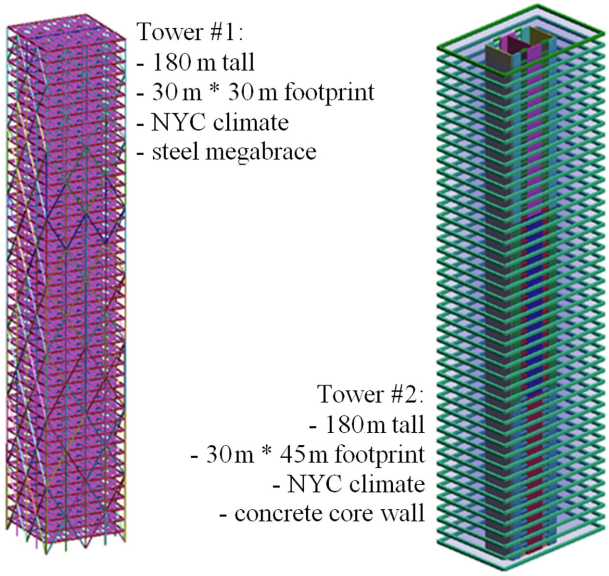


Figure 5. LS-DYNA non-linear analysis models.

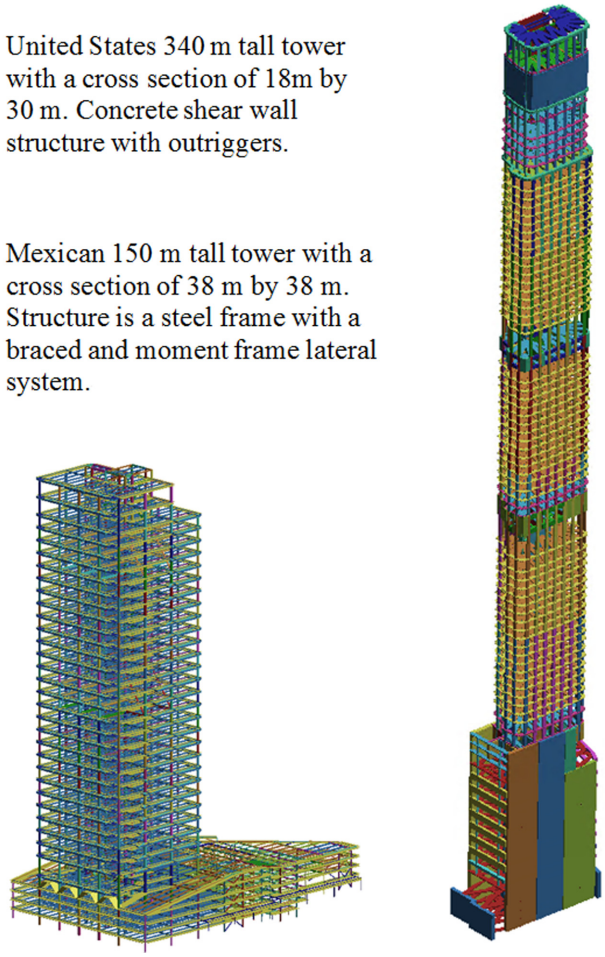


Figure 6. In-practice use of PBWD.

For the Mexican tower wind load time-histories up the height of the structure were available. Applying the Prestandard methodology revealed both benefits and potential challenges for consideration when using non-linear time history modelling for wind.

For the USA structure, with an aspect ratio of approximately 19:1, the dynamic response to wind wa critical. With increased slenderness the potential for significant non-linearity within vertical concrete elements (core walls, columns) under tensile forces induced by wind loading is increased. The Prestandard was not applied directly to this structure. Instead, quasi-static service and ultimate loads were applied to a non-linear analysis model to quantify the amount of concrete cracking and the effect this had on the dynamic properties of the structure.

Under the more extreme wind loads significant cracking in the core was observed. This resulted in a softening of the structure and a shift in its natural frequency. The implications of this when considering performance-based wind approaches are discussed in the next section.

5. Findings

5.1. Practicality

There is a practical and repeatable process to perform the performance-based methodology outlined in the Prestandard. Workflows and methodologies developed for Performance Based Seismic Design (PBSD), such as force vs. deformation-controlled elements and global acceptance criteria, with some adaptation for wind events as identified in the Prestandard, are replicative. However, a number of complexities with PBWD analyses were identified that must be considered and a cautious approach to full inclusion in design processes is warranted.

Applying wind loading to a structure requires applying varying load time histories up the height of the structure, which thereby requires mapping of floor-by-floor loading to relevant structural members at floor levels. Once mapped accurately the length of the analyses required is considerably long. For reference, a five-minute seismic event is towards the upper end of what would typically be considered for PBSD, whereas PBWD requires a suite of analyses to be completed with input time histories of around three hours. The computational power and storage space for running this quantum of analyses is significant. The analysis time grows or compresses based on the magnitude of non-linearity in the system. Cloud-computing resources are necessary given the complexity.

5.2. Potential Benefits

One of the main benefits of adopting a performance-based design approach is the ability to move away from prescriptive procedures that can lead to the overdesign of structures. By using PBWD, more efficient structures are possible through both the explicit time-history analysis and accounting for non-linear behaviour of elements in the lateral force resisting system. By allowing small amounts of non-linearity in structural elements, designers can directly save on material quantities by not designing the entire structure to remain elastic and can take benefit from energy absorption resulting from this non-linear behaviour. This design approach can also serve as capacity control, limiting the amount of load that is transferred to force-controlled elements, potentially reducing their size in turn.

By allowing targeted locations of non-linearity in structural elements energy sustained from wind events can be dissipated and the design of the building to wind can work in concert with the design of a building to seismic loading. In the classic prescriptive wind design of structures, the elastic design of deformation-controlled elements directly contradicts the seismic design.

5.3. Potential Considerations

The application of time history wind loading to highly dynamic structures is complex. A great deal of care is needed to make certain the wind loading is appropriately applied to the structural model to ensure the accurate distribution of load and that the intended response of the structure is achieved. Small differences in dynamic characteristics (e.g. observed damping level, natural frequency) can lead to significant changes in behaviour.

Tangential to the application of the load is the development of the time-histories. Inherent to the methodology in the Prestandard is ensuring the critical loading scenarios are used in the analyses. The development and definition of the critical scenarios and time histories will be based on the dynamic properties of the structure; therefore this process might become iterative if large changes are made to the structural design after the wind load time histories are developed. This is also true as the structure naturally responds to its inherent non-linearity and the dynamics of the structure changes, potentially resulting in a further critical loading scenarios to be assessed.

Understanding where and when non-linearity in structures is beneficial or detrimental to achieving the desired performance is also critical. In some of our studies, we found that softening of the structure due to non-linearity led to a longer natural period, which in turn increased the dynamic excitation of the tower, generating higher loads and more non-linearity. This cycle would continue in a ratcheting effect where the structure continued to accumulate damage over the duration of a storm. This is no different from considerations required in PBSD; however, this phenomenon might be more frequent for PBWD of tall towers due to the presence of vortex shedding peaks. Special care and deep and significant collaboration with wind consultants / experts is needed when using a performance-based approach to wind to understand the relationship between return period and vortex shedding spectral peaks to determine whether a softening could lead to increased loading or a change in consideration of the critical scenarios of interest.

Potential element fatigue also needs to be considered when non-linearity is introduced into the structure given the duration of a typical wind event.

6. Conclusions

PBWD offers significant opportunities for tall building designers to deliver robust and efficient designs. Arup has investigated how PBWD can be embedded into our design processes, drawing on our extensive experience in complex analysis for PBSD and deep expertise in wind engineering.

This work has demonstrated that there is a practical and repeatable process to perform the methodology outlined in the Prestandard. However, challenges were identified around the complexity of applying time history wind loading to dynamically sensitive structures, and in the number and length of analyses required. Robust verification against wind tunnel testing results was required to ensure that the response of the structure is accurately captured. This process should be seen as deeply iterative.

With the right collaboration at industry level and with the case studies completed there is confidence that cost effective and efficient workflows are available which can allow the benefits of PBWD to be unlocked for the future design of tall buildings.

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