NIST Grant Contractor Report
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Workshop Report

Feb. 23–24, 2023
Reston, Va.

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NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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Abstract

In September 2022, the Structural Engineering Institute of the American Society of Civil Engineers commenced a project under National Institute of Standards and Technology Contract No. 1333ND22PNB730391 to develop workshops on *Advancement in Computational Wind Engineering* and *Advancement in Performance-Based Wind Design*. This report documents the results of the workshop on *Advancement in Performance-Based Wind Design*. The workshop and subsequent roadmap for the standardization and application of performance-based wind design is to be developed by wind engineering practitioners and researchers for buildings.

Keywords

Components and cladding; Design; Performance-based wind design; System reliability; Wind engineering; Wind climate characteristics

Contents

Preface

In September 2022, the Structural Engineering Institute (SEI) of the American Society of Civil Engineers (ASCE) commenced a project under National Institute of Standards and Technology (NIST) Contract No. 1333ND22PNB730391 to develop workshops on *Advancement in Computational Wind Engineering* and *Advancement in Performance-Based Wind Design*. This report documents the results of the workshop on *Advancement in Performance-Based Wind Design*. The workshop and subsequent roadmap for the standardization and application of Performance-Based Wind Design is to be developed by wind engineering practitioners and researchers for buildings.

The impetus for the project was the extensive casualties and property losses that have occurred over the last several decades due to damaging hurricanes, tornadoes, and other wind events affecting the United States. NIST has continued to research and provide leadership in the advancement of knowledge of these hazards and to develop standards that will lead to more resilient communities across the nation.

The workshop process included a review of the literature, which identified research needs in the areas of Wind Climate Characteristics, Structural System Reliability, Wind-Structure Interaction, Structural Analysis Techniques, and Structural Design. This review was followed by an extensive workshop preparation process, a two-day workshop to obtain input from experts in these areas, and report preparation and review.

The workshop identified a broad range of research and development activities to advance the use of Performance-Based Wind Design with the goal of reducing the impacts of these severe wind events. This report includes discussion and specific recommendations on the following 10 topics:

1. Development of main wind force resisting system reliability;
2. Development of components and cladding reliability;
3. Integration of performance between the building structural system and the cladding;
4. Characterization of engineering properties of thunderstorm and tornado wind events;
5. Characterization of the wind hazard and loads for short and long return periods;
6. Improvement of the understanding of structural and material properties;
7. Improvement of physics-informed, computationally efficient methods for nonlinear analysis of wind response over long-period durations;
8. Static pushover for wind engineering to quickly evaluate nonlinear structural performance;
9. Development of wind loading protocol for experimental quantification of system performance in wind; and
10. Economic study to identify existing buildings at risk.

SEI is indebted to the leadership of Don Scott, who served as the Workshop Director; the ASCE staff—especially Bianca Augustin, who served as the Workshop Coordinator, and Amber Davis, who served as the Conference Center Manager—the Workshop Steering Committee members Melissa Burton, Roy Denoon, Russell Larsen, Seymour M.J. Spence, and Teng Wu for their contributions in putting the workshop together and development of this report; and the Workshop

Steering Committee scribes Wenbo Duan, Workamaw Warsido, Juliana Rochester, Srinivasan Arunachalam, and Baichuan Deng for helping to document the discussions and prepare the final report.

Appreciation is also extended to the many individuals who participated in the workshop. Appendix D lists the names and affiliations of all who contributed to this report.

SEI also gratefully acknowledges Long Phan, Marc Levitan, Therese McAllister, and DongHun Yeo from NIST for their input and guidance in the development of the workshop and in preparation of the report.

Jennifer Goupil, P.E., F.SEI, F.ASCE

Managing Director Structural Engineering Institute and American Society of Engineers Chief Resilience Officer

July 1, 2023

1. Introduction

The National Institute of Standards and Technology (NIST) has a long history of research and development in the area of windstorm engineering and is the lead agency for the National Windstorm Impact Reduction Program (NWIRP). This focus recently led to the development of the first-ever tornado design provisions in the 2022 edition of ASCE/SEI 7, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (ASCE/SEI 7; ASCE 2022). To continue with the efforts of windstorm impact reduction one of NIST's strategies is to further develop the use of Performance-Based Wind Design (PBWD). The workshop on *Advancement in Performance-Based Wind Design* held on February 23–24, 2023, and this resulting report provide a focus on the research and development efforts needed over the next decade to enable standardization and application of PBWD techniques in design practice.

2. Background

2.1. Workshop Purpose and Scope

The purpose of the workshop was to assess the current state of the art in PBWD and to support the future development of a Measurement Science Roadmap for advancing the knowledge in this area and its application in practice.

The workshop scope covered the broad subject area of PBWD methodologies and two associated sub-topics:

Subject Area: Performance-based wind design (PBWD)

- Sub-Topic 1: Review of Current state-of-the-art on PBWD
- Sub-Topic 2: Identification of research needs and prioritization for standardization and application in practice.

2.2. Workshop Development Process

The development of this workshop began with the selection of the Workshop Steering Committee (WSC) consisting of leading experts in the wind engineering field who have been involved in the development of previous PBWD documents. Those selected to serve on the WSC were Dr. Roy Denoon of CPP Wind Engineering Consultants, Dr. Melissa Burton of Arup, Dr. Seymour M.J. Spence of the University of Michigan, Dr. Teng Wu of the University at Buffalo, and Russell Larsen of Magnusson Klemencic Associates. Each WSC member also invited a young professional to participate in the workshop and report development process: Wenbo Duan at Arup, Workamaw Warsido at CPP Wind Engineering Consultants, Juliana Rochester at Magnusson Klemencic Associates, Srinivasan Arunachalam at University of Michigan, and Baichuan Deng at University at Buffalo (Fig. 2-1).

Fig. 2-1. Workshop Steering Committee.

The WSC started meeting in November of 2022 to begin developing the content of the workshop and to select the leaders in this field to invite to participate. The WSC decided on the following topics as the most critical issues to be addressed at the current time and the participants were selected based upon their expertise in these areas:

- Wind Climate Characteristics,
- System Reliability,
- Wind-Structure Interaction,
- Structural Analysis Techniques, and
- Design.

To help understand the current state of the art of PBWD the WSC developed a reading list of relevant documents to share with workshop participants, see Appendix B.4. As a result of developing the reading list, the WSC determined that the ASCE/SEI *Prestandard for Performance-Based Wind Design Version 1.1* (Prestandard; ASCE/SEI 2023) was the only current design document available to the profession and thus represented the state of the art. These documents were used to formulate the workshop sessions.

The two-day workshop was convened on February 23–24, 2023, to identify the highest-priority needs that form the basis of this report. The WSC, industry-leading experts, academics, and representatives from key government agencies attended the workshop, which was also open to members of the public. The workshop was held at the headquarters of the American Society of Civil Engineers (ASCE) in Reston, Virginia (Fig. 2-2).

Fig. 2-2. Participants at the NIST/SEI PBWD workshop on February 23, 2023.

The design of the NIST/SEI PBWD workshop enabled all 53 participants to contribute in multiple ways. The workshop began with several state-of-the-practice presentations and included time for the participants to ask questions. The participants were then divided into breakout groups based upon the five workshop topics selected by the WSC. In these breakout groups the participants were given four tasks: to define the current state of the art in each topic, to define the future vision for the use of PBWD, to determine the research needs required to progress from the current state of the art to the future vision for their topic, and to prioritize the research and development needs for their breakout group topic.

Each breakout group then reported back to all the workshop participants in a general session and described their prioritized research and development needs. Following these presentations and subsequent discussions, all the workshop participants prioritized the separate breakout group research and development needs. Section 6 lists the top identified research needs, and Appendix A contains a further discussion of these research needs.

2.3. Workshop Framework

The framework adopted during the workshop to advance PBWD into practice consisted of deep consideration of five key areas essential to the overall design process and verification. These areas include determining the wind climate characteristics, determining the overall structural system and building envelope reliabilities, understanding the wind-structure interaction, identifying structural analysis techniques, and determining the design methodologies for the overall building. The following briefly describes each of these areas.

Wind Climate Characteristics*:* To progress PBWD into practice, a need exists to examine the current state of knowledge regarding characteristics of different windstorm types including synoptic gales, hurricanes (tropical cyclones), thunderstorms, and tornadoes. A basis for consideration of the effects of different storm types as they relate to PBWD is also essential. Research to codify unknowns need to be identified and prioritized.

System Reliability*:* Another key need in advancing PBWD is understanding the current state of the art and prioritizing future research needs for the reliability estimation (or probability of failure) of the main wind force resisting system (MWFRS) of engineered buildings subject to extreme winds. This need extends to the envelope systems[1] of engineered buildings the reliability of which is generally coupled with that of the MWFRS. Areas of focus include fragility analysis, computational approaches for reliability/failure probability estimation (e.g., variance reduction schemes, machine learning accelerated uncertainty propagation, etc.), loss and consequence analysis, and wind demand characterization. Fragility analysis encompasses both experimental and computational approaches for characterizing the damage susceptibility of both the MWFRS and envelope components. Similarly, loss and consequence analysis are required to characterize repair costs, downtimes, and functional recovery of both the MWFRS and envelope system and may require a coupled analysis due to the interdependence of the two systems. Wind demand characterization for the MWFRS is primarily concerned with the characterization of the overall wind loads, while, for the envelope system, it requires the characterization of the wind-borne debris risk, local net pressures, wind-driven rain, etc.

Wind-Structure Interaction*:* 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. In a broad sense, wind loads on buildings are dealt with in two ways: low and medium-rise buildings with relatively rigid structural systems react to the wind loads in a static way; tall buildings, however, tend to interact with the wind in a more dynamic fashion and can be significantly more complex to predict and manage. Research is needed to enable better quantification of both the reactive behavior and the interactive (in some cases aeroelastic) feedback behavior between structural response and wind excitation.

Structural Analysis Techniques*:* A need exists to understand the current state of the art of nonlinear structural modeling and analysis techniques, especially those used for effectively addressing the challenges associated with aerodynamic loading (such as large mean load component and long durations) that are not present in seismic design. Research needs to perform nonlinear structural analysis (along with modeling of deformation-controlled elements) more efficiently and accurately under extreme wind events need to be evaluated, including efficient incremental dynamic analysis (IDA) for PBWD, development of loading protocols, efficient approaches for collapse analysis, and degradation in element strength or stiffness.

Design*:* To advance PBWD, a review of the current state of practice for design—specifically the current understanding of the apparent reliability of the building envelope (walls and roofing)—and the apparent reliability and performance of the MWFRS is needed. Techniques or strategies to make buildings more resilient and/or lessen uncertainty regarding performance outcomes in high winds need to be evaluated. Performance outcomes considered must include wind-borne debris impact, water ingress, and structural system damage caused by extreme wind events

[1] This document uses the term "building envelope" to refer to the envelope system on the walls and roof of a structure, which are intended to prevent transfer of water and thermal energy to the building interior. ASCE 7 (ASCE 2022) refers to these systems as "cladding."

(tornado, hurricane, thunderstorm, etc.). The techniques and strategies may include enhancements to building codes, enhanced testing, enhanced detailing or toughness, enhanced performance objectives, and leveraging of databases or datasets not presently in common use. The necessary research needs to enhance understanding in these areas need to be identified and prioritized.

2.4. Workshop Report Organization

Following Section 1, Introduction, and Section 2, Background, the workshop report is organized as follows:

- Section 3 describes the current state of the art of PBWD and the long-term vision for the use of PBWD.
- Section 4 describes the current challenges in using PBWD, as identified during the workshop by workshop participants.
- Section 5 describes the recommended research needs that were identified during the breakout sessions.
- Section 6 provides a description of the Prioritized Research Needs by the overall workshop participants, along with a summary of each research need that includes anticipated timelines and relative costs associated with each of the associated projects.
- Sections 7 and 8 provide a list of acronyms and abbreviations and references.

The report also includes four appendices. Appendix A includes additional discussion about the highest priority research needs identified during the workshop. Appendix B contains the workshop agenda, presentations, breakout session participants, and workshop reading list. Appendix C provides the priority research needs, as identified by the workshop participants, mapped to the initial set of workshop sessions and NIST programs. Appendix D lists the workshop participants alphabetically.

3. Vision for the Use of Performance-Based Wind Design

3.1. Current State of the Art

In developing the key topics for the workshop and examining key documents and compiling them into a reading list, the WSC came to a consensus that the current state-of-the-art document for design practice is the *ASCE/SEI Prestandard for Performance Based Wind Design* (ASCE/SEI 2023).

3.1.1. Wind Climate Characteristics

The current state of the art in defining wind climate characteristics—on which the Prestandard (ASCE/SEI 2023) is based—is to use statistical wind climate models based on a combination of historical surface data and, where appropriate, Monte Carlo simulations of hurricane (tropical cyclone) events. The most common approach is to use a Type 1 Extreme Value (Gumbel) fit to data to extrapolate to extreme events in each storm type, although versions of Weibull distributions may also be used, particularly for shorter mean recurrence interval (MRI) events. Separate fits are made to each storm type, and their probabilities are combined to determine relationships between wind speed, direction, and MRI. These data are then used in different ways (e.g., sector analysis, multisector analyses, storm passage analysis, or up-crossing) in analyzing wind tunnel data to provide the wind loading data that are the basis for design.

Current practice assumes that individual windstorms have stationary, directionally invariant boundary-layer characteristics. While this may be reasonable for long-duration storms such as synoptic gales, the duration of peak wind speeds in hurricanes may be much shorter, and other storm types, such as thunderstorms and tornadoes, have very different temporal and spatial characteristics that wind design does not currently account for. The only exceptions to this are some limited cases in which thunderstorms have been excluded from the wind climate data used to analyze serviceability responses of supertall buildings because the limited duration and lower elevation of peak wind speeds in the storms may limit their ability to generate the peak responses of interest.

3.1.2. System Reliability

Over the past decade, significant progress has been made in developing general PBWD frameworks for the probabilistic assessment of building systems subject to extreme winds. Major breakthroughs have been achieved in modeling structural and nonstructural damage and loss through probabilistic system-level metrics associated with repair costs, downtime, life-cycle costs, and occupant comfort. While many of these frameworks were initially inspired by the damage/loss modeling approaches based on fragility/consequence functions that were introduced by the Pacific Earthquake Engineering Research Center (PEER) framework (Yang et al. 2009), they have since evolved to include additional metrics, such as life-cycle costs (Cui and Caracoglia 2020); a wind-specific performance criterion associated with, for example, occupant comfort (Bernardini et al. 2015); envelope damage (Ierimonti et al. 2019; Ouyang and Spence 2020); inelasticity in the structural system (Mohammadi et al. 2019; Arunachalam and Spence 2022); and coupled envelope and structural system assessment (Ouyang and Spence 2021a).

3.1.3. Wind-Structure Interaction

Current design practices in wind engineering primarily focus on a singular occurrence interval, or return period, for a design event, which may lead to both overly conservative and simplified solutions. PBWD aims to consider the entire design space across different occurrence intervals and for varying design events, enabling the development of more resilient structures that consider this full design space. The Prestandard (ASCE/SEI 2023) serves as a summary of state-of-the-art practices and provides a nonprescriptive guide for carrying out wind-structure analysis to achieve specific performance goals.

Despite these advancements, challenges and uncertainties remain from baseline structural property assumptions, from the methodology of applying the wind load effects to structures through to establishing inspection regimes to improve performance in existing building stock.

At present, the wind engineering community is working to develop comprehensive methodologies for accounting for wind structure interaction in PBWD (Ciampoli et al. 2011; Bezabeh et al. 2020). Collaborative efforts to engage interdisciplinary research support from fields such as urban planning, architecture, materials science, and economics are in progress, as the benefit of PBWD clearly stretches beyond engineered structures and has the potential to create long-term resilience for communities. Further work is needed to raise awareness, attract funding, and promote the adoption of PBWD among practitioners and policymakers. Addressing challenges and concerns in the approaches to considering wind structure interaction is necessary to achieve this ambition.

3.1.4. Structural Analysis Techniques

Currently, the literature has limited information on performing nonlinear analysis of structures subject to wind loads. The nonlinear modeling and analysis techniques for structures under wind loads mainly refer to the guidelines and publications for performance-based seismic engineering (e.g., NIST 2010; ASCE 2017; NIST 2017; PEER 2017). However, the modeling and analysis details of structural systems may need changes according to the unique characteristics of wind loads. For example, the demand-to-capacity ratio (DCR) for deformation-controlled actions is limited to 1.25 (Method 1) or 1.5 (Method 2 and 3) in the Prestandard (ASCE/SEI 2023) partially due to the long duration of wind loads. As for the envelope system, the state-of-practice methods adopted in the analysis of high-rise buildings are mainly based on structural response (e.g., peak interstory drifts or accelerations). Although some recent studies have embedded the envelope system into the analysis model during the response history analysis (Chen et al. 2023), the envelope component mechanism properties need further investigation (Bedon et al. 2018; Wang et al. 2021).

3.1.5. Design

3.1.5.1. Design of the Main Wind Force Resisting System

PBWD design tasks require the engineer to assess the time-variable load effects established by analysis of structural components such as walls, beams, columns, and foundations. The engineer must further assess the motions (drifts, accelerations, and strains) associated with the analysis findings of the structural and nonstructural components of the structure. Assessment of the capability of structural components to accept the demands revealed by analysis requires understanding the strength, stiffness, and durability of chosen structural and nonstructural components. As of the date of this report, PBWD relies heavily upon the performance capabilities assessed for seismic motions from the Applied Technology Council (ATC) and Federal Emergency Management Agency (FEMA) FEMA P-58 program, *Development of Next Generation Performance-Based Seismic Design Procedures for New and Existing Buildings,* and the many component tests underpinning the PEER Tall Buildings Initiative publications. Additional PBWD component tests have been conducted by Wallace (2023), Abdullah et al. (2020a,b; 2021), and Motter (2019), with further testing currently underway. The findings and recommendations from these initial PBWD-specific studies have just begun making their way into research literature and practicing engineering as of early 2023.

At the time of this report, one tower in Austin, Texas, has been designed using the Prestandard (ASCE/SEI 2023). The tower design is based on Prestandard Method 1 and is expected to be completed in late 2024.

The authors of this report are not aware of specific projects that have yet utilized the component and cladding/building envelope procedures of the Prestandard.

3.1.5.2. Design of Envelope Systems

To date, PBWD for envelope systems has concentrated on reducing envelope damage and losses observed during extreme wind events. This concentration was motivated by damage assessments following Hurricanes Andrew and Hugo (Smith 2022) that revealed unacceptable losses caused by breaches or removal of envelope components by wind suction, tear-off, or debris impact. The result of these breaches is direct damage to the structure envelope and interior and rainwater penetrating the structure and causing further internal water and mold damage.

In terms of the current state of the art in envelope construction techniques, the following constitute the distilled best practices according to the experience of the workshop members:

- System design: per Chapter 8 of the Prestandard (ASCE/SEI 2023);
- Good workmanship during installation and a suitable amount of inspection during application, coupled with applicable field testing;
- Adequate maintenance after installation; and
- Replacement of the system prior to the end of its effective service life.

3.2. Long-Term Vision for Performance-Based Wind Design

3.2.1. Wind Climate Characteristics

The long-term vision for optimal use of PBWD approaches requires accurate matching of wind effects to the performance goals. This may mean that different wind climate models are used for different goals for the same building, while different wind characteristics and models may be required for different buildings on the same site. The end goal is a framework to assess the effects of different wind types and to model these appropriately through the design process using readily available techniques.

3.2.2. System Reliability

The long-term vision for PBWD and reliability foresees the integrated assessment of the MWFRS and the envelope system through computational frameworks based on the coupled and progressive probabilistic assessment of the cladding and structural system (holistic performance assessment). This will include the development of computational models for the rapid characterization of the nonlinear response of the MWFRS and the estimation of the cladding performance through the development of wind-specific fragility functions. Methods based on surrogate modeling, artificial intelligence (e.g., machine learning), and uncertainty propagation through stochastic simulation are predicted to be central to the computational approaches that will enable rapid and integrated (coupled) estimation of the reliability of the MWFRS and the envelope system. The performance of the envelope system will be addressed through holistic (multi-demand) fragility functions developed for a full range of nonstructural components. Wind demands will consider the explicit estimation of wind-borne debris risk through analytical models and approaches based on computational fluid dynamics. Reliability will be estimated for a full range of probabilistic performance matrices that go beyond the traditional definition of reliability and will enable a full characterization of the resilience of the system, a concept that holistically encompasses the design, reliability/risk assessment, and repair/recovery of the system. Within the computational environments developed for estimating the probabilistic performance matrices, simulation of fully nonstationary and non-straight-line wind events will become commonplace, as will the incorporation of nonstationary wind risk in models of climate change.

3.2.3. Wind-Structure Interaction

The long-term vision for PBWD revolves around an exhaustive understanding of the intricate feedback systems between tall building response and windstorm excitation and the reactive response of low- and medium-rise buildings to wind loads. To achieve this goal, our current understanding of structural uncertainties, wind demand characterization, load application to structural models, and the impact that aeroelastic effects have on structural demands must advance. To attain this understanding, systematic testing is necessary to dissect the complexities of structural and material properties, in conjunction with a universally adopted set of design assumptions, whether they are parametric or based on specific scenarios. Workshop participants envision the enhancement of wind tunnel testing methodologies that can capture the subtle variations in the flow behavior surrounding intricate structural forms and characterize wind load demand under many scenarios. The development of both simplified and comprehensive modeling techniques will be instrumental in transcribing this wind demand onto the structural models and in comprehending the impact of aeroelastic effects on the responses of tall buildings and special structures to wind loads.

A holistic approach to PBWD is also required to address the needs of communities that live in vulnerable, nonengineered low- and medium-rise buildings. These are often situated on the outskirts of cities, where the most devastating losses—in terms of both financial and community impact—typically occur. This will be augmented by thorough documentation of the performance of various existing building archetypes following severe windstorms, facilitating improvements in design and policy. Policies encompassing inspection and approval will be implemented, with an aim to mitigate the economic impact of such events, particularly in wind-vulnerable communities. Ultimately, this long-term vision seeks not only to enhance scientific and engineering knowledge, but also to safeguard communities and promote their resilience in this era of increasing climate uncertainty.

3.2.4. Structural Analysis Techniques

In the long-term vision of structural modeling and analysis techniques in PBWD, an ideal goal is to develop more accurate component nonlinear models and more efficient nonlinear analysis methods under wind loads (for both structural and envelope systems) to facilitate the implementation of analysis tools that enable practicing engineers to incorporate PBWD routinely. To accurately model the component nonlinear behavior under wind loads, the wind-specific datasets of the component behaviors are expected to be established, either through component tests under well-designed wind loading protocols (for various types of windstorms) or through extrapolation of the available datasets in seismic engineering with the help of high-fidelity finite element models. To realize efficient wind nonlinear response history analysis, the development of fast integration algorithms and the implementation of surrogate models and artificial intelligence techniques show great potential. The development of efficient and accurate tools for structural modeling and analysis will improve reliability, reduce the time costs, and facilitate PBWD implementation.

3.2.5. Design

3.2.5.1. Main Wind Force Resisting System

The long-term design objective of PBWD is to allow the designer/engineer to use scientifically valid methods to predict the most likely response of structures and building envelopes to the demands caused by common and extreme wind demands.

Higher-quality engineering predictions provided by more complete building component performance models, building damage prediction models, and models considering indirect impacts to building users enable the designer to make value-based design decisions considering expected loss and expected repair given defined performance requirements such as movement, acceleration, safety reserve, and financial loss targets.

Through these higher-fidelity engineering methods, the design team can allocate structural materials (e.g., rebar, concrete, steel, etc.) to maintain or exceed safety targets while minimizing initial financial, environmental, and time costs.

3.2.5.2. Building Envelope Systems

The long-term vision for PBWD of envelope systems matches the basic vision for the building MWFRS. Specifically, designers wish to reduce losses and hindrances to society as measured through financial, environmental, and quality-of-life metrics.

As of early 2023, the structural engineering community is concerned that the level of damage protection offered by envelope systems is not achieving the expected performance implied by ASCE/SEI 7 (ASCE 2022) target reliabilities. Consequently, too many buildings and facilities are taken offline, damaged, and in some cases destroyed because of the envelope system permitting wind-borne debris damage in wind events less severe than those prescribed by ASCE/SEI 7. These observations form the basis for the need for long-term building envelope system improvement.

The following topics were identified to support the long-term vision:

- Formal evaluation through testing of envelope systems to quantify performance with respect to wind effects and water infiltration,
- Reassessment of envelope testing methods to ensure the testing methods adequately predict in-place performance,
- Generation of additional performance test metrics to assess failure modes not currently tested,

- Enhancement of current testing methods deemed to fall short of desired envelope performance outcomes,
- Formal requirement for envelope system installation and in situ testing, and
- Development of methods to assess the efficacy of envelope components years to decades after installation.

4. Challenges in the Use of Performance-Based Wind Design

4.1. Wind Climate Characteristics

The key challenges in terms of wind climate characteristics are primarily associated with the differing levels of knowledge of the structures and characteristics of different windstorm types.

While ASCE/SEI 7 (ASCE 2022) gives single nondirectional wind and tornado speeds, PBWD needs separate directionality and speed characteristics for different storm types, including tropical and extratropical storms, thunderstorms, and tornadoes. These characteristics include spatial and temporal characteristics and recurrence probabilities. At present, PBWD has been based on the assumption of stationary windstorm characteristics like those of a classical synoptic storm with a turbulent boundary layer generated by surface roughness effects.

Knowledge associated with each windstorm type can be summarized as follows:

- ***Tropical storms (hurricanes):*** Good data combined with Monte Carlo modeling exist to define these reasonably well, but design does not currently account for the effects of air density variations during these events. More data are needed from dropsondes to refine the radius of maximum winds and atmospheric pressure wind relationships, and the hurricane boundary-layer characteristics.
- ***Extratropical storms:*** Data sets are generally good with availability (in the United States) of daily summaries and more detailed hourly data.
- ***Thunderstorms:*** Knowledge of the lateral extent, vertical profiles, and durations of different thunderstorm types is very limited. While most research has concentrated on downbursts, recent damage from derechos (gust front thunderstorms) has highlighted that characteristics of extreme events may be different. The vertical profiles of derechos may resemble a classical boundary layer, but no field data are available to confirm this.
- ***Tornadoes:*** Knowledge of tornado wind structure and the significance of multi-vortex tornadoes is very limited.

Another challenge that has been inadequately addressed in the past is the transfer of wind speeds and directionality from the locations at which they have been measured to sites of interest. The Deaves and Harris model (Deaves and Harris 1978), as adopted by ESDU and incorporated into ASCE/SEI 7 (ASCE 2022), is generally used for all storm types even though it was developed for extratropical storms. Its applicability to other storm types has not been fully investigated.

In addition to the characteristics of different windstorm types, and with respect to influences on design, the ways the intensities, frequencies of occurrence, or attributes of windstorm types might alter as a result of climate change will also be important to understand in coming years.

While moderate knowledge exists about this for extratropical storms and hurricanes, the effects of climate change on thunderstorms and tornadoes are much less certain.

4.2. System Reliability

Current challenges of many frameworks developed for the implementation of PBWD include the comprehensive inclusion of damage to the envelope system due to the direct action of local net wind pressure and wind-borne debris and the inelastic (or nonlinear) modeling of the MWFRS within the setting of general uncertainty. Nonetheless, notable advances have been made.

4.2.1. Envelope

With respect to envelope systems, extensions of the Florida Public Hurricane Loss Model to mid-rise residential buildings (e.g., Pita et al. 2016) have enabled various demands to be considered. Nevertheless, the intent of the Florida Public Hurricane Loss Model is the performance assessment of portfolios of buildings. The detail with which each building is modeled is not, therefore, at the level of PBWD, where the focus is on the performance assessment of individual buildings.

Explicitly focusing on individual buildings, Ouyang and Spence (2019) introduced fragility-based progressive damage models in which each component of the envelope system was modeled as susceptible to multiple coupled damage states characterized through suites of fragility functions. These models considered various wind demands, including local dynamic net pressure, interstory drifts, and wind-driven rain modeled through Eulerian multiphase models. To efficiently propagate uncertainty, the approach was embedded with stratified sampling schemes (Arunachalam and Spence 2023) and through the use of consequence analysis, the possibility of characterizing system-level performance of the envelope through decision variables such as repair costs and ingressed water was demonstrated (Ouyang and Spence 2020).

This approach has recently been extended to illustrate how nonlinearity in the MWFRS can also be considered (Ouyang and Spence 2021a), as can more complex representations of the wind hazard, i.e., the nonstationary/non-straight-line/Gaussian stochastic wind pressures (Ouyang and Spence 2021b).

4.2.2. Structural System

One challenge of including nonlinearity in the MWFRS can be traced back to the long duration (on the order of hours) of typical wind load histories, which creates a computational barrier to evaluation of probabilistic metrics, including reliability indices, related to the nonlinear performance of the system. Another challenge concerns the complexities of modeling the nonlinear response of the MWFRS in the presence, for certain wind directions, of a substantial mean wind load component, which can create theoretical challenges in applying state-of-the-art nonlinear modeling approaches developed for seismic loads without a mean load component.

These issues can also complicate the exploration of energy dissipation through nonlinear material behavior since potential difficulties can arise due to the lack of a complete internal force reversal in the structural elements and the potential susceptibility of the components to low cycle fatigue. Nevertheless, including nonlinear behavior and damage is central to the probabilistic/reliability evaluation of the MWFRS, which aims to characterize the system's performance over a full range of hazard intensities.

Motivated by this, several researchers and practitioners have pioneered approaches that explicitly treat damage through nonlinear modeling. Within the setting of probabilistic PBWD, two approaches have essentially been investigated, with the first focused on the application of the theory of dynamic shakedown (Tabbuso et al. 2016; Chuang and Spence 2017, 2019, 2020, 2022) and the second focused on applying nonlinear modeling approaches based on direct integration (Judd and Charney 2015; Mohammadi et al. 2019; Nikellis et al. 2019; Ghaffary and Moustafa 2021; Ouyang and Spence 2021a; Arunachalam and Spence 2022; Huang and Chen 2022). The fundamental idea underpinning the first approach is to rapidly identify a region in which controlled inelasticity can occur. The computational efficacy of the algorithms developed to evaluate the state of dynamic shakedown enables the evaluation of many probabilistic performance metrics through methods based on robust direct stochastic simulation (Chuang and Spence 2022). The key advantage of the second approach is the modeling flexibility it provides. The major challenge is the huge computational effort that is generally necessary to propagate uncertainty and therefore estimate the system-level damage/loss metrics that are core to probabilistic PBWD.

4.3. Wind-Structure Interaction

A primary goal of PBWD is to design efficient systems that make the best use of all the structural material; therefore, the ideal scenario is that the refinement of structural loading across the full building life cycle should result in a system in which material is introduced in locations where needed and a higher utilization of structural members is targeted, thereby ensuring no material wastage. When pushing structures to this higher utilization, more sophisticated analysis in the design stages is required. Typically, this comes in the form of nonlinear modeling. However, to capture a structure's key responses in nonlinear time history analysis an implicit understanding of each structure's unique sensitivity to wind-structure interaction is needed.

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. With taller buildings, small changes to dynamic characteristics (such as damping level or natural frequency) can lead to significant changes in behavior in the wind. Capturing this inherent uncertainty in structural modeling is challenging due to poor understanding of the magnitude of potential uncertainty, and a lack of component-level testing and system-level performance monitoring.

The analysis models and load application are easier with a more straightforward building layout; however, it is uncertain that the current methodology will hold true with a structure that has complex features or is located in complex surroundings. These complexities could further affect the critical wind profile and loading necessary to capture the peak response of the structure. Layering on top the fact that cities evolve and change over time, an approach that accounts for this natural evolution and change in wind load effects must be considered.

Applying wind loading to a structure requires applying varying load time histories up the height of the structure, which in turn requires mapping of floor-by-floor loading to relevant structural members at floor levels. Once mapped accurately, the length of the analyses required is considerable. For reference, a five-minute seismic event is toward the upper end of what would typically be considered for performance-based seismic design, whereas PBWD can require a suite of analyses to be completed with input time histories of three hours or more. 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 nonlinearity in the system.

Tangential to the application of the load is the development of the wind loading time histories. Inherent to the Prestandard methodology is ensuring the “critical loading scenarios” are used in the analyses. The development of these scenarios and time histories is based on the dynamic properties of the structure. Therefore, this process might become iterative if significant changes are made to the structural design after the wind load time histories are developed, or if system nonlinearity alters the directional response sensitivity of the structure.

The exact point at which the peak demand occurs within the time histories can also have a significant effect on the predicted performance of the structure. A nonlinear response at the beginning of the time history forces the structure to cope with this behavior for a longer response time and may lead to fatigue issues or ratcheting that could be uncaptured if the peak demand occurs later in the applied time history.

The current Prestandard methodology focuses mostly on the design of tall buildings where the over (or in some cases under) design of structures may happen under the existing prescriptive procedures. A similar focus on structures where the most damage occurs, and failures arise during significant windstorms, is needed. These structures are often low-rise structures, potentially nonengineered or engineered but with no post-construction inspection, or existing structures that were designed using outdated codes of practice. Simplified design procedures that incorporate the PBWD philosophy is needed to better capture the reactive behavior of these structures to wind loads.

Applying PBWD for tornadoes presents unique challenges. Tornadoes exhibit complex and highly localized wind fields, with rapidly changing intensities and directions. Consequently, accurately modeling tornado-induced loads and capturing their effects on structures requires tools that can account for these complexities.

4.4. Structural Analysis Techniques

Structural nonlinear modeling and analysis under seismic loads have been under development for many decades. The related challenges that this report discusses mainly concern the differences between wind loads and seismic loads, including the long duration of wind loads, the complexity of wind loading, and the importance of the envelope system.

- ***The long duration of wind loads:*** This characteristic makes low cycle fatigue a significant failure mode for structures with nonlinear behaviors. Long wind duration will also lead to different degradation properties. Current structural degradation modeling under wind loads mainly refers to the backbone curve developed for performance-based seismic design. The specific backbone curve for component modeling under wind loads is still unavailable and a better understanding of the component behavior under wind loads is critically required. A large number of component tests under wind loading protocol are needed for establishing a comprehensive structural component database for PBWD.

In addition, the long duration of wind loads will lead to difficulties in developing nonlinear response history analysis. The currently utilized nonlinear response history analysis algorithms or methods for seismic engineering are time consuming when applied to wind engineering, given that the durations of seismic and wind loads are respectively on the order of minutes and hours. Figure 4-1 presents examples of wind speed time histories that have been applied in nonlinear structural response history analysis. More efficient nonlinear response history analysis methods and collapse analysis methods are needed.

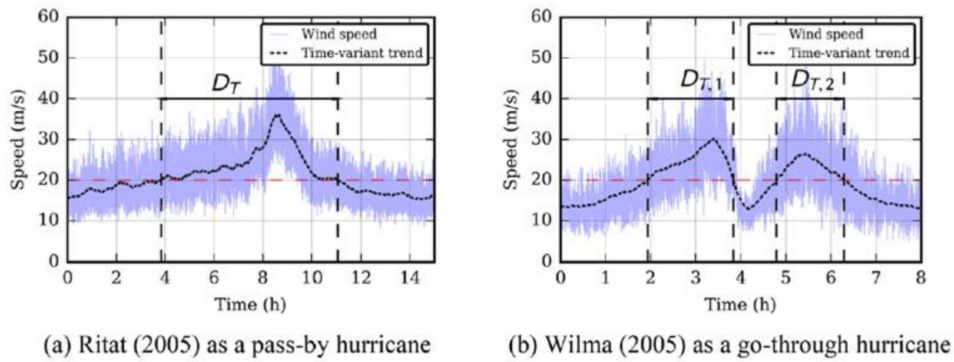

Fig. 4-1. Examples of wind speed time history applied in nonlinear structural response history analysis

Source: Wang and Wu (2022). Reprinted from *Journal of Wind Engineering and Industrial Aerodynamics,* 221, 104908, H. Wang and T. Wu, “Statistical Investigation of Wind Duration Using a Refined Hurricane Track Model,” © 2022, with permission from Elsevier.

- ***The complexity of wind loading:*** The along-wind and across-wind excitation mechanisms and their associated responses differ significantly. While the failure mechanisms initiated by along-wind loading can include along-wind (drift) ratcheting in addition to member-specific failure mechanisms, across-wind loading with a near-zero mean is in a sense closer to the cyclic loading of seismic design. This complexity of wind loads can lead to special behaviors of buildings under investigation. For example, the structural responses may be larger at lower MRI wind speeds due to vortex-induced vibrations.

- ***The importance of the envelope system:*** Damage to the envelope system of buildings under wind loads may result in large economic losses due to wind-driven rain. Therefore, performance analysis of the envelope system becomes more critical in wind engineering than in seismic engineering. Although the external wind loads directly impact the envelope system, the current practice for damage assessment of the envelope system is based on the structural drift of the lateral system. More comprehensive analyses of the envelope system under wind loads that consider the correlations among wind pressure, wind-induced drift, and wind-driven rain are needed. Further research to develop practical methods for assessing the performance of the envelope system under wind loads and to identify design strategies to mitigate wind-induced damage is also needed.

4.5. Design

4.5.1. Main Wind Force Resisting System

As of early 2023, the state of the art in PBWD of building lateral systems is based on a limited set of structural component tests that have investigated the demands caused by multi-cycle wind effects by Wallace (2023), Motter (2019), Abdullah et al. (2020a,b; 2021), and Sharooz (2019). Beyond these specific test series, the remainder of material understanding depends on available traditional monotonic load assessment (i.e., testing for permanent loads such as dead and live), high cycle fatigue assessment (e.g., bridge fatigue), or high ductility assessment (e.g., seismic performance).

However, wind loading into the yielding range of a structure differs from traditional testing assessments in that storm passage is expected to cause a limited number of cycles greater than yield among many cycles of demand below the yield point of the structure. Thus, the tests of monotonic load, high cycle fatigue, and seismic loading likely do not adequately evaluate the low cycle fatigue demands on the primary structural system of a building that are specific to PBWD . Figure 4-2 illustrates an example design space between cycle count and demand level.

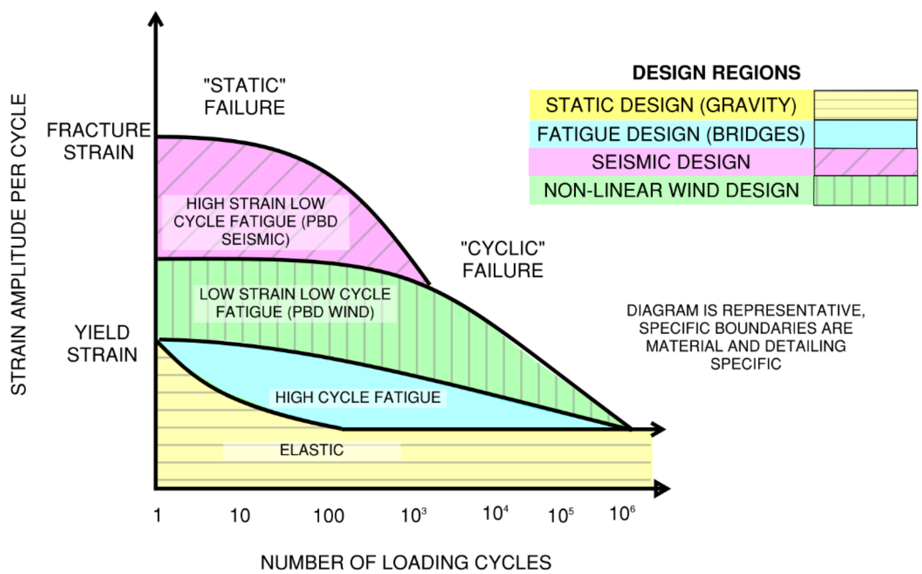

Fig. 4-2. Load Cycle versus Strain Design Space.

4.5.2. Building Envelope Systems

The current state of the art in envelope system design constitutes an assemblage of code, industry group, and best practice documents, including the *International Building Code* (ICC 2021) and the Fenestration and Glazing Industry Alliance (FGIA 2008). Additional resources and standards include various ASTM (ASTM International), Factory Mutual, and Underwriters Laboratories standards for the testing of envelope systems including water and air penetration, load resistance testing, and roofing adhesion and integrity testing.

Project implementation of these standards does not appear consistent throughout practice and certainly varies depending on geographic region, project type, and, to a degree, the design team and developer of a project.

Looking ahead, the challenge for PBWD of envelope systems revolves around many envelope systems that exist among the many types of construction in the United States. The workshop participants recommended that focusing on a select set of performance metrics can meaningfully improve envelope performance and reliability despite the many nuances of envelope design.

5. Recommendations for Research and Development Tools

5.1. Introduction

The participants were divided into smaller breakout groups that coincided with their expertise in one of the five workshop topics. These breakout groups discussed the challenges in their specific topic and what would be required to advance PBWD from the current state of the art to the long-term vision for PBWD. Each group discussed the research needs and then prioritized them in their breakout session (Table 5-1).

Table 5-1. Breakout Session Research Needs, as Identified by Workshop Participants.

No.	Research Needs
	Wind Climate Characteristics
A	Thunderstorm/tornado characterization
B	Performance-based multi-meteorological (wind/hail/rain) design
C	Transferring non-atmospheric boundary layer winds to practice in testing
D	Risk mapping for different building stock types
E	Redo Deaves and Harris model
F	Extratropical simulations/climate modeling
	System Reliability
A	Integrate performance between structural system and cladding and generate structural and nonstructural damage functions that are component-specific
A1	Address special design needs through probability: wind-borne debris, water penetration, progressive failure, and components and cladding testing
B	Improve physics-informed, computationally efficient models for nonlinear analysis of wind response over long-period durations
C	Characterize hazard and load for short and long return periods
D	Define probability-based and life-cycle cost metrics and limit state(s) of interest
D1	Consider damage, repair, and recovery, and account for impeding factors
D2	Differentiate PBWD needs for low-rise vs. high-rise building (MWFRS, components and cladding)
D3	Organize and standardize reliability targets (benchmarking ranges)
	Wind-Structure Interaction
A	Improving the understanding of structural and material properties
B	Challenges with nonlinear time history analysis

C	Performance of existing structures
D	Economic study identifying existing buildings at risk in vulnerable communities
E	Policies around inspections and approvals
F	Promoting wind engineering education and funding curriculum
Structural Analysis Techniques	
A	Development of wind loading protocols for experimental quantification of system performance in wind
B	Lab tests of various components, e.g., slab-to-column connections, walls, steel joints, etc.
C	Guidance for selection of extreme values in nonlinear response history analysis
D	High-fidelity finite element models to calibrate component modeling along with available database
E	Testing beyond yielding to understand the effects of strong nonlinearity in wind-induced response
F	Improved understanding and quantification of inherent damping
G	Leveraging the high efficiency of Method 3 of the Prestandard to study various archetype buildings to facilitate its application in design
H	Static pushover for wind engineering to quickly evaluate nonlinear structural performance
I	Theory-guided, data-driven approaches for efficient nonlinear analysis
J	Gather more full-scale structural response data
K	Improved understanding of the benefits of considering the nonlinear behavior of various foundation types
Design	
A	Re-evaluation of envelope test methods
B	Field diagnostic tests for envelope component integrity
C	Development of wind component–specific fragility curves
E	Further structural MWFRS PBWD testing
F	Further MWFRS reliability studies

Workshop participants then voted on these research needs to prioritize the top 10 research needs for PBWD discussed in Section 6.2.

5.2. Priority of Wind Climate Characteristics Topics

The breakout was composed of the following members:

Moderator:	Roy Denoon
Scribe:	Workamaw Warsido
Reporter:	Peter Vickery
Participants:	John Kilpatrick
	Greg Kopp
	Frank Lombardo
	Marc Levitan

Brian Skourup

Jason Smart

Antonio Zaldivar

The breakout group worked through a range of key topics within the field that contribute to reliability of design and identified strengths and weaknesses in the current state of the art.

5.2.1. Level of Knowledge of Different Storm Types and Climate Characteristics

While reasonable knowledge of the structure and properties of extratropical storms and tropical cyclones (hurricanes) exists, knowledge of tornadoes and thunderstorms is much sparser. In particular, no good engineering models of thunderstorms can as yet be applied to design for taller buildings. One specific area identified is the potential differences between isolated downburst thunderstorms (the subject of most of the limited research to date) and gust front thunderstorms such as those connected to the derecho events that have caused widespread damage in recent years.

While reasonable confidence exists about the influence of climate change on tropical and extratropical storms, confidence for thunderstorms and tornadoes is much lower. These effects also need to be translated to engineering models. The importance of combined wind/rain and wind/hail effects must be emphasized.

5.2.2. Translation of Wind Data to the Information Needed for Design

In terms of the ability to predict extreme windstorms, the Type 1 probability distribution is considered reasonable, but tails can be refined with the application of superstation techniques where possible. However, this does not address the difference between extreme windstorm characteristics and extreme wind effects on buildings and structures. The need to combine hazard and responses is critical considering the structural analysis demands of a reasonable number of wind time histories.

The Deaves and Harris model (Deaves and Harris 1978), as adopted by ESDU and incorporated into ASCE/SEI 7 (ASCE 2022), is generally used for all storm types even though it was developed for extratropical storms. In regions where local surface data are scant, weather research and forecasting models may be used for larger-scale events.

Large full-scale field experiments will be needed to look at both the Deaves and Harris model and thunderstorm characteristics as they might apply to design. This would assist in more clearly defining which storm types will govern which design objective and in developing methods of modeling these in wind tunnels.

Topographic effects are very simplified, have not been revisited in many years and would benefit from refinement with more experimental data to support computational fluid dynamics (CFD) modeling.

5.2.3. Significance of Different Storms Type for Load Effects

Different storm types will influence load effects differently on various buildings. The temporal effects of thunderstorms and tornadoes may limit their ability to generate large resonant responses in tall buildings. To date, vertical profiles of thunderstorms have also been assumed to be less influential on the loading and responses of supertall buildings, but this was based on the information about downburst characteristics and less so on derechos and gust front thunderstorms.

Thunderstorms are likely to govern wind loads for cladding on almost all building types. Again, water penetration following wind damage is likely to be the primary cause of loss. A suggestion was made to use PBWD savings on the primary structural system to improve the building envelope.

Risk mapping of the building stock across the United States could be used to refine the differing PBWD significance in different areas and hence the value of different components (e.g., structural vs. envelope) across the country.

5.2.4. Review of State of the Art for Testing

Boundary-layer wind tunnel testing is the current standard. Facilities capable of accurately modeling the characteristics of nonstationary storms are scarce, and therefore their use in design is limited. The ability to model the effects of different storm types on existing facilities is needed. To do this requires greater understanding of the characteristics that need to be replicated. CFD can be used to further investigate storm structures. There is a lot of work needed to be able to implement this with confidence.

5.2.5. Identified Research Needs

Key issues were grouped together and voted on in terms of their importance for PBWD (Table 5-2).

Table 5-2. Key Research Needs for Wind Climate Characteristics

Priority based on votes	Topic (votes)
A	Thunderstorm/tornado characterization (14)
B	Performance-based multi-meteorological (wind/hail/rain) design (11)
C	Transferring non-atmospheric boundary layer winds to practice in testing (10)
D	Risk mapping for different building stock types (3)
E	Redo Deaves and Harris model (2)
F	Extratropical simulations/climate modeling (2)

5.3. Priority of System Reliability Topics

The breakout was composed of the following members:

Moderator:	Seymour M.J. Spence
Scribe:	Srinivasan Arunachalam
Reporter:	Luca Caracoglia
Participants:	Michele Barbato
	Xinzhong Chen
	Do-Eun Choe
	Greg Deierlein
	Jeff Dragovich
	Terri McAllister
	Chris Raebel
	John Wallace

The main topics discussed were associated with the state of the art, the long-term vision, and research needs for estimating the reliability of the MWFRS (structural system) and the components and cladding (C&C) (envelope system). The discussion revolved around the computational modeling required to enable the reliability estimation of both the structural and the envelope systems, the need for holistic computational modeling (involving both the structural and the envelope systems) in estimating the reliability of building systems, the need to develop target reliabilities for various archetype systems, the need for wind-specific fragility functions to characterize the wind-damage susceptibility of typical structural and nonstructural components composing the building system, and the need for better modeling of the nonstationary characteristics of wind loads at aerodynamic and climatological levels.

5.3.1. A. Integrate Performance between Structural System and Cladding and Generate Structural and Nonstructural Damage Functions that Are Component-Specific

Estimating the reliability, or more generally the probability of failure, of the structural system is central to implementing PBWD for maximum benefit. The Prestandard (ASCE/SEI 2023) reflects this, suggesting three analysis methods for PBWD implementation. The methods, termed Methods 1, 2, and 3, range from simplified approaches that rely on several prescriptions (Method 1) to approaches based on the direct estimation of the reliability of the structural system (Method 3).

While Method 3–type analysis will afford the greatest design freedom—and therefore the innovations in design that can lead to advances in sustainable design, economic savings, and predictable performance in extreme events—several challenges to its implementation were identified, including the need for integrated probabilistic performance assessment frameworks that holistically treat the structural and envelope system through two-way coupled (“feedback” system) modeling based on component-specific structural and nonstructural fragility functions.

In addition, the need to understand the reliability of buildings designed to current codes and standards is a fundamental step in advancing codes and standards on PBWD. Such assessments should treat the systems as a whole and therefore consider the reliability of both the structural and the envelope systems at the component and system levels. Ideally, such assessments should be carried out over suites of archetype buildings that accurately represent the current state of practice.

5.3.2. A1. Address Special Design Needs through Probability: Wind-Borne Debris, Water Penetration, Progressive Failure, and Components and Cladding Testing

The envelope system is central to the performance of a building subject to extreme winds. However, this system is scrutinized less than the structural system. Moving to a PBWD paradigm necessitates the holistic treatment of the structural and the envelope systems, which constitutes a two-way coupled system (feedback system) that experiences progressive damage during extreme winds.

Fundamental to such a paradigm is the need for wind-specific component fragility functions for a wide array of typical envelope components. These fragility functions should take a form similar to those developed in performance-based seismic design and the FEMA P-58 procedure (FEMA 2016) but be specific to wind and therefore capture aspects such as the progressive and coupled nature of envelope damage in moderate to extreme winds. The development of such fragility functions will require a combination of experimental and computational methods and should result in databases of fragility functions that can be used in probabilistic performance assessment frameworks. Questions that require addressing in developing the fragility functions include identifying appropriate damage states and considering a full range of wind demands, e.g., wind-borne debris, local net pressure, and dynamic story drift.

The need for greater transparency and information on existing fragilities used to characterize the damage susceptibility of envelope systems was also recognized. Fundamental questions discussed included how to accommodate for established limit states the long-duration and progressive nature of wind damage mechanisms, for example, for a given amount of drift and how much capacity does an envelope component lose by withstanding dynamic net pressure. The need for local building officials to require the results of envelope tests, thereby gradually collecting data on the current performance of envelope systems, was seen as a step that would help demystify the performance assessment of envelope systems.

5.3.3. B. Improve Physics-Informed, Computationally Efficient Models for Nonlinear Analysis of Wind Response over Long-Period Durations

Estimating probabilistic metrics, such as reliability, probability of failure, or future metrics based on the decision-making process, generally requires the direct propagation of uncertainty by stochastic simulation. Even for the most efficient stochastic simulation schemes, this requires repeated evaluation of the system, necessitating rapid nonlinear time history analysis, especially considering the typical long duration of extreme windstorms (several hours). Directions discussed by the breakout group included approaches based on machine learning (ML), massive parallelization using graphics-processing units (GPUs), supercomputing, reduced order modeling, and surrogate/metamodeling approaches.

5.3.4. C. Characterize Hazard and Load for Short and Long Return Periods

Currently, performance assessments are carried out under the assumption of a stationary (invariant) wind climate. To better leverage the capacity of structural systems to resist extreme wind events through PBWD, and therefore controlled inelastic design, accounting for the potential increase in severity of future wind events over the design life span is essential. Consequently, accounting for climate change is necessary in assessing the reliability of structural systems over the time horizons inherent to the current codes and standards, e.g., 50 to 100 years.

In addition, a need exists for stochastic models capable of rapidly generating realizations of fully nonstationary and non-straight wind load records to be used in nonlinear time history analysis. While methods based on modeling the joint probability between wind speed directions, or the use of sector-by-sector approaches, can be adequate, it is generally recognized that modeling the actual time-varying wind speed and direction would increase the fidelity of the probabilistic metrics estimated from a reliability/probabilistic analysis. The possibility of harnessing CFD is a long-term goal, while the use of wind tunnel data to calibrate future models is a short-term goal.

5.3.5. D. Define Probability-Based and Life-Cycle Cost Metrics and Limit State(s) of Interest

The Prestandard (ASCE/SEI 2023) identifies three methods of analysis for carrying out PBWD. However, these analysis methods do not map to the nonstructural system, in particular the envelope system, even though the envelope system is recognized as key to the performance of the buildings. This results in the need for performance objectives that better integrate the desired performance of the envelope and the structural systems by defining new wind-specific probabilistic limit states that are related to metrics that enhance the sustainability of the building system (e.g., life-cycle analysis).

5.3.6. D1. Consider Damage, Repair, and Recovery, and Account for Impeding Factors

As PBWD moves into the future, the use of probabilistic performance metrics to characterize the performance of building systems that go beyond traditional reliability is essential. Consequently, a need exists for probabilistic performance-based design frameworks that foresee the integrated and coupled damage and loss assessment of the envelope and the structural systems through metrics that are related to the decision-making process, e.g., repair costs and downtime (including impeding factors).

5.3.7. D2. Differentiate PBWD Needs for Low-Rise vs. High-Rise Buildings (MWFRS, Components and Cladding)

To date, PBWD has focused primarily on highly engineered high-rise structures. Nevertheless, the possibility of applying it to low-rise buildings could significantly reduce the massive damages and losses that occur to low-rise residential buildings during extreme windstorms. While many concepts and methodologies translate from highly engineered high-rise systems to low-rise buildings, for the application of PBWD to low-rise buildings to succeed, differentiating the needs of low-rise building from the needs of highly engineered (high-rise) buildings is necessary. This differentiation should occur for both the structural and the envelope systems.

5.3.8. D3. Organize and Standardize Reliability Target (Benchmarking Ranges)

The full acceptance of PBWD requires an understanding of the performance of building systems built to current codes and standards in terms of the probabilistic metrics that will characterize PBWD in the future. In the breakout discussion, participants felt that there is less of a need for target reliabilities than there is a need for system metrics that enable decision-making based on benchmarking of the metrics for buildings that satisfy current codes and standards.

In addition, the development of rating systems that promote the enhanced performance of buildings designed following PBWD procedures was identified as a means to encourage the adoption of PBWD in practice. For example, the Leadership in Energy and Environmental Design rating system has become very successful in promoting greater sustainability. A similar system could be developed to promote greater resiliency in design. Such a system would be related to the probabilistic PBWD metrics associated with a holistic characterization of the building performance, e.g., repair cost, recovery time, and life-cycle costs.

5.4. Priority of Wind-Structure Interaction Topics

The breakout was composed of the following members:

Moderator:	Melissa Burton
Scribe:	Wenbo Duan
Reporter:	Jason Garber
Participants:	Ramon Gilsanz
	Larry Griffis
	Wendy Reyes
	Ahmad Rahimian
	Dan Rhee

The workshop participants brainstormed many ideas for research that is needed to address the challenges identified during the workshop discussion. In analyzing the information gathered during the breakout session, participants developed research ideas on sticky notes that were then mapped to a list of generalized research needs. The workshop participants then voted on these research needs. The following subsections discuss the top five research needs. A final suggestion identifying the importance of education in overarching performance-based design was also highlighted.

5.4.1. A. Improving the Understanding of Structural and Material Properties

A more comprehensive understanding of structural and material properties is crucial for the successful implementation of PBWD. To elucidate the impact of wind-structure interaction and accurately model the behavior of structures under wind loading, several research directions can be explored. First, a need exists to understand and quantify inherent damping properties across existing building stock, ideally from tall buildings through to supertall buildings. Second, understanding and quantifying structural parameters like stiffness and the impact that cracking has on changing stiffness of various structural systems will provide confidence and inform modeling assumptions. Building a consensus regarding analysis model assumptions is essential for consistent practice. Research on nonlinear analysis of concrete buildings and the behavior of structural members in different building systems will provide insights into their responses to wind loads. The impact of these parameters can significantly influence the wind-structure interaction. Addressing challenges due to uncertainties in structural properties, lack of component testing, and system-level performance monitoring is essential.

5.4.2. B. Challenges with Nonlinear Time History Analysis

Applying time history wind loading to highly dynamic structures is a complex process that requires careful consideration of structural models for accurate load distribution and intended interaction response. Standardizing wind tunnel testing techniques and characterizing wind load response time series formats can ensure consistency and accuracy in application of wind loads to structural models. Assessing the impact of changes in the structure's surroundings on wind loads, including documenting assumptions in surrounding models, is important. Analyzing structures with complex features or surroundings may necessitate investigating wind design restrictions on seismic design and exploring methods for integrating both approaches. The development of critical loading scenarios and time histories, based on a structure's dynamic properties, may become iterative, especially if significant design changes occur. With nonlinear time history analyses for PBWD requiring significant computational power and storage space the desire to limit the conditions considered is natural but given some of the uncertainties listed previously doing that poses a risk. Ultimately, developing an understanding about some of these concerns will help refine the requirements for an adequate time history suite for PBWD applications.

5.4.3. C. Performance of Existing Structures

Comparative studies of buildings constructed over previous decades, such as the 1960s, 1980s, and 2000s, which were designed using varying codes and standards, can provide valuable insights into the overall performance and effectiveness of code changes in improving wind resistance. Funding research for wind event monitoring, improved documentation of damage and building details, and continued support for initiatives like Structural Extreme Events Reconnaissance (STEER) can help drive advancements in wind engineering and promote the development of resilient communities. This research need is linked to research needs 1 and 6 described in Section 6.

5.4.4. D. Economic Study Identifying Existing Buildings at Risk in Vulnerable Communities

Conducting comprehensive studies that demonstrate the wide-ranging benefits of PBWD, including economic, sustainability, comfort, safety, recoverability, and equity aspects, can help build a strong case for its implementation and prioritize retrofitting and adaptation efforts for high-risk structures in vulnerable communities. Identifying potential improvements for existing building stock, in building performance and long-term resilience, and providing a funding mechanism to embrace these enhancements could be persuasive for building owner participation. Such incentives could potentially involve tax breaks or subsidies, or rebate programs to support the funding of performance or resilience improvement. This exercise could extend beyond engineered structures and into communities requiring the biggest resilience-based engineering retrofits.

Proposing feasible adaptation measures; considering structural, economic, social, and equity factors; and investigating opportunities to convert building usage to more resilient or lower-risk functions can enhance community resilience while preserving the value of existing buildings. Exploring resilience opportunities during re-cladding processes and assessing the potential benefits of incorporating wind-resistant features can lead to improved building performance. Funding research for wind event monitoring, improved documentation of damage and building details, and continued support for initiatives like STEER can help drive advancements in wind engineering and promote the development of resilient communities.

5.4.5. E. Policies around Inspections and Approvals

Developing effective policies for inspections and approvals is crucial for ensuring the successful implementation of PBWD in practice. The following research ideas were discussed during the workshop to address these needs:

- Developing special inspection requirements and standardized cladding and building envelope detailing can help ensure structural integrity and safety during wind events.
- Engaging with policymakers and local jurisdictions, promoting the benefits of PBWD, and providing educational resources can facilitate its incorporation into local codes and regulations.
- Collecting and analyzing data on construction methods used across different regions can help identify best practices and areas for improvement, informing the development of region-specific guidelines and recommendations for building construction and inspection while considering the unique characteristics of various building materials and designs.

5.4.6. F. Promoting Wind Engineering Education and Funding Curriculum

The workshop emphasized the importance of increasing awareness and knowledge about wind engineering among professionals such as engineers, architects, contractors, building officials, and inspectors. Creating a series of educational webinars tailored to different professionals in the building industry can help disseminate knowledge about wind engineering principles and practices, covering topics ranging from basic concepts to advanced design methodologies.

To encourage attendance and engagement in these webinars, offering incentives for participation is essential, which could include continuing education credits, professional development hours, or even financial rewards for attending the webinars and implementing the learned concepts in participants' work. Collaborating with professional organizations and industry associations can further increase the reach of these educational efforts, as leveraging the networks and resources of these organizations enables the wind engineering community to effectively promote the adoption of advanced wind design practices and foster a culture of continuous learning among industry professionals.

5.5. Priority of Structural Analysis Technique Topics

The breakout was composed of the following members:

Moderator:	Teng Wu
Scribe:	Baichuan Deng
Reporter:	Ricardo Medina
Participants:	Kevin Aswegan
	Scott Erickson
	Jennifer Goupil
	Hitomitsu Kikitsu
	Marcos Martinez
	Viral Patel
	Juan Paulino
	Donghun Yeo

The breakout session participants first reviewed and formed a consensus on the current state of the art in structural modeling and analysis techniques. As the Prestandard (ASCE/SEI 2023) states, the literature has little information on performing nonlinear analysis of structures subjected to wind loads. Hence, the current structural analysis techniques are essentially based on information related to performing nonlinear analysis under seismic loading. However, the breakout session participants agreed that these techniques need to be revisited due to the significant differences between wind and seismic loads. Then, the research needs and priorities discussed centered on two aspects, namely structural modeling and structural analysis. Finally, the breakout group proposed the following 11 research needs and priorities.

5.5.1. A. Development of Wind Loading Protocols for Experimental Quantification of System Performance in Wind

To develop the component backbone curve and refine the DCR limitations for deformation-controlled components, it is important to establish a comprehensive procedure to evaluate current loading protocols for extreme wind performance cyclic testing of MWFRS members and, if needed, adjust the currently used loading protocols. Several key features need to be identified, such as the number, amplitude, and sequence of cycles.

5.5.2. B. Lab Testing of Various Components, e.g., Slab-to-Column Connections, Walls, Steel Joints, etc.

Similar to the component model development process in seismic engineering, lab tests of various components under rational wind loading protocols are required to develop the backbone curve of various components, e.g., columns, beams, slab-to-column connections, shear walls, and steel joints.

5.5.3. C. Guidance for Selection of Extreme Values in Nonlinear Response History Analysis

Proper treatment of extreme values in wind loading time history records is very important. In the wind tunnel test, peaks always occur due to the random nature of wind pressure. These peaks will directly lead the force-controlled element to exceed acceptance criteria while this phenomenon will rarely lead to component failure. The selection and post-processing methods for wind loading records require further study.

5.5.4. D. High-Fidelity Finite Element Models to Calibrate Component Modeling along with Available Database

The large-scale component lab test is time consuming and requires a large amount of financial support. High-fidelity finite element models provide an alternative way to estimate and calibrate parameters to construct numerical models of structural components under wind loading protocols. Current practice is based on the available database developed under seismic loading protocols.

5.5.5. E. Testing beyond Yielding to Understand the Effects of Strong Nonlinearity in Wind-Induced Response

Currently, the allowed nonlinear behaviors during wind design are very limited (DCR<1.5) in the Prestandard (ASCE/SEI 2023). To better understand the components’ behavior in wind-induced response, the strong nonlinear behaviors can also be included in lab tests.

5.5.6. F. Improved Understanding and Quantification of Inherent Damping

The understanding of inherent damping is significant in estimating wind-induced structural performance because it contributes to significant energy dissipation due to limited nonlinearity/ductility in the response.

5.5.7. G. Leveraging the High Efficiency of Method 3 of the Prestandard to Study Various Archetype Buildings to Facilitate Its Application in Design

The fully coupled uncertainty assessment is challenging for PBWD due to the large computational costs. Rapid methods are proposed such as the dynamic shakedown and reduced-order model, but these methods are mostly validated with limited archetype buildings. It is necessary to validate and extend the applications of these methods.

5.5.8. H. Static Pushover for Wind Engineering to Quickly Evaluate Nonlinear Structural Performance

Static pushover is a classical method suggested in seismic engineering, but current wind engineering practice barely uses it. Introducing static pushover to the nonlinear structural analysis under wind loads provides a way to develop efficient estimation for nonlinear structural behaviors.

5.5.9. I. Theory-Guided, Data-Driven Approaches for Efficient Nonlinear Analysis

With the recent development of artificial neural networks and other ML techniques, a promising way to efficiently get the structure response is based on data-driven models. While the limited physical meaning of the “black-box” surrogate models poses an obstacle to implementing them in the structural performance evaluation, theory-guided, data-driven approaches (e.g., knowledge-enhanced machine learning) provide an alternative way to improve the performance of the surrogate model and make it more reliable for application in engineering practice.

5.5.10. J. Gather More Full-Scale Structural Response Data

Although modern structural wind engineering has been developed for decades, real field measurement data remain limited (e.g., the wind pressure applied to real buildings and the structure responses under wind loads). To validate analysis results of PBWD, more full-scale structural response data and on-site wind pressure measurements are needed.

5.5.11. K. Improved Understanding of the Benefits of Considering the Nonlinear Behavior of Various Foundation Types

Research on the nonlinear behaviors of various foundation types and their effects on wind-excited tall buildings is very limited. It is important to explore the nonlinear behaviors of various foundation types in evaluating controlled inelastic responses of wind-excited tall buildings.

In addition to the aforementioned topics discussed during the breakout session, the modeling and analysis of envelope systems are also considered very important. Therefore, high-fidelity finite element models of the envelope system need to be developed for effective characterization and quantification of the damage it sustains during various windstorms (along with water penetration amount). Some research tools are also needed to better understand the interaction between the main wind force resisting system and the envelope system.

5.6. Priority of Design Topics

The breakout was composed of the following members:

Moderator:	Russell Larsen
Scribe:	Juliana Rochester
Reporter:	Juliana Rochester
Participants:	David Bott
	Mehedy Mashnad
	Angela Mejorin
	Long Phan
	Don Scott
	Pataya Scott
	Tom Smith

The breakout session participants identified five overarching areas of design-related research needs. The following discusses each area. The order in which they are presented reflects the breakout participants' view of relative importance to the advancement of building performance, from critically important to important.

5.6.1. A. Re-Evaluation of Envelope Test Methods

Entry of water into the interior of a building as a result of wind-driven rain or breaches of the building envelope (by wind-borne debris impact or wind pressure) greatly magnifies the degree of loss brought about by severe weather. Current envelope testing methods do not apply wind pressures as large as those required for structural design. These tests, including water plus wind testing, wind-borne debris impact testing, and the loading regimen of each should be reassessed for their effectiveness in managing loss.

5.6.2. B. Field Diagnostic Tests for Envelope Component Integrity

The ability of an envelope system to successfully resist the demands of severe weather depends in large part on quality installation and compatible details. Assessment of installation quality relies on mock-up tests or in-field nondestructive tests. Not all envelope components have standardized nondestructive tests, and mock-ups, while best practice, are not required. Additional nondestructive tests, industry group guidance for mock-up testing, and assessment of newer construction performance in high winds would provide evidence of when envelope systems are installed well and what envelope systems perform well.

5.6.3. C. Development of Wind Component–Specific Fragility Curves

The FEMA P-58 initiative (FEMA 2016) generated fragility curves for building components responding to seismic demands. Similar curves need to be generated for wind demands. Many of the seismic fragility findings can be recalibrated or extended to wind response. Wind-specific damage states considering, for example, wind pressure damage and debris impact need to be developed.

5.6.4. D. Further Structural MWFRS PBWD Testing

As of early 2023, no traditional structural steel assemblies have been evaluated for the expected low cycle fatigue cyclic loading in PBWD. Seismically detailed assemblies may be assessed using strain-based methods such as Coffin-Manson relationships (Coffin 1954; Manson 1953). While testing has been carried out on non-seismically detailed structural concrete assemblies, no similar non-seismically detailed structural steel assemblies have been tested. These structural steel assemblies include non-seismically detailed (R=3) braced frame connections and non-seismically detailed (R=3) moment frame connections.

5.6.5. E. Further MWFRS Reliability Studies

Formal adoption of PBWD in the ASCE/SEI 7 standard (ASCE 2022) requires assessment of PBWD protocols relative to the safety (reliability) targets expressed in Chapter 1 of ASCE/SEI 7 (ASCE 2022). The present Chapter 1 reliability targets are based on component response in lieu of global system reliability. PBWD requires consideration of the overall margin of safety achieved by a structural system, and hence research and review are required to determine appropriate building global reliability targets that agree with the present levels of safety achieved by ASCE/SEI 7.

6. Prioritization and Benefits of Recommended Research Topics

6.1. Prioritization of Research Topics by Workshop Participants

Following the breakout sessions, the workshop participants reconvened into a single group and reviewed the recommended research needs from each breakout session. Table 5-1 summarizes the breakout session research needs. After the breakout session reporters presented and described their sessions' research needs, the full group of participants voted to prioritize the research recommendations from all breakout sessions.

6.2. Overview of Recommended Research Topics, Activity Costs, and Time Requirements

Based on participant votes and the combination of similar research needs by the Workshop Steering Committee, the research priorities were selected and the most urgent needs identified (Table 6-1). The table shows the order of priority, the Priority Research Need, and its estimated cost and time. Section 6.3, Summaries of Research Priority Needs, describes the needs in greater detail. These summaries include a description, estimated cost, estimated time, measurement science challenges and potential solutions, stakeholders and roles, and impacts on standardization and application in practice. Sections 6.4 and 6.5 describe the comprehensive schedule, costs, and benefits.

The Workshop Steering Committee provided the cost estimates, based upon its members' knowledge of costs of similar research efforts. Estimated costs for each research topic are provided using one of the following ranges: less than $1,000,000 (low cost); $1,000,000–$3,000,000 (moderate cost); and more than $3,000,000 (high cost).

Similarly, the Workshop Steering Committee estimated the time requirements to properly address each research topic, based on member experience with comparable research efforts. Estimates are provided using the following time period ranges: 1–2 years (short time period), 2–5 years (moderate time period), and 5–10 years (long time period).

Table 6-1. Priority Research Needs, as Voted on by the Workshop Participants and then Grouped by the Workshop Steering Committee.

Rank	Priority Research Needs	Estimated Cost	Estimated Time
1	Development of Main Wind Force Resisting System Reliability	Moderate cost	Short and moderate time periods
2	Enhancement of components and cladding reliability through re-evaluation of testing	High cost	Long time period
3	Integrate performance between structural system and cladding	High cost	Moderate time period
4	Characterization of engineering properties of thunderstorm and tornado wind events	High cost	Moderate to long time period
5	Characterize hazard and loads for short and long return periods	Moderate cost	Moderate time period
6	Improve understanding of structural and material properties	Moderate cost	Long time period
7	Improve physics-informed, computationally efficient methods for nonlinear analysis of wind response over long-period durations	High cost	Long time period
8	Static pushover for wind engineering to quickly evaluate nonlinear structural performance	Low cost	Moderate time period
9	Development of wind loading protocol for experimental quantification of system performance in wind	Low cost	Moderate time period
10	Economic study to identify existing buildings at risk	High cost	Long time period

As noted previously, some of the research needs identified in the individual breakout sessions were similar in scope, and thus the Workshop Steering Committee combined similar research needs. These research needs were then prioritized based on votes from the workshop participants. The following summarizes how these research needs were combined.

Priority Research Need 1: Development of main wind force resisting system reliability: This research need was identified in the Design breakout session and was brought to the top of the list because one of the main goals of the workshop was to identify needs that would allow PBWD to be standardized in practice. An understanding of the structural reliability of the MWFRS as provided by current code-/standard-conforming designs compared with an understanding of the structural reliability provided by the Prestandard (ASCE/SEI 2023) are essential to progress PBWD procedures to a consensus-based standard.

Priority Research Need 2: Enhancement of components and cladding reliability through re-evaluation of testing: This research need was identified in the Design breakout session as its number 1 and number 2 priorities. The research need was determined from combining the research needs (A) Re-evaluation of envelope test methods and (B) Field diagnostic tests for envelope component integrity.

Priority Research Need 3: Integrate performance between structural system and cladding: This research need was identified in the System Reliability breakout session as (A) Integrate performance between structural system and cladding and generate structural and nonstructural damage functions that are component-specific and combined with (C) Development of wind component–specific fragility curves from the Design breakout session.

Priority Research Need– 4: Characterization of engineering properties of thunderstorm and tornado wind events: This research need was identified as the top priority in the Wind Climate Characteristics breakout session.

Priority Research Need 5: Characterize hazard and loads for short and long return periods: This research need was identified as priority I in the System Reliability breakout session.

Priority Research –Need 6: Improve understanding of structural and material properties: This research need combines priorities (A) Improving the understanding of structural and material properties from the Wind-Structure Interaction breakout session and (F) Improved understanding and quantification of inherent damping from the Structural Analysis breakout session.

Priority Research –Need 7: Improve physics-informed, computationally efficient methods for nonlinear analysis of wind response over long-period durations: This research need aims to reduce the computational time required for nonlinear analysis for wind response of structures and combines the priorities identified in the System Reliability breakout session, (B) Improve physics-informed, computationally efficient models for nonlinear analysis of wind response over long-period durations, and the Structural Analysis breakout session, (I) Theory-guided, data-driven approaches for efficient nonlinear analysis.

Priority Research Need 8: Static pushover for wind engineering to quickly evaluate nonlinear structural performance: This research need was identified as (H) in the Structural Analysis breakout session.

Priority Research –Need 9: Development of wind loading protocol for experimental quantification of system performance in wind: This research need was identified as priority (A) in the Structural Analysis breakout session.

Priority Research Need 10: Economic study to identify existing buildings at risk: This research need combines the priorities identified in the Wind-Structure Interaction breakout session, (D) Economic study identifying existing buildings at risk in vulnerable communities, and the Wind Climate Characteristics breakout session, (D) Risk mapping for different building stock types.

Section 5 describes in further detail the priorities identified by the breakout groups, which were combined to form the Priority Research Needs in Table 6-1.

6.3. Summaries of Research Priority Needs

The Workshop Steering Committee developed the following in-depth summaries of the Priority Research Needs identified in Section 6.2, which include a description, estimated cost, estimated time, measurement science challenges and potential solutions, stakeholders and roles, and impacts on standardization and application in practice.

Priority Research Need 1: Development of Main Wind Force Resisting System Reliability

Description

Identification of the collapse reliabilities associated with building systems designed to comply with the current provisions of the Prestandard (ASCE 2023) and knowledge of how these reliabilities compare with those associated with buildings designed to satisfy current prescriptive standards and codes is critical to advance performance-based wind design (PBWD) into structural engineering practice.

For this research topic, collapse reliability should be characterized both at the component level, which is consistent with Table 1.1-3 of the design standard ASCE/SEI 7(ASCE 2022), and at the system level. In estimating reliability, a full range of uncertainties must be considered to ensure consistency with the reliability underpinning current codes and standards. Modeling of the main wind force resisting system will be carried out using nonlinear finite element approaches that fully capture all effects generated by large deformation and material nonlinearity. The collapse reliability will be estimated for a full range of limit states and over a comprehensive set of archetype buildings that adequately represent current building practices in terms of materials and systems. A second, smaller scoped research initiative supports current assessments of structural reliability associated with stress, drift, and avoidance of incipient collapse limit states modeled using simplified approaches for building systems designed to comply with the current provisions of ASCE/SEI 7 (ASCE 2022).

Estimated Cost

1.1. Collapse assessment: \$1,500,000–\$3,000,000

1.2. ASCE/SEI 7 system reliability review: \$600,000

Estimated Time

1.1. Collapse assessment: 3–5 years

1.2. ASCE/SEI 7 system reliability review: 2–3 years

Measurement Science Challenges and Potential Solutions

Challenges	Potential Solutions
Need for a large suite of archetype buildings that are representative of current building practices	Engagement of practicing engineers
The significant computational resources (at the supercomputer level) necessary to run the reliability analysis	The use of computer clusters

Stakeholders and Roles

Stakeholder	Role

Universities/Research Organizations	Conduct research and identify the reliabilities of the buildings built to current codes and standards
Industry	Provide the suite of archetype buildings, advise on limit states, and review results
Standards Organizations	Adopt the identified reliabilities as targets

Impacts on Standardization and Application in Practice

- Determines the reliability of buildings built to current codes and standards.
- Provides the fundamental knowledge and critical data for understanding PBWD reliability to advance the standardization and application of PBWD for practice.

References

ASCE. (2022). ASCE/SEI 7, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. Reston, VA: American Society of Civil Engineers.

ASCE/SEI. (2023). *Prestandard for Performance-Based Wind Design Version 1.1*. Reston, VA: American Society of Civil Engineers.

Priority Research Need 2: Enhancement of Components and Cladding Reliability through Re-Evaluation of Testing

Description

This combined category stems from the observation that modern structural systems stand up well to high winds. Unfortunately, envelope systems—which are the first defense against wind forces—often fail. That failure then leads to internal building damage and in some cases structural failure. This research priority stresses the critical need to improve the reliability of the components and cladding (C&C) systems to take advantage of the benefits of performance-based wind design (PBWD). The following subtopics have also been identified: improvement of current envelope system tests (for walls and roofs) to identify weak points of cladding testing before installation, generation of new or more stringent performance requirements to overcome these weak points, and creation or confirmation of in situ testing methods to demonstrate satisfactory in-place/as-installed performance.

Estimated Cost

2.1. Extend FEMA P-58 (FEMA 2016) fragility dataset: $100,000–$500,000

2.2. Components and cladding water infiltration study: $3,000,000

2.3. Create field diagnostic in situ tests for components and cladding: $100,000–$500,000

2.4a. Develop site-specific wind-borne debris impact design framework: $500,000–$1,000,000

2.4b. Derive roof tile wind uplift loads: $1,000,000–$3,000,000

2.4c. Evaluate envelope for multi-meteorological event: $3,000,000

2.5. Reassessment of existing envelope testing for wind pressure: $100,000–$500,000

2.6. Evaluation of current components and cladding testing methods: $100,000–$500,000

Estimated Time

2.1. Extend FEMA P-58 (FEMA 2016) fragility dataset: 1–2 years

2.2. Components and cladding water infiltration study: 3–5 years

2.3. Create field diagnostic in situ tests for components and cladding: 1–2 years

2.4a. Develop site-specific wind-borne debris impact design framework: 1–2 years

2.4b. Derive roof tile wind uplift loads: 2–5 years

2.4c. Evaluate envelope for multi-meteorological event: 2–5 years

2.5. Reassessment of existing envelope testing for wind pressure: 1–2 years

2.6. Evaluation of current components and cladding testing methods: 1–2 years

Measurement Science Challenges and Potential Solutions

Challenges	Potential Solutions
Consideration of water intrusion	Early inclusion of envelope manufacturers
Creation of useful testing techniques	Early inclusion of contractors using the tests

Stakeholders and Roles

Stakeholder	Role
Universities/Research Organizations	Assess wind/rain application histories to understand appropriate test wind pressures, rain pressures, and application times Continued assessment of post-disaster performance of cladding, specifically, looking for evidence of particularly good or particularly poor performance of buildings constructed in the last +/- 20 years
Industry	Collection of best practices to inform standard development
Standards Organizations	Tightening of standards to inhibit water intrusion

Impacts on Standardization and Application in Practice

- Reduce losses from moderate wind hazards by confirming the building envelope can remain functional with the building movements and external wind pressures required by PBWD.
- Confirm the reliability required by PBWD by comparing the design intent and in-place performance of envelope components.

Reference

FEMA. (2016). FEMA P-58, *Seismic Performance Assessment of Buildings*. Washington, DC: Federal Emergency Management Agency.

Priority Research Need 3: Integrate Performance between Structural System and Cladding

Description

The performance-based wind design frameworks of tomorrow will require the explicit treatment of uncertainty and damage to both structural and nonstructural components and the consideration of the interdependent (feedback system) and progressive nature of wind damage accumulation. This research topic encompasses research into novel computational modeling frameworks that respond to this need and the characterization of the wind damage susceptibility of structural and nonstructural components. This can be achieved by developing appropriate fragility functions through the extension of the FEMA P-58 (FEMA 2016) seismic fragility dataset to consider wind damage and consequence. This extension is expected to encompass repurposing some existing FEMA P-58 seismic fragilities while developing new fragilities that explicitly consider wind-specific damage (such as wind-induced pressure damage, water intrusion, and damage due to cyclic long-duration effects).

Estimated Cost

$3,000,000–$6,000,000, including the development of computational frameworks and physical/computational testing of dozens of archetype envelope components

Estimated Time

3–6 years

Measurement Science Challenges and Potential Solutions

Challenges	Potential Solutions
Computational modeling will be multi-hazard, coupled, and progressive	Use of disparate simulation methods and advances in uncertainty propagation
Many envelope systems are proprietary	Some fragilities may be generic, as was done with FEMA P-58
Water intrusion likely requires physical testing/multi-physics modeling due to the complexity of air/water/cladding interaction	Conduct physical testing first and use multi-physics modeling in the computational frameworks

Stakeholders and Roles

Stakeholder	Role
Universities/Research Organizations	Develop holistic computational modeling frameworks Assemble existing testing data and reassess FEMA P-58 fragility dataset for wind Advise on sensible wind pressure/rain intensity rates

	Carry out physical/computational testing of envelope components to determine damage states and demand parameters
Industry	Assemble repair time, repair cost, and casualty risk datasets
Standards Organizations	Enable code-based fragility assessment benefits within standards

Impacts on Standardization and Application in Practice

- Enable the introduction of a new generation of holistic (combined structural and nonstructural) performance objectives.
- Enable data-driven, value-based, and risk mitigation design decisions.
- Reduce high wind damage to future building stock and/or refurbished facilities following the generated guidelines.

Reference

FEMA. (2016). FEMA P-58, *Seismic Performance Assessment of Buildings*. Washington, DC: Federal Emergency Management Agency.

Priority Research Need 4: Characterization of Engineering Properties of Thunderstorm and Tornado Wind Events

Description

The temporal and spatial characteristics of large-scale storms is relatively well known. For much of the United States, however, the strongest wind events (as measured at 33 ft.) are governed by thunderstorms and tornado events. Their structure is much less well understood. This research topic requires gathering field data to build engineering models of these storms. These storms can then be incorporated into design methodologies so that their effects can be more appropriately considered during design to optimize performance of building structures and envelope systems. This research topic is critical because no time history data are available for a performance-based wind design (PBWD) analysis for regions of the country where these non-synoptic storm types govern design wind speeds.

Estimated Cost

4.1. Field instrumentation, deployment, and measurements: More than $5,000,000

4.2. Development of implementation methodologies: $1,000,000

Estimated Time

4.1. Field instrumentation, deployment, and measurements: 3–5 years

4.2. Development of implementation methodologies: 1–2 years

Measurement Science Challenges and Potential Solutions

Challenges	Potential Solutions
Capturing enough field data	Funding for sufficient instrumentation in enough locations
Integration of findings into design processes	Use modifications to existing methodologies, whether analytical or experimental

Stakeholders and Roles

Stakeholder	Role
Universities/Research Organizations	Gather field data and develop engineering models of smaller-scale storm types
Industry	Investigation of effects of new engineering storm models on design reliability
Standards Organizations	Provide standardized methods for integration of new knowledge into the design process

Impacts on Standardization and Application in Practice

- Provides understanding of wind profiles that allow for standardization of wind hazard time histories to be used in PBWD and other designs.

- Provides critical data to include dominant storm types for many regions of the United States, which is needed to execute PBWD in these regions.

Priority Research Need 5: Characterize Hazard and Loads for Short and Long Return Periods

Description

The state of the practice for defining wind loads to be used in implementing performance-based wind design (PBWD) is based on idealizations of the local wind climate and the aerodynamic loads impacting the building. Current practice assumes winds to be straight (including no change of wind direction) and stationary (including no change of wind speed) for a duration of 1 hour or longer.

PBWD centers on leveraging the inherent capacity of the system by permitting inelasticity during extreme wind events. Greater emphasis must therefore be placed on the detailed modeling of the local wind climate and the associated aerodynamic loads. Capture of the nonstationarities in the wind climate (including climate change) and aerodynamic loads (including changing wind speeds and directions during the wind event) is necessary to execute PBWD. Methods that can leverage existing climatological data, downscaling of global weather models, and standard boundary-layer wind tunnel data have potential for immediate impact on design practice.

Estimated Cost

$1,000,000–$2,500,000

Estimated Time

3–5 years

Measurement Science Challenges and Potential Solutions

Challenges	Potential Solutions
Modeling of extreme wind events, including nonstationarity, utilizing standard wind tunnel facilities	Use of state-of-the-art wind tunnel facilities/computational methods
Uncertainty in future weather predictions	Identify the key climatological parameters affecting the building response

Stakeholders and Roles

Stakeholder	Role
Universities/Research Organizations	Develop and validate the nonstationary wind climate and aerodynamic load models
Industry	Provide insight into the current capabilities of state-of-the-art wind tunnel facilities
Standards Organizations	Incorporate provisions for nonstationary wind climates

Impacts on Standardization and Application in Practice

- Develops estimations of the inelastic performance of buildings subject to extreme winds with high confidence.

- Develops recommended selections of wind records for time history analysis that are needed for PBWD analysis.
- Creates models for enabling climate impacts to be incorporated in standards.

Priority Research Need 6: Improve Understanding of Structural and Material Properties

Description

A comprehensive understanding of structural and material properties is crucial for the successful implementation of performance-based wind design, as the uncertainties in the modeling assumptions around these parameters can often overwhelm the changes in the wind load effect at various performance levels. To improve the identification of the wind-structure interaction and accurately model the behavior of structures under wind loading, several research directions can be explored, for example, quantifying inherent damping properties across all building types, understanding structural parameters like stiffness, and assessing the impact of component cracking on these properties. Building consensus on analysis model assumptions and researching nonlinear material behavior will provide valuable insights. Addressing uncertainties in structural properties, component testing, and system-level full-scale monitoring are essential for consistent practice and enhanced wind-structure interaction understanding.

Estimated Cost

$500,000–$3,000,000

Estimated Time

2–6 years

Measurement Science Challenges and Potential Solutions

Challenges	**Potential Solutions**
Difficult to get access to existing buildings for full-scale monitoring	Strengthen collaboration among stakeholders such as property owners and local authorities
Large quantity of components/material to study	Start with components/materials that are most used in the industry and most sensitive to long-duration wind loads and build a network of researchers to tackle different categories

Stakeholders and Roles

Stakeholder	**Role**
Universities/Research Organizations	Develop framework and tools for full-scale monitoring of existing buildings Develop methodology to quantify structural properties for different building materials
Industry	Provide feedback on the developed framework Develop relationships with property owners Identify opportunities for full-scale monitoring (could be short-duration monitoring around storm chasing or

	long-duration monitoring, which would provide insight in how properties change over time and post cumulative storm events)
Standards Organizations	Incorporate the outcomes of the monitoring into standards Define structural property assumptions to be made in design

Impacts on Standardization and Application in Practice

- Enables designers to assess the structural performance of buildings in design consistently using accurate modeling assumptions.
- Reduces the uncertainty in structural performance modeling and optimizes building designs.
- Standardizes the approach to addressing risk of nonlinear behavior in taller buildings.

Priority Research Need 7: Improve Physics-Informed, Computationally Efficient Methods for Nonlinear Analysis of Wind Response over Long-Period Durations

Description

Performance-based wind design (PBWD) is based on evaluation of the nonlinear dynamic response of the main wind force resisting system. The need to estimate the performance of the main wind force resisting system in terms of probabilistic performance metrics—both traditional, such as reliability, and future metrics, such as repair costs and time—generally requires the propagation of uncertainty through nonlinear finite element models that are subject to long-duration dynamic wind loads (on the order of several hours), which are generally characterized as nonstationary vector valued stochastic processes.

This presents a significant computational burden (weeks of computational time on current supercomputers for each time history of interest) that cannot be overcome by simply using additional computational resources. This challenge can only be overcome by developing new computational methods and strategies based on, for example, metamodeling, reduced order modeling, data-/physics-informed artificial intelligence (such as machine learning), and novel strategies based on leveraging graphics-processing unit computing and massive parallelization.

Estimated Cost

$2,500,000–$5,000,000

Estimated Time

3–6 years

Measurement Science Challenges and Potential Solutions

Challenges	Potential Solutions
To have practical significance the algorithms/approaches must be capable of handling general problems	Ensure the algorithms are developed with input from the industry
Ensuring methods based on artificial intelligence have buy-in from industry	Partnering with industry to solve problems of practical interest

Stakeholders and Roles

Stakeholder	Role
Universities/Research Organizations	Conduct research and develop the necessary algorithm advances
Industry	Provide the practical problems to solve
Standards Organizations	Endorse the use of new technologies

Impacts on Standardization and Application in Practice

- Creates a method to rapidly carry out nonlinear response history analysis required for PBWD.
- Provides the fundamental knowledge necessary to standardize methods based on explicit nonlinear time history analysis and uncertainty propagation needed for PBWD.

Priority Research Need 8: Static Pushover for Wind Engineering to Quickly Evaluate Nonlinear Structural Performance

Description

This research establishes a comprehensive framework for inelastic static pushover (SPO) analysis in wind engineering. In performance-based wind design (PBWD), the computational demands for nonlinear response history analysis are extremely high. As an alternative method, SPO analysis shows potential to provide an efficient way to quickly assess the structure's performance with respect to the performance objectives required in PBWD. No codes and standards in wind engineering incorporate SPO analysis, and the research on PBWD using SPO is mainly based on the seismic assessment framework. Establishing wind SPO analysis for PBWD will provide an efficient method of acquiring wind force and deformation demands for performance evaluation of structures under extreme winds.

Estimated Cost

$500,000–$1,000,000

Estimated Time

2–3 years

Measurement Science Challenges and Potential Solutions

Challenges	**Potential Solutions**
Lateral loading profile considering nonlinear structural behaviors	Adaptive loading distribution
Interaction between along-wind and crosswind responses	Multidirection SPO
Connection between SPO and incremental dynamic analysis	Comprehensive simulation and validation

Stakeholders and Roles

Stakeholder	**Role**
Universities/Research Organizations	Develop analysis tools
Industry	Validate the performance of the proposed wind SPO analysis framework in engineering practice Provide feedback on the quality of the methods
Standards Organizations	Adopt wind SPO analysis in standards

Impacts on Standardization and Application in Practice

- Provides an alternative efficient method to assess structural performance.
- Promotes the implementation of PBWD with efficient, practical tools.

Priority Research Need 9: Development of Wind Loading Protocol for Experimental Quantification of System Performance in Wind

Description

This research develops rational loading protocols for extreme wind performance cyclic testing of deformation-controlled main wind force resisting system members. While the nonlinear response history analysis is introduced to performance-based wind design (PBWD), the current backbone curve used in component modeling is mainly based on research in seismic engineering, with the exception of recently published PBWD-specific research (Abdullah et al. 2020, Motter 2019, Sharooz 2019). To develop wind-specific backbone curves for deformation-controlled members, well-designed (or confirmed) testing protocols are needed. Present loading protocols are based on statistical analysis and are specific to reinforced concrete and structural steel. Further statistical analysis is needed to extend loading protocols to wood structures and to assess windstorm type–specific (synoptic and non-synoptic wind) effects. Upon completion, the research will result in loading protocols that engineers can follow for pre-qualification of component details to use in performance-based wind design of structural members.

Estimated Cost

$750,000–$1,500,000

Estimated Time

1–3 years

Measurement Science Challenges and Potential Solutions

Challenges	**Potential Solutions**
Loading protocols depend on windstorm types	Generate intensity-duration-frequency curves for each storm type and develop corresponding wind tunnel facilities/techniques
Loading protocols depend on structural materials	Develop high-fidelity finite element models
A large number of nonlinear structural analyses are needed	Develop efficient computational algorithms or approaches

Stakeholders and Roles

Stakeholder	**Role**
Universities/Research Organizations	Develop simulation and wind tunnel tests
Industry	Review the proposed loading protocol
Standards Organizations	Adapt wind-specific loading protocol in standards Provide feedback

Impacts on Standardization and Application in Practice

Provides a criterion for material-specific component tests to develop backbone curves required for nonlinear analysis for PBWD.

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Priority Research Need 10: Economic Study to Identify Existing Buildings at Risk and Risk Mapping for Different Building Stock Types.

Description

This research will quantify the economic impact of wind damage to existing buildings and the potential benefits of implementing performance-based wind design measures, such as to enable adaptation or change use of existing buildings. The risk mapping will help identify areas where different types of buildings are most vulnerable to wind damage and provide guidance on the most effective measures for mitigating damage of these buildings.

Estimated Cost

$3,000,000–$5,000,000

Estimated Time

5–10 years

Measurement Science Challenges and Potential Solutions

Challenges	Potential Solutions
Difficult to acquire damage observations on a large scale that are representative of various existing building types	Identify regions with diverse building typologies that have experienced strong windstorm events Collaboration between researchers and governmental organizations to share data
Addressing the multiple vulnerabilities that may exist across existing building stock	Separate existing building stock into subsets and address the most typical points of failure or vulnerability for the subset

Stakeholders and Roles

Stakeholder	Role
Governmental Organizations	Provide feedback and access to data on building stock and classifications
Universities/Research Organizations	Conduct research Develop methodology for data collection Develop points of vulnerability for different building types
Industry	Develop relationship between cost and damage for different building types Support the mapping of risk to vulnerable communities
Standards Organizations	Address code changes that specifically address vulnerabilities in existing building stock

Impacts on Standardization and Application in Practice

- Creates methodology for retrofitting and adaptation efforts using performance-based wind design to reduce overall costs.
- Enables high-risk existing structures in vulnerable communities to consider cost-effective options.

6.4. Proposed Program Budget and Schedule for the First 10 Years

Based on the Priority Research Summaries provided in Section 6.3, Table 6-2 summarizes the proposed program budget and schedule for the first 10 years. Effort was made to identify where, and which, research efforts depend on or need subsequent efforts. These relationships are explained in more detail following the table.

Table 6-2. Proposed Program Budget and Schedule for the First 10 Years (Amounts Shown in Thousands of Dollars).

Rank No.	*Priority Research Needs*	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Total
1	Development of Main Wind Force Resisting System (MWFRS) reliability.											
	1.1 Collapse assessment	$600	$600	$600	$600	$600						$3,000
	1.2 ASCE/SEI 7-22 system reliability review	$200	$200	$200								$600
2	Enhancement of Components and Cladding (C&C) reliability through re-evaluation of testing.											
	2.1. Extend FEMA P-58 fragility dataset	$250	$250									$500
	2.2. C&C water infiltration study	$600	$600	$600	$600	$600						$3,000
	2.3. Create field diagnostic in-situ tests for C&C components	$250	$250									$500
	2.4a. Develop site-specific wind-borne debris impact design framework	$500	$500									$1,000
	2.4b. Derive roof tile wind uplift loads	$600	$600	$600	$600	$600						$3,000
	2.4c. Evaluate envelope for multi-meteorological event	$600	$600	$600	$600	$600						$3,000
	2.5. Reassessment of the existing envelope testing for wind pressure	$1,500	$1,500									$3,000
	2.6. Evaluation of current C&C testing methods	$600	$600	$600	$600	$600						$3,000
3	Integrate performance between structural system and cladding.	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000					$6,000
4	Characterization of engineering properties of thunderstorm and tornado wind events.											
	4.1 Field instrumentation, deployment, and measurements	$1,000	$1,000	$1,000	$1,000	$1,000						$5,000
	4.2 Development of implementation methodologies						$500	$500				$1,000
5	Characterize hazard and loads for both short and long return periods.	$500	$500	$500	$500	$500						$2,500
6	Improve understanding of structural and material properties.					$500	$500	$500	$500	$500	$500	$3,000
7	Improve physics-informed, computationally efficient methods for nonlinear analysis of wind response over long-period durations.					$833	$833	$833	$833	$833	$833	$5,000
8	Static pushover for wind engineering to quickly evaluate nonlinear structural performance.						$333	$333	$333			$1,000
9	Development of wind loading protocol for experimental quantification of system performance in wind.	$500	$500	$500								$1,500
10	Economic study to identify existing buildings at risk and the risk mapping for different building stock types.	$500	$500	$500	$500	$500	$500	$500	$500	$500	$500	$5,000
Total Research Estimated Costs:		**$9,200**	**$9,200**	**$6,700**	**$6,000**	**$7,333**	**$3,667**	**$2,667**	**$2,167**	**$1,833**	**$1,833**	**$50,600**

6.4.1 Interrelationship of Research Activities

Tables 6-1 and 6-2 list the top 10 research needs identified during the workshop. Each of these research needs seeks to improve the built environment by maintaining or enhancing safety, reducing loss, and minimizing resource allocation when challenged by extreme weather events.

Consequently, completion of certain research needs will depend on the status, development, and perhaps completion of other research needs. The Workshop Steering Committee offers the following commentary regarding the likely interrelationships of the research needs.

Priority Research Need 1 can proceed immediately with the understanding that present wind engineering is based on wind engineering protocols developed for synoptic- and hurricane-dominated wind risks. Priority Research Need 1 can begin with evaluation of present design performance achieved by national design standards (e.g., ASCE/SEI 7 (ASCE 2022), AISC 360 (AISC 2022), and ACI 318 (ACI 2019)) with the objective of finding appropriate building system–based reliability targets.

Priority Research Needs 2 and 3 pertain to reduction of undue damage observed in envelope systems. Launch and completion of Priority Research Needs 2 and 3 can and should take place concurrently with the other research needs.

Current non-PBWD design is also developed on assumptions of synoptic- and hurricane-dominated wind fields, hence once the study of Priority Research Needs 4 and 5 are complete and published, updates to the Prestandard (ASCE/SEI 2023) and PBWD engineering practice can be pursued by the various national design standards. Priority Research Needs 4 and 5 can likely proceed in parallel.

Priority Research Need 9 considers the appropriate application of loads and deformations to laboratory tested components subject to wind demands. Until a consistent loading history is agreed upon (or at least followed) within the testing community there is a risk of incompatible or conflicting findings within the work of Research Needs 6, 7, and 8.

Priority Research Needs 6 and 7 consider methods to expand or make structural components, analysis techniques, or design approaches more efficient. These initiatives must either begin after Priority Research Needs 1 and 9 or must be conducted so as to avoid relying upon the present assumptions or the current state of practice with regard to structural system safety (Priority Research Need 1) or the specific level of loading (cyclic or otherwise) of Priority Research Need 9. Hence, NIST is advised to require researchers evaluating Priority Research Needs 6 and 7 to conduct their work either with knowledge of the outcomes or directions of Priority Research Needs 1 and 9, or in such a way that would accept future refinements of Priority Research Needs 1 and 9.

Priority Research Need 8 represents a simplified solution to full nonlinear time history evaluation of system safety. Consequently, Priority Research Need 1 must be complete (and preferably codified) before similar implementation of Priority Research Need 8. Additionally, it would be helpful for Priority Research Needs 6 and 7 to be underway or complete before codification of Priority Research Need 8. Finally, outcomes of Priority Research Needs 4 and 5 could notably affect Priority Research Need 8.

Priority Research Need 10 can commence immediately as it primarily serves to inform national codes and standards. Existing post-disaster reconnaissance reports contain sufficient guidance that Priority Research Needs 2 and 3 can proceed independently of Priority Research Need 10. Ideally the findings of Priority Research Need 10 can be provided in stages to provide those findings more quickly to designers, researchers, and policymakers.

6.5. Benefits of Implementing Research Activities for Performance-Based Wind Design

The benefits of the recommended research program include

- Fundamental knowledge and critical data for understanding PBWD reliability to advance the standardization and application of PBWD in practice;
- Reduction of high wind damage to future building stock and/or facilities refurbished utilizing PBWD methodologies;
- Lower initial and retrofit costs related to wind-resistant construction;
- Increased reliability of buildings with minimized overdesign;
- Increased confidence in the estimation of the inelastic performance of buildings subjected to high winds;
- Fewer lives lost in destructive windstorms (especially tornadoes); and
- Better written, more easily understood codes and standards.

For the nation, implementation of the proposed research program will yield the following major benefits:

- Reduction in traumatic life loss, injury, damage, and economic impacts when windstorm events occur;
- Rapid recovery and restoration of physical communities and economic activities following a significant windstorm event; and
- Reduced initial investments required to achieve risk-consistent design and construction of buildings subjected to wind events.

Benefits will accrue to design practice almost immediately after this program begins because the Prestandard (ASCE/SEI 2023) is currently utilized for the design of buildings and results from the recommended program can be implemented immediately. Researchers and design practitioners in the wind engineering community have been requesting research help for these technical issues, particularly as they relate to envelope system design and installation, for many years now. Implementation of the proposed research program will immediately signal an important positive change to the profession and research communities that should yield new enthusiasm for pursuing worthy research and developmental efforts that will improve current knowledge about windstorm hazards and ways to significantly reduce impacts felt from these events.

7. Acronyms and Abbreviations

ANN	artificial neural network
ASCE	American Society of Civil Engineers
ASTM	ASTM International
ATC	Applied Technology Council

building envelope	assemblage of wall and roof coverings providing resistance to air and water infiltration
C&C	components and cladding
CFD	computational fluid dynamics
DCR	demand-to-capacity ratio
FEMA	Federal Emergency Management Agency
GPU	graphics-processing unit
IDA	incremental dynamic analysis
LIDAR	light detection and ranging
LSTM	long short-term memory
MDOF	multi degree of freedom
ML	machine learning
MPA	modal pushover analysis
MRI	mean recurrence interval
MWFRS	main wind force resisting system
NIST	National Institute of Standards and Technology
NWIRP	National Windstorm Impact Reduction Program
PBD	performance-based design
PBWD	performance-based wind design
PEER	Pacific Earthquake Engineering Research Center
Prestandard	ASCE/SEI *Prestandard for Performance-Based Wind Design Version 1.1* (ASCE/SEI 2023)
SEI	Structural Engineering Institute of ASCE
SHM	structural health monitoring
SDOF	single degree of freedom
SODAR	sonic detection and ranging
SPO	static pushover
SPO2IDA	static pushover to incremental dynamic analysis
STEER	Structural Extreme Events Reconnaissance
WSC	Workshop Steering Committee

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Appendix A. Further Discussion of Priority Research Needs from Section 6

A.1. Priority Research Need 1: Development of Main Wind Force Resisting Systems Reliability

ASCE/SEI 7 (ASCE 2022) defines the minimum required building loading for code-compliant structures in the United States. At the heart of the ASCE/SEI 7 standard is the objective of protecting the life safety of building occupants. A single table in Chapter 1 of ASCE/SEI 7 summarizes this objective, which is expressed as the reliability against failure of various structural components with respect to different limit states of increasing severity. This table is predicated upon the idea that if all the structural components of a building respond with a certain reliability (margin of safety against collapse, failure, etc.), then the entire building (considered as a system) will achieve that reliability. Reliability as defined in the table is, therefore, not defined in terms of the overall reliability of the structure, nor do the values directly consider global building responses, such as stability and drift, or the possibility of load redistribution through damage, e.g., yielding and/or buckling.

The design community recognizes that the main objective of PBWD, namely the explicit estimation of damage, risk, and overall performance, can only truly be achieved through treating the *building as a whole* (i.e., as a system composed of multiple components that interact in determining the overall performance of the structure). System reliability represents a means to this end by providing a holistic understanding of performance while allowing system-based choices when allocating material and development resources.

Motivated by system reliability, researchers and practitioners have over the past five years pioneered approaches that explicitly treat damage through nonlinear modeling within the context of system reliability. These include approaches based on the application of the theory of dynamic shakedown (Chuang and Spence 2022; Spence et al. 2022) and the application of nonlinear modeling approaches based on direct integration (Arunachalam and Spence 2022; Xu and Spence 2022). The fundamental idea underpinning the first approach is to rapidly identify a region in which controlled inelasticity can occur. The computational efficacy of the algorithms developed to evaluate the state of dynamic shakedown enables the direct evaluation system reliability by robust direct stochastic simulation (Chuang and Spence 2022). The key advantage of the second approach is the modeling flexibility it provides. The major challenge is the huge computational effort that is generally necessary to propagate uncertainty and therefore estimate system-level reliability. Notwithstanding, the use of supercomputers and specialized uncertainty propagation schemes (Arunachalam and Spence 2023) has allowed progress in this direction (Arunachalam and Spence 2022; Xu and Spence 2022).

As a direct consequence of the fundamental and immutable importance of safety to the ASCE/SEI 7 (ASCE 2022) standard, no progress in the implementation of PBWD can be achieved until the system reliability of buildings designed to current codes and standards is understood over an adequate number of archetype structures that properly represent current practices in the design of steel, reinforced concrete, and hybrid MWFRS. The ASCE/SEI 7 and research communities are beginning to evaluate suites of structures for system reliability. Extension of this work to more building types, geometries, and lateral system configurations is needed. A robust evaluation of the forms of structures being designed will enable not only an educated and appropriate update of the component reliabilities within ASCE/SEI 7 but also the fundamental extension to building system reliability. The participants of the workshop are aware that efforts are underway within the Structural Engineering Institute of ASCE to address system reliability and that progress is being made. Research and review continue to be needed. NIST resources, if applied soon, would accelerate this critical need.

A.2. Priority Research Need 2: Enhancement of Components and Cladding Reliability through Re-Evaluation of Testing

This research category aims to improve the observed poor performance of envelope systems to high winds. Several initiatives were identified with the common goal of reducing the economic and societal losses attributed to failure of the envelope system to prevent damage to the internal areas of buildings due to wind-borne debris, water intrusion, or wind pressures.

As voiced by nearly all workshop participants, the penetration of water and moisture into a building through breaches or failures of the envelope endangers the internal contents and continued use likelihood of nearly all building types. While life safety is the stated design objective of model codes (i.e., the International Building Code (ICC 2021) and ASCE/SEI 7 (ASCE 2022)), the economic and societal penalties when a building is taken offline following modest storms or hurricanes is not in keeping with the level of performance expected by ASCE/SEI 7. Put simply, the workshop participants feel the degree of envelope damage and or internal damage initiated by envelope damage observed following modest winds is too great considering the satisfactory performance of the main structural systems of the same facilities. In the hopes of rectifying this disconnect in performance level, the workshop participants suggest advancement in the following areas:

- ***Re-Evaluation Area 1:*** Creation and adoption of the formal evaluation, through testing, of envelope systems to quantify performance relative to wind effects *with water infiltration*.
- ***Re-Evaluation Area 2:*** Requirement for water intrusion resistance of envelope systems at pressures commensurate with the pressures mandated within ASCE/SEI 7 (ASCE 2022). At present water intrusion pressure testing occurs at 6% to 12% of the allowable stress design pressures mandated for structural design.
- ***Re-Evaluation Area 3***: Reassessment of envelope testing methods to ensure the testing methods adequately predict in-place performance coupled with expansion of testing during envelope installation.
- ***Re-Evaluation Area 4:*** Establish if present wind-borne debris impact testing is representative of true impact risks and generates the desired level of performance in situ. Further details of this initiative are provided subsequently.
- ***Re-Evaluation Area 5:*** Reassessment of the frequency, magnitude, and duration of air pressure applied during ASTM E 331 (ASTM 2016) and AAMA 501.1 (AAMA 2017b) testing.
- ***Re-Evaluation Area 6:*** Comprehensive review of testing methods relative to contemporary envelope systems, materials, and location. The workshop participants specifically suggest the various segments of the building envelope industry should be

tasked with evaluating their existing test methods and developing a priority list for re-evaluation.

A.2.1. Detailed Commentary on Re-Evaluation Area 1

The FEMA P-58 (FEMA 2016) research initiative provided the design community with a scientifically based method to assess likely damage, facility use interruption time, and risk to occupants (casualties) as a function of seismic hazard and the specific structural and nonstructural composition of a facility. With the methods of the FEMA P-58 initiative, designers can inform building users of the likely result of design decisions insofar as future risk. With respect to predicting seismic damage, the heart of the FEMA P-58 method is a suite of fragility curves. Each curve is specific to a building component or building content object (e.g., beams, columns, connections, mechanical objects, pipes, bookshelves, stairs, interior walls, etc.), and these fragilities have been used at the research level to consider likely building outcomes in high wind scenarios.

The fragility predictions offer for a suite of building components and systems the most likely consequences from the most relevant sources of loss, which are

- Direct damage (damage to materials),
- Indirect damage (damage due to water leaks and internal mechanical systems),
- Facility downtime (time and cost to repair), and
- Risk to occupants (risk of casualties).

Several limitations exist when attempting to transcribe the seismic fragilities into wind response, including the following:

- Seismic fragilities were created with seismic response in mind. Consequently, the goodness of fit between the raw data and the fitted fragilities was biased toward the levels of response seen in earthquakes. Consequently, for example, not all the cladding fragilities fit the lower magnitude interstory displacements expected in wind versus much higher displacements observed in seismic response.
- The FEMA P-58 (FEMA 2016) fragility curves did not consider damage mechanisms outside of seismic response. Low or high cycle fatigue was not a testing or failure condition of envelope systems or internal walls or components. The long duration and multi-cycle realities of wind response motivate additional damage and repair states when extending the present seismic fragilities to wind response.
- Wind-specific response was not considered by the seismic FEMA P-58 initiative (FEMA 2016). Consequently, the FEMA P-58 fragilities lack wind-borne debris impact or air pressure–based damage predictions. Addition of air pressure and wind-borne debris-based damage states to the envelope fragilities is critically important.
- Addition of water infiltration damage states. This damage state is the specific risk of water forcing its way through the envelope at door and window joints, louvers and vents, or any other avenue of entry not brought about by cladding breach (i.e., debris breaking glass, puncturing walls, roof tear-off, etc.).

Much of the FEMA P-58 (FEMA 2016) fragility dataset can be leveraged for wind engineering. The damage metrics associated with interior building damage from broken water pipes can be directly applied to water intrusion damage caused by cladding breaches. Furthermore, the cost and consequence data of FEMA P-58 is equally applicable to wind damage as it is seismic damage.

Nevertheless, to make valid predictions of building performance, the design community needs data linking building engineering parameters (drift, lateral acceleration, wind pressure, and wind-borne debris density) to building damage and consequence metrics (cost, downtime, and societal impact). With these links a designer, policymaker, or user can make value- and outcome-based decisions.

A.2.2. Detailed Commentary on Re-Evaluation Area 2

Water entering a building initiates a damaging chain of loss beginning with direct water damage, which potentially leads to mold and decay of interior building contents. This loss risk is compounded in storms in which wind-borne debris breaches the envelope system either directly (e.g., breakage of windows), or indirectly through tears or dislocation of envelope components that lead to water intrusion. Furthermore, large storms may disable or destroy mechanical systems or city utilities. Loss of building environmental control (i.e., HVAC systems) increases the risk of mold or decay in cases where humidity control is lost, thus allowing moisture to persist. Finally, in the largest storms the building occupants may have relocated due to the storm risk and will be unable to conduct timely cleanup of water within the building interior.

At present, Fenestration and Glazing Industry Alliance testing includes a suite of ratings for door and window assemblies with respect to the resistance to water intrusion for increasing levels of applied pressure (FGIA/AAMA/I.S.2/A440). These tests assess water intrusion for wind pressures between 6% and 12% of allowable stress design wind pressures with optional elevated performance grades approaching structural design allowable stress pressures.

The workshop participants are concerned that the present water intrusion performance class tests are allowed to assess wind risk disproportionately below the performance targets otherwise required for cladding wind resistance. Given that nontrivial water intrusion through an envelope can cause equal or greater overall building use interruption and/or loss than outright damage to that same envelope, the workshop participants feel an unacceptable disconnect exists between the pressures an envelope system must resist for safety purposes versus the level of pressure an envelope system must resist for water resistance purposes.

Consequently, the workshop participants recommend that NIST and/or the design and standards communities formally assess (and seek to improve) the present water intrusion testing metrics applied to residential-, commercial-, and architectural-grade envelope systems.

Intrusion of water can also be traced to direct impingement through louvers, vents, and similar openings through the envelope and through similar openings breached by the dislocation of rooftop or similar equipment. Opportunities exist to assess, for example, louver systems that may or may not close and seal against water intrusion. Other opportunities exist for further code guidance for the attachment of ventilators, rooftop equipment, and other objects subject to missile impacts that can dislodge objects. At present those objects are not required to have direct missile impact energy force resistance.

Finally, water intrusion can occur through tears, separations, or similar breaks in an envelope system (e.g., roofing membrane, coping materials, gutter tear-offs, flashing uplift, etc.). Educational materials, field testing methods, and where needed code requirements for the securing and integrity of these elements appear overdue and useful.

A.2.3. Detailed Commentary on Re-Evaluation Area 3

During the Design breakout session, envelope system design practitioners and envelope system researchers identified failure or damage mechanisms inherent to envelope systems that currently lack assessment (testing) techniques readily available for field use. Thus, the following suggests creation of evaluation techniques and/or design profession or standard community calls for the testing of envelope components that are not assessed at present.

This category also includes continued assessment of newly constructed facilities that have been subject to high winds to evaluate performance improvement brought about by recent code revisions, industry changes, or elective performance enhancements.

- Create field diagnostic tests for envelope component integrity where deficiencies in performance are found and assessment of the deficiency is not supported by inspection or verification tests.
- Establish formal requirements for envelope system installation and in situ testing.
- Develop methods to assess the efficacy of envelope components years to decades after installation. The workshop members are concerned that degradation of seal and jointing materials is not quantified or well understood. Assessment is recommended around the degradation of materials causing joints to open, seals to lose efficacy, and envelopes to lose resistance.
- Implement an industry group evaluation of best practices, maintenance, and replacement protocols or guidance relative to materials commonly utilized in the envelope system community. Ideally such a group would produce nonbiased and freely available educational materials for facility operators and owners speaking to the needs for preventative maintenance and inspection of envelope system materials.
- Incentivize insurance premium rebates for developments that adopt envelope performance improvements above code and industry group minimums.
- Assess newer existing structures that have been subject to high wind events and determine whether impact-resistant design generates the desired level of performance in situ.

A.2.4. Detailed Commentary on Re-Evaluation Area 4–Part I

Extreme wind events affect the urban environment, heavily damaging buildings. A major cause of building damage is wind-borne debris impact, especially on the building envelope. Post-event surveys highlight that even if the wind event does not affect the structure, if the building envelope is breached serious consequences can occur, such as internal pressurization, water infiltration, property losses, and fatalities, such as the 14 patients at the St. John Medical Center of Joplin, Missouri, in 2011. In such scenarios, the building envelope is the first barrier to protect or at least mitigate against the effects of extreme wind events on people and property.

Current impact testing to certify glazed assemblies, sectional and rolling doors, and storm shelters to resist wind-borne debris impacts are based on the following test methods:

- ASTM E1996 (ASTM 2020), *Standard Test Method for Performance of Exterior Windows, Curtain Walls, Doors, and Impact Protective Systems Impacted by Wind-Borne Debris in Hurricanes;*
- ASTM E1886 (ASTM 2019), *Standard Test Method for Performance of Exterior Windows, Curtain Walls, Doors, and Impact Protective Systems Impacted by Missile(s) and Exposed to Cyclic Pressure Differentials;*
- ICC 500 (ICC 2020), *ICC/NSSA Standard for the Design and Construction of Storm Shelters;* and
- DASMA (2017), *Standard Method for Testing Sectional Doors, Rolling Doors, and Flexible Doors: Determination of Structural Performance Under Missile Impact and Cyclic Wind Pressure*

These methods adopt standard “missiles” and impact velocities. These consider the complete failure of typical balloon frame construction—the flight of structural members (large missiles, representative of the 2x4 in. section wood frame construction) and the roof aggregate (small missiles)—to conduct impact tests on glazed assemblies. The current testing protocols, therefore, also assume that wind-borne objects have these two features. Thus, the impact energies are not based on the aerodynamics of wind-borne debris in local environments, nor is a database with wind-borne debris speeds in windstorms of various intensities available. The weights and velocity of the testing projectiles change according to the building’s wind zone and level of protection (ranging from Wind Zone 1 to Wind Zone 4, following ASCE/SEI 7 (ASCE 2022)). The design wind pressures (inward and outward) from the Building Code are therefore used to determine the pressure cycling to be performed on the façade once the impact test passes. It is necessary to do 4,500 cycles of positive and negative pressure, with each cycle lasting 1–3 seconds.

Through a process of consensus building, the ASTM E1886 (ASTM 2019) standard test method was created with the participation of manufacturers, consultants, building code authorities, and other specialists. The standard includes the permitted tolerances for the testing criteria for both debris projectile impacts, develops the pressure cycle program, and defines the test loading sequence and conditions. The performance requirements were developed through an empirical approach.

ASTM E1886 (ASTM 2019) standard requirements give façade designers the opportunity to go through engineering assumptions and calculations to develop ad hoc wind-borne debris impact tests for their projects, using “other missiles” for the impact tests. This ability to adopt “other missiles” allows impact testing that represents the local environment both in terms of debris type and impact features on the building envelope (impact velocity, impact orientation, impact locations, etc.). In extreme wind events, debris can originate from the failure of materials and pieces from source buildings and other manmade structures.

To perform wind-borne debris impact tests that represent the local environment, two design steps should be conducted: debris failure wind speed assessment and wind-borne debris flight trajectory assessment.

Debris failure wind speed assessment: Various methods are available to estimate the failure wind speeds of an object. The failure of a building component is assumed to occur when the aerodynamic force exceeds the total hold-down force on the debris element. The evaluations can be conducted through a deterministic or a stochastic approach, or through a combination thereof. Potential debris sources in the surroundings include surrounding buildings' roof tiles, roof aggregate, roof pavers, and other building envelope components.

To design such elements, peak pressure coefficients (ASCE/SEI 7) have been developed through wind tunnel tests of different building geometries, terrain conditions, and directions. The code requirements, therefore, have been maximized, considering the worst case in terms of negative/positive pressures acting on the building envelope. The design (*GCp*) is identified for various areas on the walls and on the roof slopes, for various building types. Even though this outcome is conservative in terms of building envelope design (maximum and minimum pressure to test the façade element), it does not accurately estimate the wind speed at which a component of the building envelope might fail and thus become wind-borne debris. A larger localized suction on the roof can occur at a lower than design wind speed, resulting in a localized building component failure. Accordingly, if the failure occurs at a lower than design wind speed, in some scenarios the designer can underestimate the problem of wind-borne debris.

Wind-borne debris flight trajectory assessment: The first wind-borne debris studies to assess flight and trajectory were developed by Tachikawa (1983), who defined the equations of motion for a general wind-borne debris object, in uniform flow. Debris failure is associated with wind gusts, and Kordi et al. (2010) found that the 3-second gust failure wind speed represents a practical and reasonable upper-bound wind speed to estimate the upper-bound flight trajectory, but that it overestimates the mean trajectory.

Experimental results for plate-like debris showed that, considering numerical results to estimate flight speeds, the ranges of debris speed are

- Between 40% and 120% of the 3-second gust wind speed at failure for roof shingles (Kordi and Kopp 2011),
- Between 20% and 95% of the 3-second gust wind speed at failure for roof sheathing panels (Kordi et al. 2010), and
- Between 30% and 60% of the 3-second gust wind speed at failure for roof tiles (Kordi and Kopp 2011).

A.2.5. Detailed Commentary on Re-Evaluation Area 4–Part II

Further research is needed to assess the near-roof surface flow to derive roof tile wind uplift loads, the same way that Peterka et al. (1997) did for asphalt shingles. ASCE/SEI 7 (ASCE 2022) requirements extend wind-borne debris impact testing up to 1 mile (1.6 km) from an Exposure D condition. It should be determined if rod-like wind-borne debris can reach greater flight distances, based on the source location. Datasets to validate the numerical calculations of wind-borne debris trajectory analysis are limited, and most studies do not consider real-world scenarios in which the wind-borne debris element originates from a source building. Developing a wider database on various wind-borne debris types, based on various building components or objects in the urban environment identified as prone to failure in extreme winds, would be useful. Considering the source building, studying the failure and trajectory of wind-borne debris elements from low-rise and high-rise buildings and for various roofing systems (roof tiles, shingles, roof aggregate, roof pavers, green roof technologies, etc.) and roofing shapes (gable/hip/flat roof types) would also be useful. Tall buildings have not yet been assessed through wind tunnel experiments for wind-borne debris generation.

A.2.6. Detailed Commentary on Re-Evaluation Area 4–Part III

With regard to performance-based multi-meteorological (wind/hail/rain) design, when a building envelope fails under wind loads, the primary damage to the building and contents often results from damage due to water infiltration. At present, joint probability models for wind and precipitation are not readily available. A need exists to conduct these analyses to develop maps for different MRIs across the United States. Incorporating such joint probabilistic analyses would allow total reliability to be determined based on the watertightness and wind resistance of different building envelope system types. As discussed elsewhere, consistent reliability across components of a building is needed to ensure that the building meets its performance goals, and this is currently missing. This research will be a major contributor to design and verification of total building reliability in limiting losses due to wind effects.

A.2.7. Detailed Commentary on Re-Evaluation Area 5

Workshop participants voiced concern that tests for wind and pressure of cladding may not recreate relevant real-world demands on cladding systems.

Water penetration testing of cladding commonly employs two test types: static water penetration and dynamic water penetration.

ASTM E 331, *Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls Uniform Static Air Pressure Difference* (ASTM 2016), describes the static testing method by which water is sprayed at a constant rate (5 gal/hr/ft^2, corresponding to a heavy rainfall of 8 in./hr) onto the exterior face of a cladding specimen while a pressure differential is maintained across the specimen. The static test is meant to be performed for 15 minutes at a minimum pressure differential of 2.86 psf, but for the architectural cladding industry it is more frequently conducted at a minimum pressure of 6.24 psf, or at greater pressures of up to 12 or 15 psf (approximately equivalent to 50, 69, and 77 mph static wind pressures, respectively). The AAMA 101 standard (AAMA 2022) recommends testing a minimum of 15% of the positive design cladding pressure for residential and commercial windows, skylights, and doors, and 20% of the positive design pressure for architectural grade cladding on buildings. The AAMA 101 narrative also suggests that 15 psf should be the maximum pressure considered for testing. Note also that AAMA states, “It is important to design and select products that will not permit significant leakage under normal service conditions. It is generally accepted, however, that water leakage can be tolerated during periods combining high winds and heavy rains. In recognition of this, water resistance is generally determined at a pressure less than Design Pressure.”

AAMA 501.1, *Standard Test Method for Water Penetration of Windows, Curtain Walls and Doors Using Dynamic Pressure* (AAMA 2017b), describes the dynamic testing method by which water is sprayed at a constant rate (5 gal/hr/ft^2) onto the exterior face of a cladding specimen while a wind-generating device (i.e., airplane propellor) produces a dynamic velocity pressure against the specimen. The test is performed for 15 minutes at a selected dynamic pressure anywhere from 6.24 psf up to 15 psf (approximately equivalent to 50 and 77 mph winds, respectively). Typically, both static and dynamic tests would be conducted at the same pressure for a given project.

Both tests are intended to simulate storm conditions and evaluate the ability of the cladding system to resist water penetration. Workshop participants are concerned that the duration of the tests and test pressures utilized may not realistically recreate storm conditions that the cladding may experience. In addition, the relatively high frequency of simulated air gust application during the dynamic test may not represent the lower-frequency, longer-duration application of wind and water demands during storm conditions. Longer-duration rain events and slower variation of wind pressure (relative to pressures observed in the AAMA 501.1 test) may permit greater levels of air and water infiltration than suggested by testing.

Workshop participants are also concerned that current testing does not consistently assess the relationship between building movement (which displaces seals and joints) and simultaneous application of wind and water loads. More extensive testing of the assembly under a realistic displaced condition like testing per AAMA 501.4, *Recommended Static Test Method for Evaluating Curtain Wall and Storefront Systems Subjected to Seismic and Wind Induced Interstory Drifts* (AAMA 2017a), would be valuable.

A.2.8. Detailed Commentary on Re-Evaluation Area 6

Workshop participants voiced a desire for a comprehensive review of testing methods relative to contemporary envelope systems, materials, and locations. The workshop participants specifically suggested that various segments of the building envelope industry should be tasked with evaluating their existing test methods and developing a priority list for re-evaluation. However, the following selection of tests were highlighted for reassessment:

- ANSI/SPRI/FM 4435 ES-1, *Test Standard for Edge Systems Used with Low Slope Roofing Systems* (ANSI 2017);
- ANSI/SPRI GT-1, *Test Standard for External Gutter Systems* (ANSI 2022);
- ASTM E907, *Standard Test Method for Field Testing Uplift Resistance of Adhered Membrane Roofing Systems* (ASTM 1996); and
- Lab and field test methods for evaluating wind-driven rain resistance of glazed assemblies.

Of this list, tests ES-1 and GT-1 are most in need of review, due to the many roof failures being initiated with lifting of edge flashing, copings, or gutters.

Notably, these tests do not evaluate dynamic (cyclical) loading. Because these assemblies typically use light gauge metals, which are susceptible to failure due to dynamic loading, urgent testing may not adequately evaluate long-term performance.

ASTM E907 (ASTM 1996) is an important test for evaluation of in-place membrane roofs. However, it has several potential limitations. Finally, laboratory tests for wind-driven rain resistance are generally lacking and do not assess sufficiently high pressures in view of the workshop participants.

The enhancements to current envelope system design practices suggested here represent a notable departure from current practice and represent a substantial research initiative to fully implement. The workshop members suggest that industry groups with the support of NIST (or other similar organizations) carry out many of these enhancements. Certain enhancements, such as a requirement for structures to resist wind-driven rain, could be implemented by code changes with little to no direct cost to NIST.

A.3. Priority Research Need 3: Integrate Performance between Structural System and Cladding

Estimating the overall performance of building systems subject to extreme winds involves estimating the performance of both the structural and the envelope systems. Both systems are key to the overall integrity of the building. Because of the way in which wind damage occurs, the performance assessment of the two systems cannot be separated from one another. They comprise a two-way coupled system that is progressive in nature. For example, the dynamic net pressure wind demand on the building envelope components is coupled with the damage occurring in the envelope components themselves. In other words, a damage state that occurs in an envelope component can cause an opening in the building envelope, thus dramatically altering the internal pressure (which will, in general, become dynamic) and thereby changing the dynamic net pressure wind demand on any envelope component that is affected by the change of internal pressure. This can cause further damage and thus further changes in net pressure demands.

In addition, a damage state that occurs in an envelope component can change the capacity of the component to resist other wind demands. For example, envelope components are susceptible to several damage states related to excessive dynamic interstory drift. The occurrence of one of these damage states will, in general, affect the capacity of the envelope component to resist dynamic net pressure, water penetration due to concurrent rain, and wind-borne debris. Therefore, not only are wind demands often two-way coupled, but the damage states (which can be initiated by various wind demands, e.g., dynamic net pressure, dynamic drift, and wind-borne debris) are also coupled.

Note that wind damage is progressive in nature as it accumulates over the duration of the wind event, i.e., identifying a single instant during the wind event in which the damage occurs is not possible. This makes the simulation of wind damage a complex task. This is further complicated if propagating uncertainty through the coupled and progressive damage process is desired to estimate the probabilistic damage and loss metrics that are key to effectively communicating the advantages of PBWD to decision-makers and stakeholders who may have various technical and nontechnical backgrounds. These wind-specific aspects differentiate the development of probabilistic performance-based wind frameworks from those for performance-based earthquake engineering and, in particular, from the FEMA P-58 (FEMA 2016) procedure for the implementation of second-generation, performance-based earthquake engineering that is based on decoupling loss analysis from damage analysis, which in turn is decoupled from demand analysis, which is assumed independent of hazard analysis. This defines a Markov (Levin and Peres 2017) model that substantially simplifies the implementation of performance-based earthquake engineering.

Notwithstanding the differences between the evaluation of damage and loss between wind and seismic engineering, recently several researchers have taken the basic framework underpinning the FEMA P-58 procedure (FEMA 2016), i.e., the probabilistic framework developed by the PEER center (Yang et al. 2009), and applied it to performance-based wind design (Ciampoli et al. 2011; Spence and Kareen 2014). Notably, over the past five years, significant steps have been taken to explicitly account for the two-way coupling and progressive nature of wind damage accumulation and loss estimation (Bernardini et al. 2015; Chuang and Spence 2017; Cui and Caracoglia 2018; Judd 2018; Ierimonti et al. 2019; Mohammadi et al. 2019; Ouyang and Spence 2019; Cui and Caracoglia 2020; Ouyang and Spence 2020; Ghaffary and Moustafa 2021; Ouyang and Spence 2021a,b; Arunachalam and Spence 2022; Chuang and Spence 2022). Nevertheless, much work remains before probabilistic frameworks are available that enable the holistic estimation of wind damage and losses in terms of a class of wind-specific probabilistic metrics related to aspects such as repair costs, downtime (including impeding factors), injuries, and life-cycle costs. This list of metrics will likely expand as more fundamental research is carried out in this area.

In developing probabilistic frameworks that enable the estimation of probabilistic metrics related to the holistic performance of the building system (structural and nonstructural), a key concept that requires attention is the development of databases of fragility functions describing the damage susceptibility of typical structural and nonstructural (with particular emphasis on the envelope) components to extreme winds. Indeed, fragility functions are a key component of a probabilistic damage assessment framework. To date, fragility functions used in performance-based wind design frameworks have been based on simply adopting the fragility functions developed for seismic engineering. While this has allowed the concept of PBWD to be demonstrated, the next step is to begin creating wind-specific fragilities that account for the multiple demands a component will generally experience during a windstorm. For example, an envelope component may be exposed to interstory drift demands, net pressure demands, and impact demands coming from wind-borne debris. To bridge this gap, both experimental testing of typical wind components (structural and nonstructural) computational modeling are necessary for developing fragility functions (or surfaces) that relate wind-specific damage states (e.g., water penetration, wind-borne debris penetration, and cracking due to excessive pressure/drift) to component wind demands (e.g., wind-borne debris impact energy, dynamic net pressure, and dynamic wind drift). While characterizing the fragility functions of envelope components will likely provide the largest advances in the development and practical application of probabilistic PBWD frameworks, testing of structural components to wind-specific loading protocols and damage states is also fundamental.

A.4. Priority Research Need 4: Characterization of Engineering Properties of Thunderstorm and Tornado Wind Events

Thunderstorms and tornadoes cause the highest design wind speeds for significant parts of the building stock throughout much of the United States. However, current design processes are based on characteristics gathered from much larger-scale storms. Examples of characteristics that do not necessarily apply to thunderstorms and tornadoes are the assumptions of boundary-layer wind speed profiles and turbulence intensities (and length scales) that are a function of upwind terrain roughness. The characteristics are also assumed to be fundamentally self-stationary in terms of wind speed and directionality over time periods long enough to generate peak loads and responses of buildings and structures subject to resonant dynamic responses.

Current wind climate models used in engineering are based, with the exception of hurricanes, on historical data typically measured at 33 ft above ground. Since Automated Surface Observing System implementation this has become the standardized measurement height in the United States, and recorded data on both mean and gust wind speeds are available. Other meteorological data gathered at the same time can help identify the storm types associated with each wind record. However, full time histories are generally unavailable, and information is lacking on the variation of the wind speeds and directionality with height.

Some very limited data are available on tornado wind speed profiles, which were used in developing the current ASCE/SEI 7 Chapter 32 tornado profile (ASCE 2022). The data on which this profile was developed showed a very large degree of variation over the small number of measured tornado profiles (fewer than 30 field radar snapshots and eight radar averages) on which they were based. The existing data are not sufficient for the development of reliable engineering models. Large assumptions were made in the incorporation of what is intended to be a conservative profile in ASCE/SEI 7. Much less data are available on thunderstorms.

However, difficulties exist in gathering more field data. These are events that, as well as being far more limited in extent and duration, are not as forecastable as larger-scale storms such as hurricanes. So, measurement instrumentation must be distributed across areas where these storms are likely and where both temporal and spatial attributes of the storms can be captured. This type of work has been done, and continues to be executed, for hurricanes and larger-scale storms with the use of arrays of mobile masts that are deployed across regions in advance of incoming storms. However, these masts are of limited height and so only provide information in the lowest 100 ft or so of the storm profile. This may provide much of the information needed for low-rise buildings but not for high-rise structures. Larger masts with permanent instrumentation to greater heights are present in a few locations, such as at the Wind Engineering Research Field Laboratory at Texas Tech University. However, consistent data in severe storm events from locations like this are very limited, as the storm must pass over the site to be recorded. To obtain data higher above the ground, other mobile technologies will need to be employed.

To obtain the necessary information erecting masts is not possible, and hence nonphysical approaches will be required, such as radar, sonic detection and ranging (SODAR), and light detection and ranging (LIDAR). SODAR is a good technology for obtaining vertical profiles at a site but is limited in the extent of its measurements and frequency responses at greater heights. LIDAR is the technology that is most likely suited to most of this work as it can provide data at a greater range of heights and over a larger area. Where necessary, this can be supplemented by other instrumentation.

To develop engineering models of the windstorm characteristics, locating instrumentation in regions where this type of storm is common and then deploying it based on weather forecast and radar predictions will be necessary. In the case of thunderstorms, the goal must be to capture sufficient information on all types of thunderstorms. Most of the work to date has been on downburst events, but in recent years significant damage has occurred due to derecho-type events where lines of thunderstorms are translated on a gust front. Workshop participants posited that these derecho events may have structures more similar to boundary-layer events with higher wind speeds at upper levels, but little data are available to support this at the present time.

The end goal of this work will be to develop modifications to engineering models of wind characteristics that can be incorporated into codified methods to better assess the effects of different storm types on different building components. This will aid in increasing building resiliency while decreasing materials usage and construction costs.

To do this, developing alternative methodologies for physical or numerical predictions of the effects of different storm characteristics on building performance will be necessary, in addition to codified approaches. One main outcome will be the development of methods using existing technology and facilities to ensure that new knowledge can be widely implemented to improve design.

A.5. Priority Research Need 5: Characterize Hazard and Loads for Short and Long Return Periods

The assessment of structures for wind loads has traditionally been carried out using idealizations of the wind hazard, which involves idealizations of the local wind climate and the aerodynamic loads impacting the building. Current wind practices for characterizing these aspects are based on many years of accumulated knowledge and best practices that have been developed based on available knowledge, computational resources available to practicing engineering and researchers alike, and experimental methods. The resulting state of practice is generally based on assuming winds to be straight (i.e., no change of wind direction) and stationary (no change of wind speed) over a duration of 1 hour (a duration that can find its roots in the spectral gap in the Van der Hoven spectrum; Van der Hoven 1957).

While this situation reconciles relatively well with classic wind design approaches based on elastic response analysis, PBWD seeks to push the structure beyond the elastic state with the aim of producing innovative designs that are more sustainable without loss of reliability. Consequently, emphasis needs to be placed on modeling the local wind climate and the associated aerodynamic loads in greater detail, especially given that inelastic analysis, unlike elastic analysis, is path-dependent and therefore inherently sensitive to the evaluation of the wind loads impacting the building system. In practical terms, this means that the evolution of the wind direction and wind speed occurring during a wind event may well be critical in driving the performance of the system.

Even wind events associated with large weather fronts can have wind direction changes of up to 180 degrees during their passage (Cook 1982), and hurricanes and tornadoes are characterized by major swings in wind direction throughout their duration and major changes in wind speed. The capture of these phenomena requires a far more complex characterization of the underlying stochastic process governing the evolution of these events. Indeed, the assumption of a stationary and straight-line wind event greatly simplifies the probabilistic modeling of wind loads not only in an experimental setting, i.e., wind tunnels, but also in a computational setting. While experimental and computational efforts to explore approaches for better characterizing the nonstationarity and non-straight-line nature of wind events are growing in number, much remains to be done, especially if robust models and methodologies are to be defined for use with confidence in probabilistic frameworks for the implementation of PBWD.

From a climatological standpoint, another major issue associated with nonstationarity relates to climate change. Once again, the desire in PBWD to achieve designs that seek to push the building system to the limit of capacity through rational design procedures, ultimately leading to greater sustainability through reduced use of materials, requires the wind loads used in assessing performance to account for any likely increases over the next century or more (Esmaeili and Barbato 2022). The continued use of traditional approaches that are predicated on a stationary wind climate over long time horizons (i.e., maximum design wind speeds characterized by stationary probability distributions) risks leading to systems that are underdesigned if the wind hazard increases in intensity as many climate models predict. Therefore, investigating this issue as it pertains to PBWD is imperative.

A.6. Priority Research Need 6: Improve Understanding of Structural and Material Properties

Several factors including shape, stiffness, mass, and damping govern the dynamic response of tall buildings. A thorough understanding of structural and material properties, such as structural stiffness, material strength, and inherent damping, is essential for accurate structural modeling and analysis. This is true for both traditional design and for performance-based approaches.

Damping accounts for energy dissipation within the structure due to material and geometric nonlinearities. The damping level has been shown to vary with the material used in design, with the amplitude of the response, and with building height. In current structural modeling, damping is commonly applied using estimates and recommendations that have become standard best practice using values formulated from a very small research sample (Davenport and Hill-Carroll 1986; Kareem and Gurley 1996; NRCC 2015). The damping estimates used in practice vary significantly around the globe and among design firms. The selection of appropriate damping ratios for these analyses is often based on empirical relationships or simplified assumptions derived from past experiences, laboratory tests, and theoretical models. However, this approach may not accurately capture the changes in damping levels arising from wind-induced nonlinearities or other complex behaviors (Charney 2008). The possibility to experimentally determine damping characteristics from full-scale measurements has been investigated over the years (Jeary 1996; Tamura and Suganuma 1996; Kijewski-Correa et al. 2006; Guo et al. 2012). Although there are many measurements of damping under low wind speeds, there are very few under the wind speeds considered for service conditions, let alone ultimate conditions (Smith 2016). Several damping models have been proposed for damping estimation from measurement data; however, many in the literature are inappropriate for tall buildings (Bashor et al. 2005). Actual energy dissipation in buildings is very complex and has been observed as being amplitude-dependent, deformation history–dependent, and frequency-independent (Spence and Kareem 2014).

In addition to research aimed at better understanding the damping levels assumed in design, frequencies derived during structural analysis in the design stage require further study because they often differ from the actual frequencies of motion measured in buildings. In most cases, full-scale studies reveal higher frequencies (indicating stiffer structures) than those assumed in the design. Typically, this would result in a reduced resonant wind load, but in some cases negative effects can occur at MRIs of interest in the assessment of performance goals. However, for very tall or very slender buildings, the increased frequencies may result in vortex-induced vibration being exhibited under higher wind speeds and thereby the wind load effect increasing beyond that considered in design. In some rare instances, frequencies measured in taller buildings are lower than the design frequencies. This has the inverse effect to that previously described. The mismatch between design frequencies and full-scale frequencies has been attributed to multiple factors, such as connection detailing, modeling assumptions (e.g., rigid diaphragms or levels of cracking), material properties, and foundation stiffness.

The development of advanced monitoring and sensing techniques, such as structural health monitoring (SHM) systems, can provide real-time data on structural performance and material properties during and after extreme loading events. The integration of SHM systems into the design process can help engineers better understand the actual behavior of structures under various loading conditions.

In summary, undertaking a wide-reaching, full-scale SHM monitoring campaign that includes the deployment of suitable motion-monitoring devices in taller buildings (either a short-term storm-chasing campaign, or a long-term campaign) would enable better assumptions to be made in the design stage. Better assumptions in the design stage lead to a more accurate assessment of the wind load effect and an enhanced ability to represent taller buildings in nonlinear modeling approaches used in PBWD.

A.6.1. Material Testing to Further Develop Understanding of Material Properties

Material properties and component strength are typically determined through laboratory testing of small-scale specimens, which may not fully represent the complexities of full-scale structures. Factors such as manufacturing processes, aging, and environmental conditions can introduce variability in material properties, potentially affecting the accuracy of structural performance predictions. One commonly used approach to address these complexities is the application of stiffness modifiers. Stiffness modifiers have long been used in elastic analysis methods to capture the effective stiffness of cracked concrete elements, permitting the adoption of simple linear material models that neglect the initial uncracked stiffness of concrete. However, the elastic stiffness modifiers applied to core walls, coupling beams, basement walls, and diaphragms vary widely in practice.

Despite the extensive laboratory testing and research conducted over the past few decades on material properties and nonlinear behaviors under loading protocols, most of these studies have focused on short-duration, high-intensity loads typical of seismic zones. Very little research has looked into long-duration loading protocols that are more representative of wind loading (Abdullah et al. 2020, 2021). Considering that wind events can last for several hours, this could potentially induce a distinct type of response in components exhibiting nonlinear behavior and, in some cases, may lead to low cycle fatigue.

Workshop participants suggest that researchers address these limitations and uncertainties related to material properties under wind loading protocols by developing comprehensive testing regimes, similar to those undertaken in recent years for seismic loading (Golestani et al. 2023), to better understand the impact of nonlinear behavior in structures subjected to wind loads. This can be achieved through advanced experimental techniques, such as large-scale testing and hybrid testing, and computational methods that better characterize material behavior, including nonlinearities under various loading conditions.

A.6.2. Standardization of Assumptions across Design Firms

Several years ago, the American Concrete Institute undertook a study to survey design firms across the United States that were designing tall buildings at that time. The survey reviewed typical assumptions made in the design of this building typology: levels of cracking assumed, foundation stiffness included, levels of damping assumed, etc. The results were staggering, demonstrating the lack of consistency in the assumptions made. Given that accurate characterization of wind loading and responses hinges on these fundamental assumptions, clear value exists in not just refining the understanding of the dynamic response of taller buildings under wind loads but also in standardizing a baseline for assumptions to be included in design. Even if these assumptions need to be parametric or scenario-based bringing forward some consistency to the approach has value.

Potentially quantifying the impact of current simplified (or conservative) assumptions on predicted wind effects would provide engineers with a better understanding of the underlying uncertainty when employing these assumptions. Comparative analysis between simplified models and those derived from more advanced models and experimental data can help identify areas where simplified assumptions may lead to significant discrepancies in structural performance predictions.

The development of probabilistic models for material properties and damping levels could be another avenue for enhancing the reliability of structural designs. These models can account for the inherent variability and uncertainties in material properties and damping levels, allowing designers to assess structural performance under possible scenarios. Incorporating these findings into the design process will allow designers to account for variability in material properties and damping levels, resulting in more accurate structural performance predictions and optimized building designs.

A.7. Priority Research Need 7: Improve Physics-Informed, Computationally Efficient Methods for Nonlinear Analysis of Wind Response over Long-Period Durations

A key foundation of PBWD is the potential to design buildings that take full advantage of the inherent capacity of the structural system through explicit nonlinear analysis. This will lead to systems with not only increased sustainability and design innovation due to greater material efficiency and freedom from prescriptive requirements but also increased reliability due to explicit modeling of system response over a full range of wind events. Central to this vision is the possibility to estimate system performance by evaluating many probabilistic metrics associated with wind-specific design variables. This will generally include traditional metrics, such as structural system and component system reliability, and new metrics, such as repair costs, downtime, and life-cycle costs.

Within the paradigm of PBWD, all these metrics require the estimation of inelastic responses over suites of dynamic wind load histories derived from appropriate wind tunnel records or stochastic wind load models. While estimating probabilistic metrics through specialized algorithms and schemes for efficient propagation of uncertainty is possible and encouraged, hundreds, if not thousands, of nonlinear time history analyses are generally required. In recognizing that typical windstorms have durations on the order of hours, the computational burden required for propagating uncertainty and estimating the probabilistic metrics becomes clear. It is important to underline how the use of nonlinear analysis will make the problem path-dependent, i.e., the response used to estimate the metrics will depend on the record-to-record variability inherent to different wind load histories. This eliminates the ability to apply many of the general methods used for probabilistically characterizing the response of wind-excited systems that are founded on an elastic system and therefore path-independent responses.

These issues have been recognized recently with various approaches proposed for modeling the inelastic response of structural systems subject to long-duration wind loads. However, most work to date has primarily focused on establishing the feasibility of carrying out nonlinear wind analysis and is based on direct integration approaches developed in seismic engineering. While recent advancements have occurred in this area—for example, the suite of methods that combine direct stochastic simulation with dynamic shakedown (Chuang and Spence 2019, 2020, 2022), the approaches based on reduced order models (Wu 2013; Wu and Kareem 2015; Zhao et al. 2019; Li et al. 2021; Li and Spence 2022a,b,c), and the methods that leverage machine learning (Li and Spence 2022a; Preetha Hareendran et al. 2022)—much work remains to solve the problem of rapidly evaluating the nonlinear response of wind-excited structural systems in ways that are both robust to the complexity of the computational models that describe the nonlinear response of systems and compatible with general purpose uncertainty propagation schemes. Areas with promises in this respect are those related to metamodeling/surrogate modeling, reduced-order modeling, methods for leveraging massive parallelization through GPUs and supercomputing, and methods that leverage artificial intelligence (e.g., physics-informed and/or data-driven machine learning).

While the physics-based reduced-order models have performed well in the nonlinear dynamics' simulations of selected structures, the numerical and/or experimental identification of their parameters remains quite challenging (Wu 2013; Wu and Kareem 2015). However, data-driven reduced-order models have recently become a popular choice for modeling complex nonlinear dynamics, due partially to the emergence of numerous well-designed training/learning algorithms (e.g., Peherstorfer and Willcox 2015). Among the data-driven models, the artificial neural network (ANN) associated with the rapid development of machine learning techniques shows great promise in modeling nonlinear structural responses (Wu and Snaiki 2022). While ANN models have been used extensively to analyze the response of structures, their application to tall buildings has been limited due to the large number of degrees of freedom involved, which makes training the models computationally intensive. Preetha Hareendran et al. (2022) recently investigated the use of a long short-term memory (LSTM) architecture to predict the story displacement and acceleration of a 150 m tall steel building under wind loads while Li and Spence (2022a,b,c) combined LSTM architectures with reduced-order modeling in defining a global LSTM network capable of predicting the time history response of all degrees of freedom of high-dimensional systems from a single LSTM network. However, further research is needed to fully explore the feasibility and accuracy of data-driven methods for tall buildings.

While ANN models have become popular for structural analysis, they are often viewed as "black-box" models due to their lack of interpretability and reliance on labeled data. This can lead to reduced accuracy and generalizability, especially when data are scarce, incomplete, or noisy. To address this limitation, scientific principles such as partial differential equations and boundary conditions can be incorporated into deep neural networks to ensure compliance with physical laws. Wang and Wu (2020) proposed a knowledge-enhanced deep learning model for wind-induced nonlinear structural dynamic analysis, leveraging machine-readable knowledge in the form of physics-based equations and semi-empirical formulas to enhance the regularization mechanism during deep network training.

To efficiently estimate nonlinear structural responses, reduced-order modeling methodologies using either physics-based analytical models or data-driven metamodels have been widely employed. Wu (2013) utilized the truncated Volterra model to predict nonlinear wind-induced bridge deck response. The statistical linearization approach, where the nonlinear system is represented by an equivalent linear system, has been utilized by Di Matteo et al. (2014), Feng and Chen (2017; 2018), and Saitua et al. (2018). Recently, Zhao et al. (2019) combined the proper orthogonal decomposition with statistical linearization to efficiently estimate nonlinear structural response under nonstationary excitation. Li and colleagues (Li et al. 2021; Li and Spence 2022a,b) effectively combined proper orthogonal decomposition for model order reduction with both nonlinear autoregressive exogenous models and LSTM networks for the time history response estimation of wind and seismically excited multi-degree-of-freedom systems.

A.8. Priority Research Need 8: Static Pushover for Wind Engineering to Quickly Evaluate Nonlinear Structural Performance

Static pushover analysis, developed in seismic engineering, aims to efficiently approximate structural response under external dynamic excitation. Saiidi and Sozen (1981) simplified a structure to a single-degree-of-freedom (SDOF) system and applied incremental static loading to estimate the structural capacity. Krawinkler and Seneviratna (1998) provided a comprehensive review of SPO and pointed out its assumptions: a) a single mode controls the response of the structure and b) the mode shape remains constant throughout the time history response. Despite these two strong assumptions, several studies have shown that SPO can provide good predictions of the structural responses for multi-degree-of-freedom (MDOF) structures (Lawson et al. 1994; Miranda and Bertero 1994).

In the mid-1990s, the rapid development of performance-based seismic design required an efficient method to assess structural performance. The seismic engineering community widely accepted SPO at that time, such as FEMA 273, *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* (FEMA 1997), and ATC-40, *Seismic Evaluation and Retrofit of Concrete Buildings* (ATC 1996). Although SPO has limitations in applying static analysis to estimate the dynamic response, the large computational demands, modeling procedure, and software development limited the nonlinear response history analysis at an early time. SPO limitations mainly come from its inherent inability to capture structural dynamic properties such as the following:

- Multi-mode dynamic behavior, which limits SPO to the analysis of low-rise buildings or buildings controlled by first mode response;
- Materials' and components' degradation and cyclic behavior;
- Single failure mode; failure mode may be different for structures under different time history loads, while SPO can only provide single failure mode;
- Rate-dependent effects (interactions between structure and soil, structure and dampers, and structure and isolation system); and
- Characteristics of different external excitations (spectral shape, duration).

To overcome these limitations, research has been done in various aspects. To capture the multi-mode dynamic behavior, Chopra and Goel (2002) proposed the modal pushover analysis (MPA) procedure, in which different lateral load patterns determined by different modal responses are used to develop SPO separately and then combined using the modal superposition strategy to develop the final structural behavior. The MPA has attracted attention in recent years, and much work has been done to validate the method using three-dimensional and unsymmetric structures (Reyes and Chopra 2011a,b), to validate the application to buildings with dampers (Hassan and Reyes 2020), and to extend the application to bridges (Bergami et al. 2020). However, the theory of the application of modal superposition in nonlinear analysis is still not rigorous.

To capture material degradation, Fajfar and Gašperšič (1996) proposed the N2 method to estimate cumulative damage using the Park-Ang damage model with the structural maximum static response and yield response. In recent years, the cyclic pushover method has also been proposed with an incremental cyclic quasi-static loading protocol applied to the structure to account for material degradation (Panyakapo 2014). However, the degradation property is highly path-dependent, and the accuracy of the aforementioned methods need further examination.

With improvements in computational capacity, nonlinear response history analysis can be more routinely applied in engineering practice. Currently, SPO is applied in engineering practice mostly to a) verify nonlinear analysis models before running a nonlinear dynamic analysis and b) interrogate a structure to understand its nonlinear behavior.

While incremental dynamic analysis (Vamvatsikos and Cornell 2002), also known as dynamic pushover analysis, is widely used for structural fragility analysis, the computational demand for IDA remains a challenge. In FEMA P-58 (FEMA 2016), static pushover to incremental dynamic analysis (SPO2IDA) is suggested as an alternative way to estimate IDA curves with high efficiency. In this method, the SPO curve is simplified to several linear shapes (bilinear, trilinear, or quadrilinear) and described with parameters that can be used to fit the IDA curves. Good accuracy is shown with a validation using an SDOF structure (Vamvatsikos and Cornell 2006), and this method has also been applied to MDOF structures (Vamvatsikos 2002). A static pushover to fragility analysis tool was also developed based on SPO2IDA (Baltzopoulos et al. 2017). As for the MDOF structure, to account for the high mode effects, SPO2IDA was also combined with MPA (Han and Chopra 2006).

In wind engineering, SPO is not yet commonly used. Most SPO applications have focused on analysis of transmission towers and offshore turbines (Bienen and Cassidy 2006; Banik et al 2010). With the increasing attention on PBWD, research on performance assessment for structures under wind loads has been developed and SPO has usually served as one of the assessment steps for tall buildings (Mohammadi et al. 2019; Ghaffary and Moustafa 2021; Preetha Hareendran et al. 2022). Huang and Chen (2023) applied modal pushover to wind analysis for a 60-story high-rise steel building. The displacement-controlled loading pattern was simply used in their pushover analysis, without capturing stiffness degradation of the structure.

To apply the IDA approach to wind engineering for fragility analysis, challenges arise due to the significantly longer duration of wind time histories (typically several hours) compared with seismic records (typically on the order of 60 seconds). Therefore, practical methods need to be developed for efficient fragility analysis of structures under wind loads, as required by the Prestandard (ASCE/SEI 2023). Investigating the implementation of the SPO method to wind engineering in detail is crucial, as this approach shows promise for fragility analysis of structures.

To effectively apply SPO to wind engineering, several key research needs are identified as follows.

Determination of the loading profile: During SPO analysis, the determination of the lateral loading profile needs careful investigation. In FEMA 356 (FEMA 2000), two groups with five methods are proposed for the determination of lateral loading for seismic analysis. Group 1 is mainly based on the modal of the structure and provides three methods, namely the loading distribution proportional to a factor associated with story height, mass, and the building's natural frequency; the loading distribution proportional to the shape of the fundamental mode; and the loading distribution proportional to the story shear distribution calculated by combining modal responses from a response spectrum analysis of the building. Group 2 contains two methods, namely the uniform loading distribution (or the distribution proportional to the story mass) and the adaptive loading distribution that changes as the structure is displaced. In wind engineering, Ghaffary and Moustafa (2021) developed the SPO to wind analysis for a 20-story steel building with the loading distribution proportional to a value associated with story height, mass, and the building's natural frequency (Group 1, Method 1), which is the most widely used method in seismic analysis. However, most of the wind SPO developed for tall buildings directly use and scale the equivalent static wind load from the ASCE/SEI 7 (ASCE 2022) directional procedure based on Davenport's gust loading theory (Davenport 1967; Mohammadi et al. 2019; Preetha Hareendran et al. 2022). The purpose of developing the equivalent static wind load is to use the static method to predict the maximum dynamic response. Further validation is needed to demonstrate that the corresponding deformation can represent the lateral vibration mode, especially when structures enter the nonlinear regime.

Interaction of the along wind and crosswind: Crosswind effects can be significant for tall buildings. The general SPO procedure and post-processing method only takes a single direction load into consideration. More research is required to develop the multi-direction SPO for wind engineering, especially considering that the quasi-steady assumption cannot be used in crosswind and that higher-mode contributions may need to be considered.

Development of PBWD-specific performance assessment criteria using SPO: In the research using SPO to develop wind analysis, the corresponding performance assessment is still based on the seismic criterion. A specific performance assessment criterion to evaluate structural performance objectives for wind engineering under SPO analysis is needed.

Transformation from wind SPO to wind IDA: The development of a procedure to transform from wind SPO to IDA, as in the FEMA P-58 (FEMA 2016) methods for seismic engineering, provides an efficient way to obtain the fragility curves (Vamvatsikos and Cornell 2006). To develop this procedure, the stiffness degradation in wind SPO and the influence of the directionality consideration of wind in IDA needs to be further examined.

A.9. Priority Research Need 9: Development of Wind Loading Protocol for Experimental Quantification of System Performance in Wind

In the analysis of buildings, the structural response is typically simulated using macro-elements at the component level. Accurate characterization of component behavior relies heavily on the calibration of the strength-deformation relationship, which is often informed by component testing. When structures enter a nonlinear regime, the strength and deformation capacities of their components depend on cumulative damage, which means that a component's past loading history is retained in its permanent memory and can influence its response to subsequent loading. As such, the loading path becomes a critical factor in the analysis of structures. Ideally, to accurately capture the real behavior of components under external loads such as seismic or wind, component testing should replicate the loading path experienced in the actual structure. However, the loading protocol aims represent different wind records or seismic records in the real world, so two problems result when developing the loading protocols on component testing: a) how to determine the cycles, amplitude, and sequence of cycles for the loading protocol and b) how to generalize the results of one experiment under a predetermined loading history.

Krawinkler (1996) developed a loading protocol for structures under seismic loads. In this study, a set of SDOF systems with different natural frequencies were used as prototype buildings and a set of 15 ground motions were selected to develop the response history analysis. From the response history analysis results, the statistical method can be applied to determine the number of cycles, inelastic excursions, and amplitude of deformation and then form a generalized loading protocol. Generally, the loading protocol should also be material based, which Krawinkler does not mention. With a similar concept, SEAOSC/SAC (2000) developed the widely used SAC Steel Project loading protocol for steel beam-to-column assemblies. CUREE (2002) developed the Consortium of Universities for Research in Earthquake Engineering loading protocol for wood frame shear walls.

In wind engineering, very limited work has been done to develop a component test under wind loading protocol. One important reason is the linear structural response limitations of the MWFRS in the codes and standards for wind design. For the envelope system, Kopp et al. (2012) introduced a pressure-loading actuator and used the scaled recorded wind pressure in wind tunnel tests to study the performance of the toe-nailed roof-to-wall connections for low-rise wood buildings. The pressure-loading actuator can also be applied to other envelope components (e.g., doors and glass panels).

With the development of PBWD, the nonlinear response of deformation-controlled elements is allowed with a DCR limitation of 1.5. To develop an experimental test for coupling beams, which are highly deformation-controlled components, Abdullah et al. (2020) proposed a method to develop loading protocols. In this study, the amplitude of the loading protocol is determined with DCR limitations of <1.5, and the number of cycles is determined with a wind tunnel test of a tall concrete building. Note that the developed loading protocol may not meet the requirement of generalization because it comes from only one wind tunnel test scenario. Hence, whether the protocols currently used are more or less demanding compared with a rationally developed testing protocol that reflects realistic wind loading histories on buildings is unknown. To this end, establishing a basic procedure to develop the loading protocols for extreme wind performance testing of deformation-controlled MWFRS members is important. In Wang (2021), hurricane events are selected as the typical extreme winds to develop the component test loading protocol design framework. In the proposed framework, the wind hazard, building aerodynamics, and structural dynamics are discussed in sequence without consideration of structural motion-induced effects. Loading protocols for hurricane winds are determined based on the obtained statistics of structural member demand time history.

To confirm the wind loading protocols used in component tests, several research needs are identified as follows.

Simulation-based wind loading protocol design: Validation of current wind loading protocols is required because they are mostly designed case by case. For instance, the design is usually based on the numerical simulation of a certain case building under a specific wind time history. A more comprehensive approach using structures with various natural frequencies and wind time histories that can represent the statistical properties of wind hazards needs to be developed for a rational wind loading protocol design. Many computation realizations need to be generated using the high-fidelity numerical model with different materials and/or building types.

Material-specific loading protocols design: Buildings constructed with different materials may have different response characteristics at the component level, and the designed cycles and amplitude should be varied in accordance with construction materials. Hence, the design loading protocol should be material-specified, and high-fidelity models provide a promising way for validation purposes.

Wind hazard–specific loading protocol design: The current consideration of wind loading protocols focuses on large-scale winds (e.g., tropical cyclones), while characteristics of non-synoptic winds, such as thunderstorms and tornadoes, are usually not accounted for. The unique characteristics of these non-synoptic winds require specific wind loading protocols for the component tests.

A.10. Priority Research Need 10: Economic Study to Identify Existing Buildings at Risk

As stated in earlier sections of this report, one impetus for this work with NIST is the extensive casualties and property losses that have occurred over the last several decades due to damaging hurricanes, tornadoes, and other wind events affecting the United States. More than half of these losses were uninsured and resulted from large-scale wind events impacting communities with a high percentage of un-engineered buildings. Delivering to these communities means and methods to improve the performance of these built structures could reduce both casualties and property loss. Starting from improved performance and ultimately moving to enhanced resilience within these communities is part of the overarching goal. Resilience provides communities the ability to adapt to changing conditions and to withstand and recover positively from large-scale wind events.

Economic studies on the impact of strong wind events such as hurricanes and tornados to the built environment are crucial for understanding the potential financial consequences of such events and guiding decision-makers in allocating resources for adaptation, mitigation, preparedness, and recovery efforts. Comprehensive analysis of the economic costs associated with natural hazards can inform policy development, help prioritize investments, and enhance the resilience of communities to withstand disasters. A clear understanding of the financial impact from wind damage could also help stakeholders establish a realistic performance objective at the onset of design and/or result in building investments in performance improvements and adaptation in securing insurance against windstorms.

Over the years, several studies have focused on the economic cost of individual events. For instance, the economic impact of Hurricane Sandy, which struck the United States in 2012, was extensively researched (de Moel et al. 2013; Strauss et al. 2021). Initiatives like STEER also produced reports that detail the damages observed on site after Hurricane Michael (Alipour et al. 2018), Hurricane Ida (Prevatt et al. 2021), Texas and Louisiana tornadoes (Roueche et al. 2022), Hurricane Ian (Prevatt et al. 2022), and others. In terms of tornado events, Prevatt et al. (2012) summarized the post-tornado building damage surveys that were carried out after the 2011 tornado outbreak in the United States. These studies examined the financial implications of this significant event and provided valuable insights into the associated direct and indirect costs. However, few studies tackle the economic impacts of strong wind events on a national level with a focus on vulnerable communities.

The FEMA National Risk Index is an innovative tool that aims to address this gap by providing a comprehensive analysis of the risk associated with various natural hazards across the United States (Zuzak et al. 2022). The National Risk Index estimates the expected annual losses for multiple hazards, including strong winds and tornadoes. The expected annual losses for strong wind events are calculated by considering the frequency and intensity of strong wind events, the vulnerability of exposed assets (such as buildings and infrastructure), and the value of these assets. Historical wind data, building inventories, and vulnerability curves are used to derive the expected annual losses at a county or census track level for strong wind events. Using this level of risk refinement and understanding the communities at greatest risk for economic loss, programs could be devised to address performance improvements for the existing building stock in these locals.

By understanding the distribution of building stock across the nation, the societal benefits of different components of PBWD can be assessed in relation to the predominant storm types. For example, in major cities along the hurricane coast with a high density of highly engineered tall buildings, the economic and sustainability benefits of PBWD may be shown to developers to encourage its use in the design of MWFRS components, while concurrently increasing the reliability and resiliency of the building envelope. In inland regions, where thunderstorms or tornadoes may dominate design wind effects, PBWD efforts may be better focused on building envelopes to increase resiliency and reduce losses following severe wind events. This knowledge can be used to increase the use of PBWD by educating Authorities Having Jurisdiction about its benefits and potentially provide financial incentives through insurers to adopt more detailed wind engineering of new buildings to reduce risk of losses.

Recognizing that the greatest losses, both financially and from a community perspective, often occur in vulnerable, nonengineered low- and medium-rise housing communities situated at the periphery of cities is also key. The need for improved connectivity and performance across all these layers of a city must remain a key focus in adopting PBWD approaches. All three layers need to recover post event, and therefore a holistic and broad-thinking approach to PBWD is necessary to address the varying needs of diverse communities. By involving local governmental organizations in this effort and in providing information about their building stock, the opportunity exists to engage a much larger group of stakeholders in advancing PBWD for overall societal benefit.

Appendix B. February 2023 Reston, Virginia Workshop

B.1. Workshop Agenda

SEI-NIST Performance-Based Design Workshop
DATE: Feb. 23–24, 2023
LOCATION: ASCE Bechtel Conference Center;
1801 Alexander Bell Drive, Reston, VA 20191

Workshop Agenda: FINAL_v3
Presiding: Workshop Director Don Scott, S.E., P.E., F.SEI, F.ASCE

Day 1: Thurs., Feb. 23; 9:00 am–5:00 pm Eastern

GENERAL SESSION

9:00 am–9:30 am: Welcome

- Purpose, Goals, and Workshop Agenda
    - Opening Remarks from Long Phan, Ph.D., P.E., M.ASCE, F.ACI; NIST
    - Welcome from Laura Champion, P.E., F.SEI, F.ASCE; ASCE/SEI
- Introductions

9:30 am–12:00 pm: State-of-the-Art Presentations/Panel Discussions

- **Case study: 321 W 6th Street–Practical Implementation of the Prestandard for Performance-Based Wind Design**
  Kevin P. Aswegan, P.E., S.E.; Senior Associate, Magnusson Klemencic Associates
- **Case studies: Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design**
  Seymour M.J. Spence, Ph.D.; Associate Professor, University of Michigan
- **Case studies: Structural Wall and Coupling Beam Component Testing in Support of Performance-Based Wind Design**
  John Wallace, Ph.D.; Professor, University of California, Los Angeles
- **Panel discussion: The paradigm shift to PBWD–how can we get there and where could it go wrong?**
  Moderator: Melissa Burton, Ph.D., C.Eng; Principal, Arup

  Panelists:
    - David Bott, P.E., S.E., AIA; Principal, Heintges Consulting Architects & Engineers
    - Xinzhong Chen, Dr. Eng.; Professor, Texas Tech University
    - Mehedy Mashnad, Ph.D., P.E., Principal, Walter P. Moore
    - Roy Denoon, Ph.D., Senior Principal, CPP Wind Engineering Consultants

BREAKOUT SESSIONS

12:30 pm–4:45 pm: Five concurrent sessions

1. Wind climate characteristics, Moderator Roy Denoon
2. System reliability, Moderator Seymour M.J. Spence
3. Wind-structure interaction, Moderator Melissa Burton
4. Structural analysis techniques, Moderator Teng Wu
5. Design, Moderator Russell Larsen

4:45 pm–5:00 pm: Reconvene

Summary and Adjourn Day 1

Day 2: Fri., Feb. 24; 8:00 am–12:00 pm Eastern

GENERAL SESSION

8:00 am–8:15 am: Welcome

Purpose and Goals of Day 2

8:15 am–11:45 am: Report-Out and Prioritization

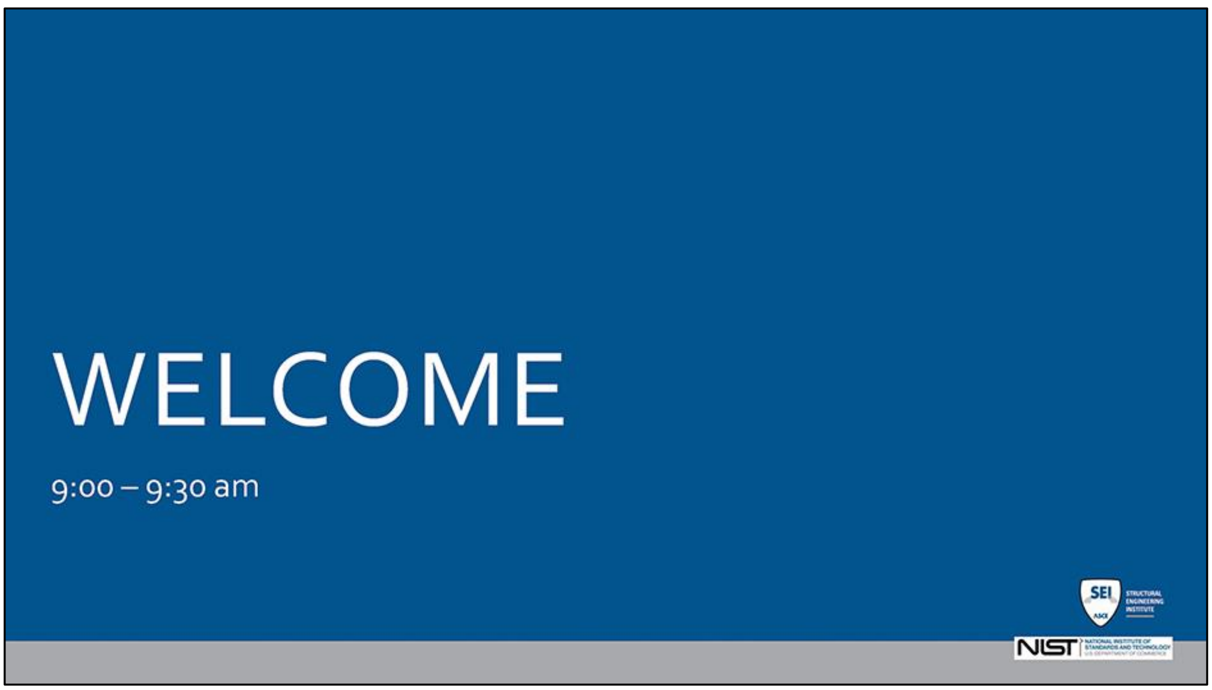
- Breakout Session Report-Out:
    1. Wind climate characteristics
    2. System reliability
    3. Wind-structure interaction
    4. Structural analysis techniques
    5. Design
- Moderated Panel Discussion of Workshop Steering Committee
- Prioritization of Research Needs

11:45 am–12:00 pm: Conclusion

Summary and Adjourn Day 2

12:00 pm–4:00 pm: Workshop Steering Committee Meeting

B.2. Workshop Presentations



GENERAL SESSION

Workshop Director:
Don Scott, P.E., S.E., F.SEI, F.ASCE

- **Purpose**
- **Goals**
- **Agenda**
  - *Digital Package*


12:00pm-12:30pm – WORKING LUNCH PROVIDED

SEI-NIST
Performance Based Design Workshop
DATE: Feb. 23-24, 2023
LOCATION: ASCE Bechtel Conference Center;
1801 Alexander Bell Drive, Reston, VA 20191

Workshop Agenda – FINAL_v3
Presiding: Workshop Director Don Scott, S.E., P.E., F.SEI, F.ASCE
Link to Digital Materials Package (password: pbd) - PBD Workshop Materials

Day 1: Thurs., Feb. 23; 9:00am – 5:00pm Eastern
8:00am-9:00am – CONTINENTAL BREAKFAST PROVIDED

GENERAL SESSION
9:00am-9:30am – Welcome
- Purpose, Goals, and Workshop Agenda
  - Opening Remarks from Long Phan, Ph.D., P.E., M.ASCE; NIST
  - Welcome from Laura Champion, P.E., F.SEI, F.ASCE; ASCE/SEI
- Introductions

9:30am-12:00pm – State of the Art Presentations/Panel Discussions
- **Case study: 321 W 6th Street - Practical Implementation of the PreStandard for Performance-Based Wind Design**
  Kevin P. Aswegan, P.E., S.E.; Senior Associate, Magnusson Klemencic Associates
  [30 mins. = 20 mins PPT + 10 mins Q&A]
- **Case studies: Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design**
  Seymour MJ Spence, Ph.D.; Associate Professor, University of Michigan
  [25 mins. = 15 mins PPT + 10 mins Q&A]

15-minute COFFEE BREAK
- **Case studies: Structural Wall and Coupling Beam Component Testing in Support of Performance-Based Wind Design**
  John Wallace, Ph.D.; Professor, University of California, Los Angeles
  [25 mins. = 15 mins PPT + 10 mins Q&A]
- **Panel discussion: The paradigm shift to PBWD – how can we get there and where could it go wrong?**
  Moderator:
  Melissa Burton, Ph.D, C.Eng, Principal, Arup
  Panelists:
  - David Bott P.E., S.E., AIA; Principal; Heintges
  - Xinzhong Chen, Dr. Eng.; Professor, Texas Tech University
  - Mark Lavery BEng, CEng, FIStructE; Director, BuroHappold
  - Chris Letchford, Professor and Department Head, Rensselaer Polytechnic Institute

  [40 mins. = 30 mins PPT + 10 mins Q&A]

PURPOSE AND GOALS

Performance-Based Wind Design Methodologies

1. Review of the Current State-of-the-Art of Performance-Based Wind Design
2. Identification of Research Needs and Prioritization for Standardization in Practice.

GENERAL SESSION

- **Opening Remarks:**
  Long Phan, Ph.D.; Group Leader, NIST

- **Welcome:**
  Laura Champion, P.E., F.SEI, F.ASCE; ASCE Managing Director of Global Partnerships and Director of SEI

SEI-NIST Performance Based Design for Wind Workshop

February 23-24, 2023 – ASCE, Reston, Virginia

Long Phan, Ph.D., P.E., F.ACI, M.ASCE
Leader, Structures Group
Engineering Laboratory, NIST
long.phan@nist.gov
https://www.nist.gov/people/long-phan

NIST ENGINEERING LABORATORY

SEI STRUCTURAL ENGINEERING INSTITUTE

Welcome and Thanks!

- To SEI (Jennifer Goupil, Don Scott, Bianca Augustin, Laura Champion): For organizing, supporting, and serving as Project Manager and Workshop Director
- To all members of Workshop Steering Committee (Roy Denoon, Seymour Spence, Melissa Burton, Teng Wu, Russell Larsen) and scribes: For your help with brainstorming, formulating, conducting and recording the workshop, and
- To all workshop participants who are the experts and practitioners in the wind engineering community: For participating and providing your expertise.

NIST ENGINEERING LABORATORY

SEI-NIST Performance Based Design for Wind Workshop
February 23-24, Reston, Virginia

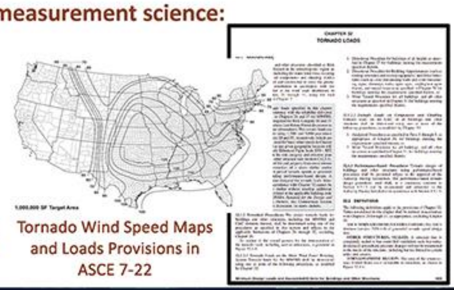
SEI STRUCTURAL ENGINEERING INSTITUTE ASCE

Motivation and Goals

- **NIST Overarching Goal:**
  To reduce the risk and enhance the resilience of buildings, infrastructures, and communities to wind hazards through advances in measurement science.

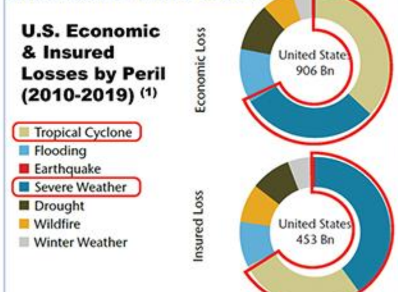
Examples of advances in measurement science:

Basic Wind Speed Maps for non-tornadic extratropical storms regions in ASCE 7-16



Tornado Wind Speed Maps and Loads Provisions in ASCE 7-22

Motivation: Wind Losses



(1) Data: Aon, Catastrophe Insight (2019)

- Wind is a major driver of damage to the built environment!
- Most wind fatalities occurred inside buildings

NIST ENGINEERING LABORATORY

SEI-NIST Performance Based Design for Wind Workshop
February 23-24, Reston, Virginia

SEI STRUCTURAL ENGINEERING INSTITUTE ASCE

Motivation and Goals

Workshop Goals:

- To review current state-of-the-art and identify research needs for development, validation, and utilization of PBWD methods for designing structures for wind loads, and
- To provide information for development of a focused NIST wind research roadmap for advancing the application and standardization of PBWD methods for safe and economical design of structures.

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February 23-24, Reston, Virginia

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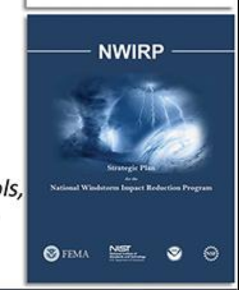
Process



- Responding to identified research needs/gaps in current knowledge:
  - R&D Roadmap for Windstorm and Coastal Inundation Impact Reduction
    - **Recommended R&D Topics**:
      - Performance levels and acceptance criteria for wind hazards;
      - PBWD analysis procedures for nonlinear system behavior;
      - Cyber-based tools to support PBWD; and
      - Measurement of windstorm resilience and benefits of PBWD
  - Strategic Plan for the National Windstorm Impact Reduction Program (NWIRP)
    - **Strategic Priority #4**: Develop PBD for Windstorm Hazards
      - Public Law 114-52: NWIRP to *"support the development of PB engineering tools, and work with appropriate groups to promote commercial application of such tools, including wind-related model building codes, voluntary standards, and construction best practices"*

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SEI-NIST Performance Based Design for Wind Workshop
February 23-24, Reston, Virginia

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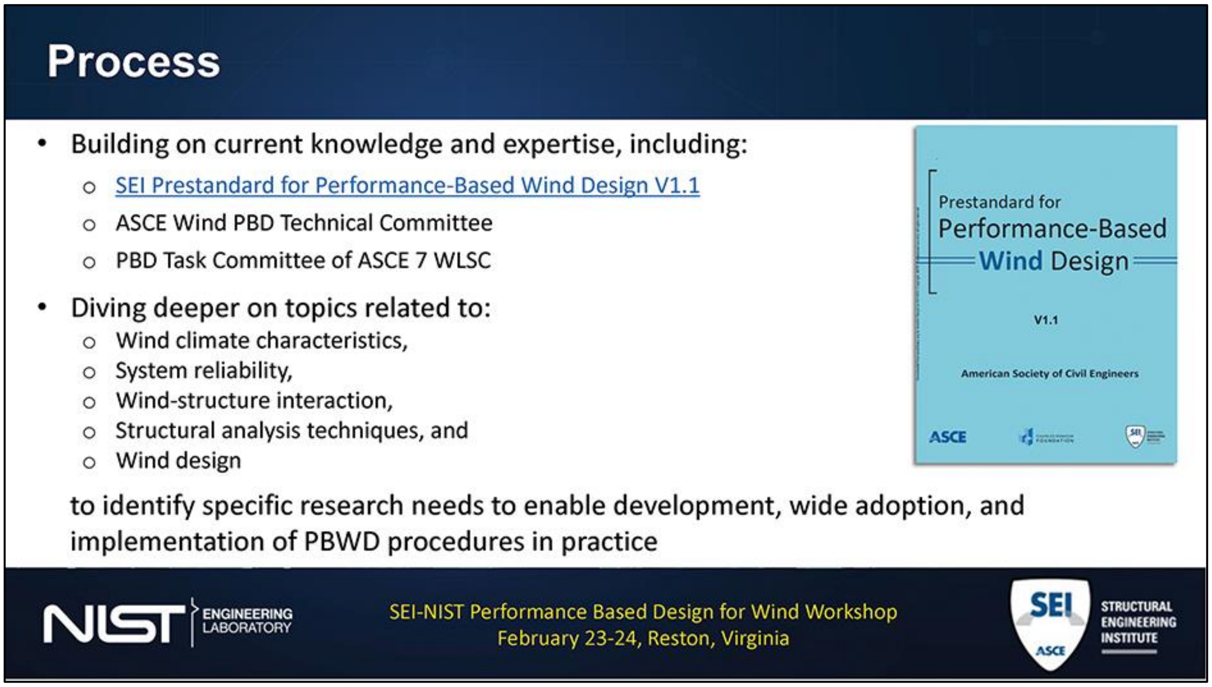
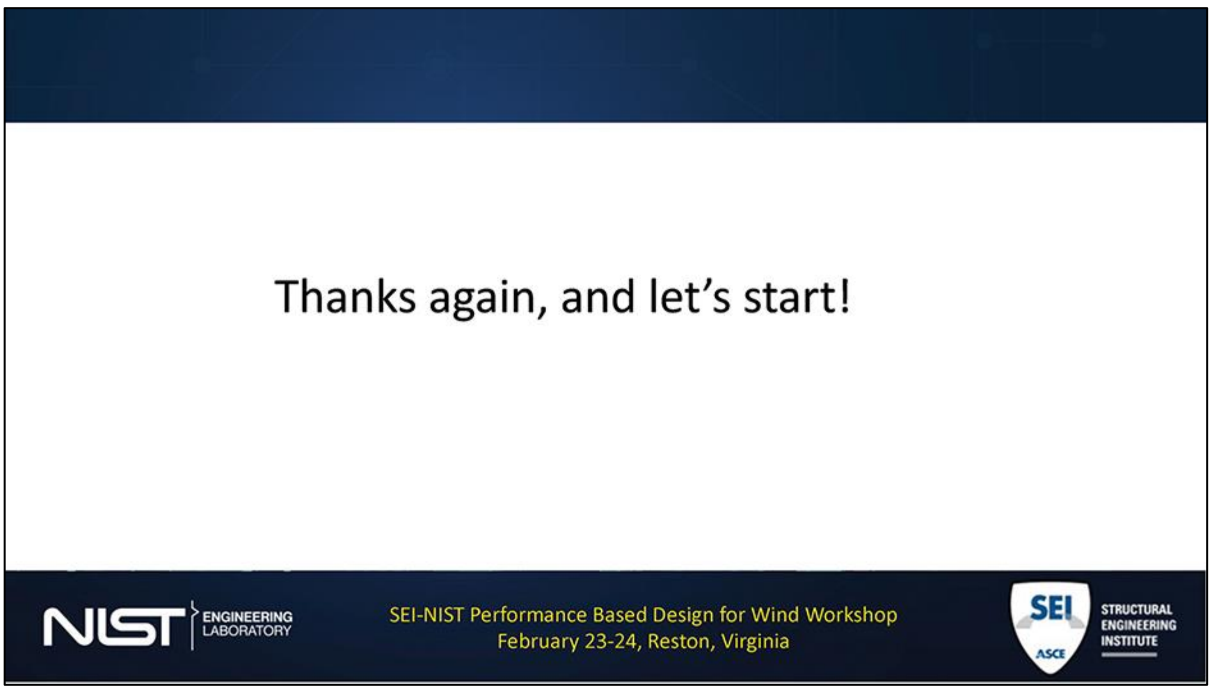
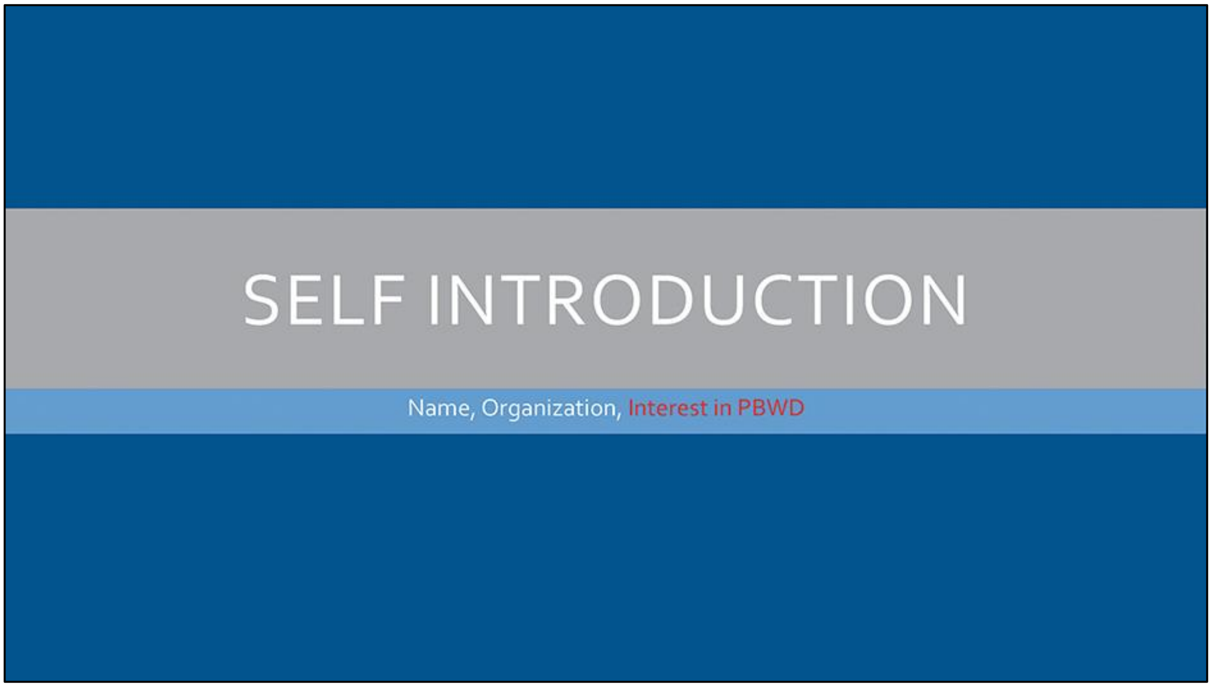
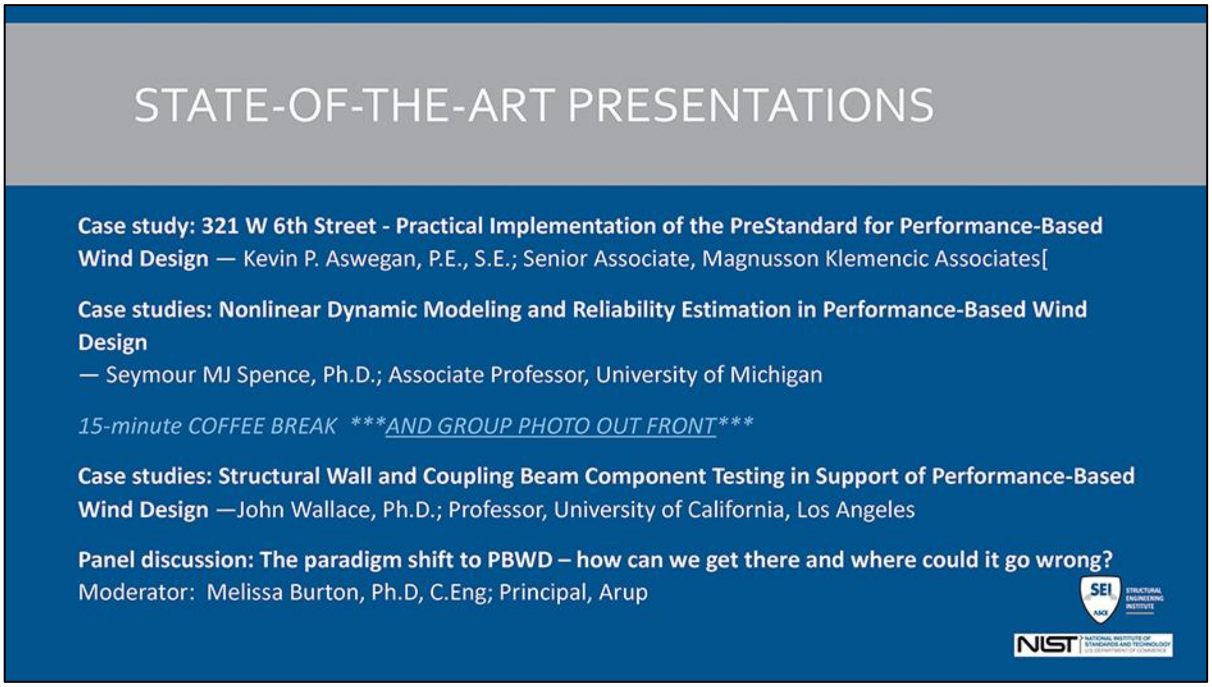
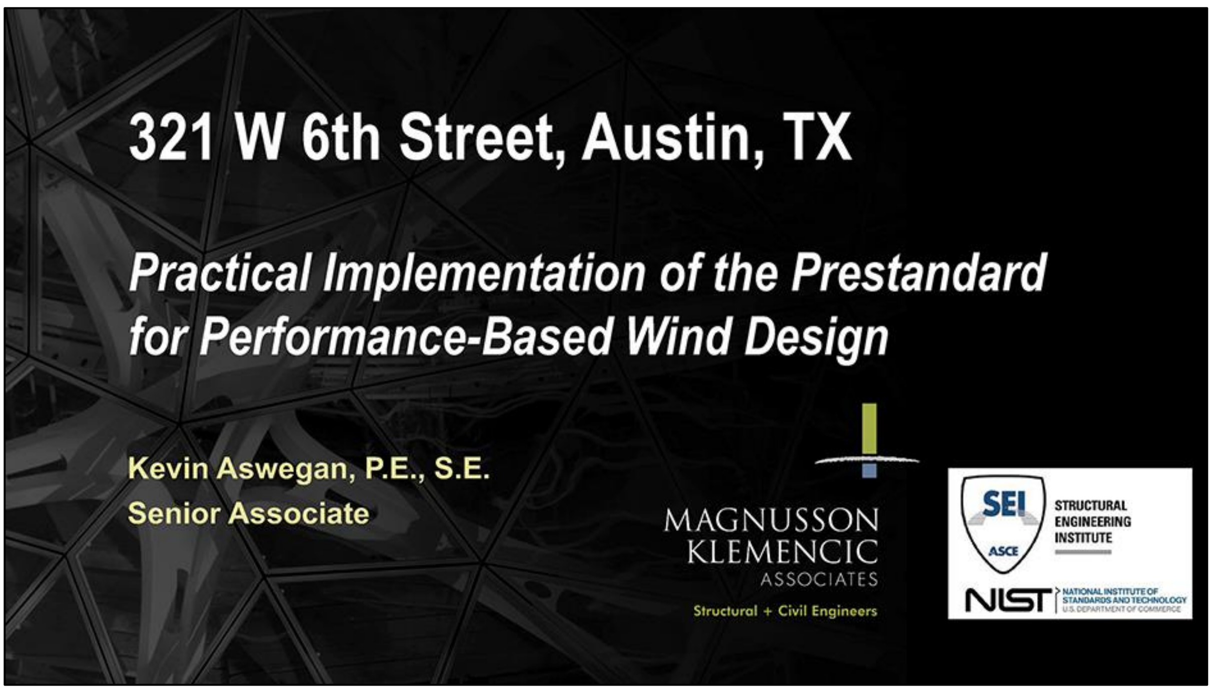

Process
Building on current knowledge and expertise, including:
SEI Prestandard for Performance-Based Wind Design V1.1
ASCE Wind PBD Technical Committee
PBD Task Committee of ASCE 7 WLSC
Diving deeper on topics related to:
Wind climate characteristics,
System reliability,
Wind-structure interaction,
Structural analysis techniques, and
Wind design
to identify specific research needs to enable development, wide adoption, and implementation of PBWD procedures in practice
Prestandard for
Performance-Based
Wind Design
V1.1
American Society of Civil Engineers
ASCE
NIST ENGINEERING LABORATORY
SEI-NIST Performance Based Design for Wind Workshop
February 23-24, Reston, Virginia
SEI ASCE STRUCTURAL ENGINEERING INSTITUTE

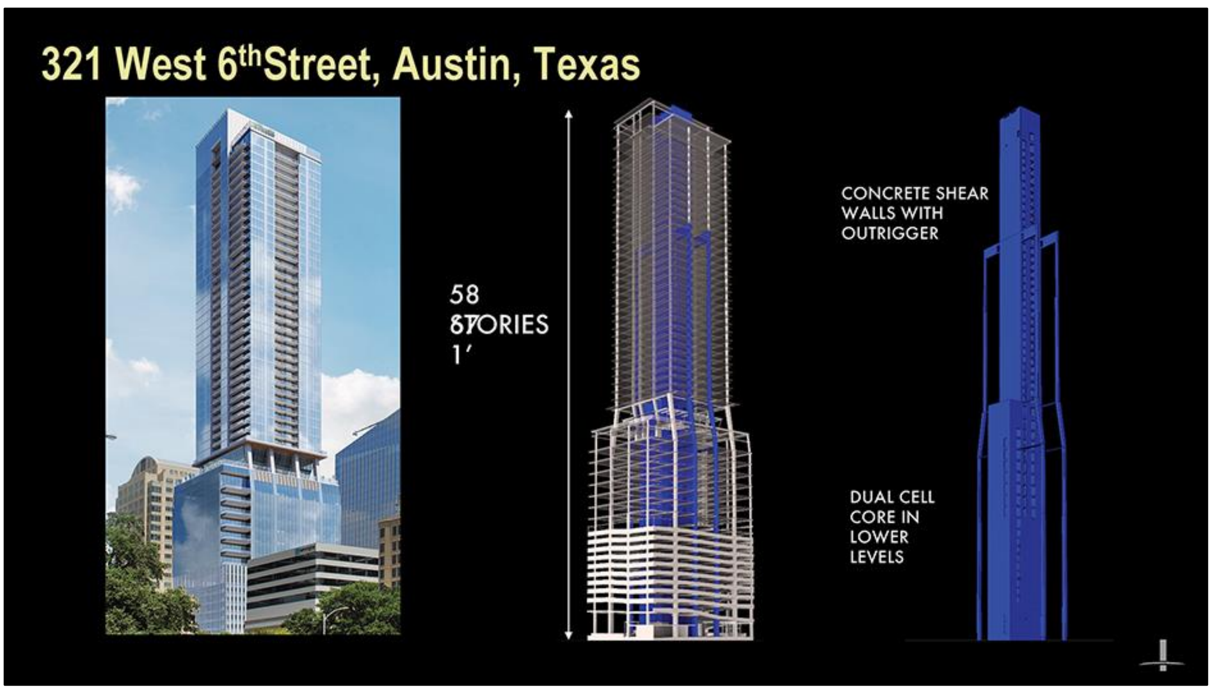

Thanks again, and let's start!
NIST ENGINEERING LABORATORY
SEI-NIST Performance Based Design for Wind Workshop
February 23-24, Reston, Virginia
SEI ASCE STRUCTURAL ENGINEERING INSTITUTE

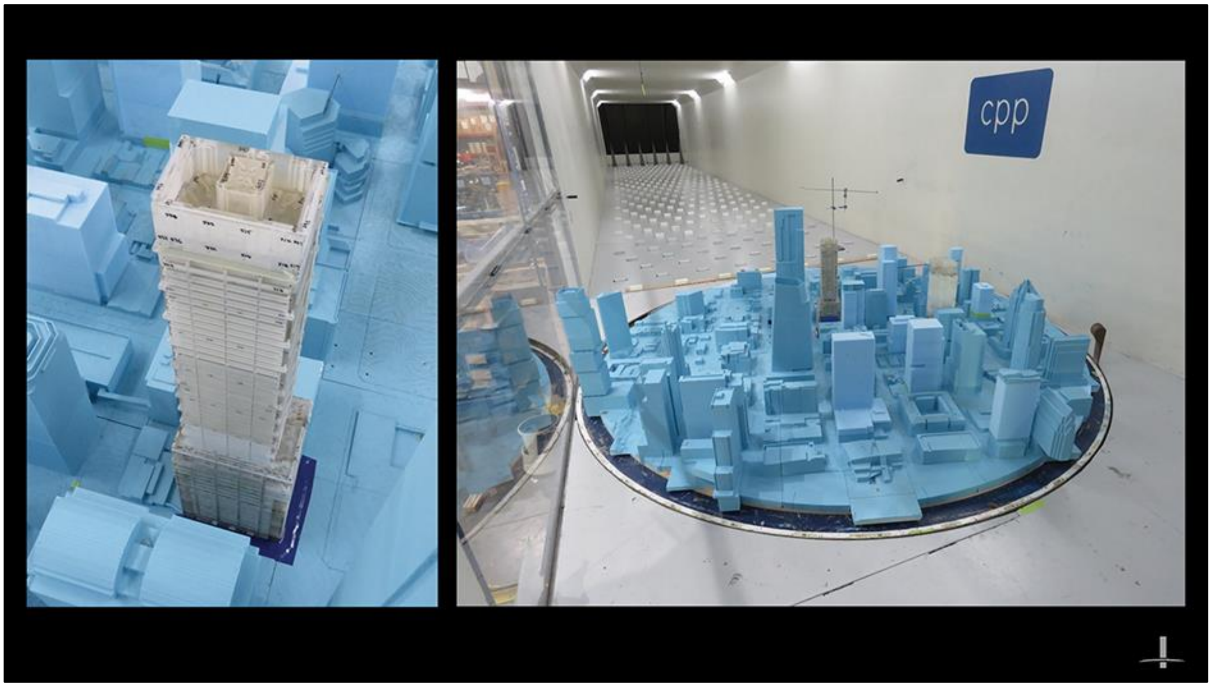

SELF INTRODUCTION
Name, Organization, Interest in PBWD


STATE-OF-THE-ART
9:30 am – 12:00 pm


STATE-OF-THE-ART PRESENTATIONS
Case study: 321 W 6th Street - Practical Implementation of the PreStandard for Performance-Based Wind Design — Kevin P. Aswegan, P.E., S.E.; Senior Associate, Magnusson Klemencic Associates[
Case studies: Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design
— Seymour MJ Spence, Ph.D.; Associate Professor, University of Michigan
15-minute COFFEE BREAK ***AND GROUP PHOTO OUT FRONT***
Case studies: Structural Wall and Coupling Beam Component Testing in Support of Performance-Based Wind Design —John Wallace, Ph.D.; Professor, University of California, Los Angeles
Panel discussion: The paradigm shift to PBWD – how can we get there and where could it go wrong?
Moderator: Melissa Burton, Ph.D, C.Eng; Principal, Arup


321 W 6th Street, Austin, TX
Practical Implementation of the Prestandard for Performance-Based Wind Design
Kevin Aswegan, P.E., S.E.
Senior Associate
MAGNUSSON KLEMENCIC ASSOCIATES
Structural + Civil Engineers
SEI
STRUCTURAL ENGINEERING INSTITUTE
ASCE
NIST
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE


321 West 6thStreet, Austin, Texas
58
STORIES
871'
CONCRETE SHEAR
WALLS WITH
OUTRIGGER
DUAL CELL
CORE IN
LOWER
LEVELS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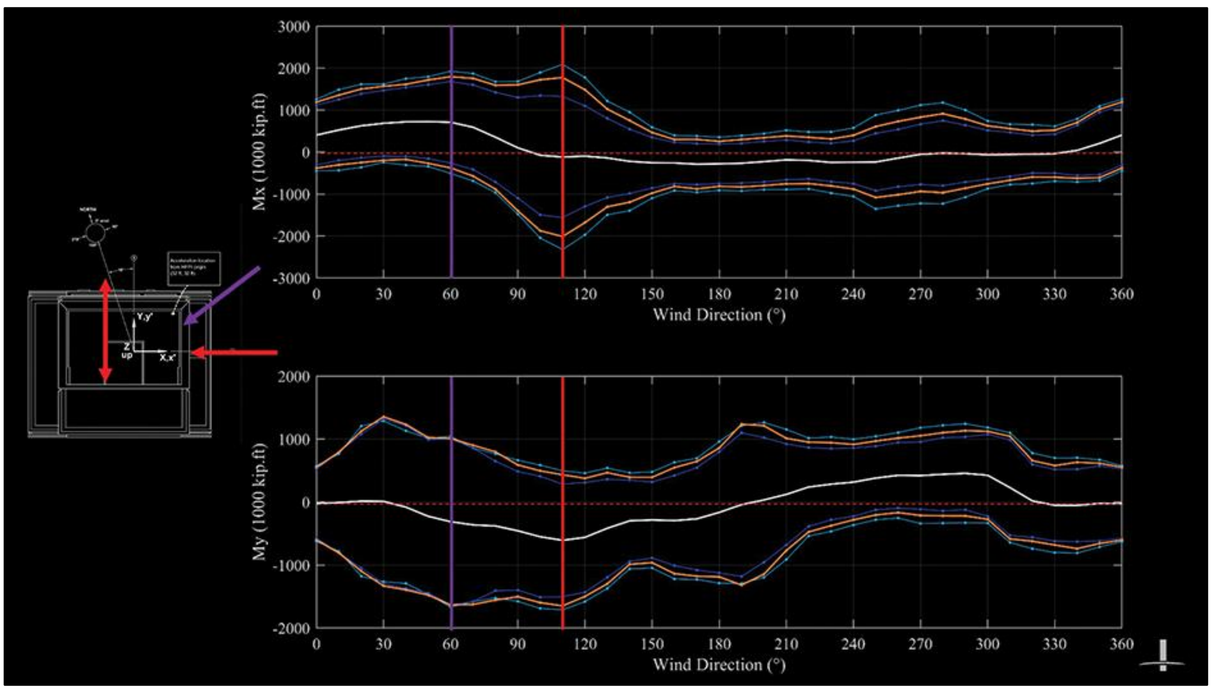
Mx (1000 kip.ft)
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-2000
-3000
0 30 60 90 120 150 180 210 240 270 300 330 360
Wind Direction (°)
My (1000 kip.ft)
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1000
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-1000
-2000
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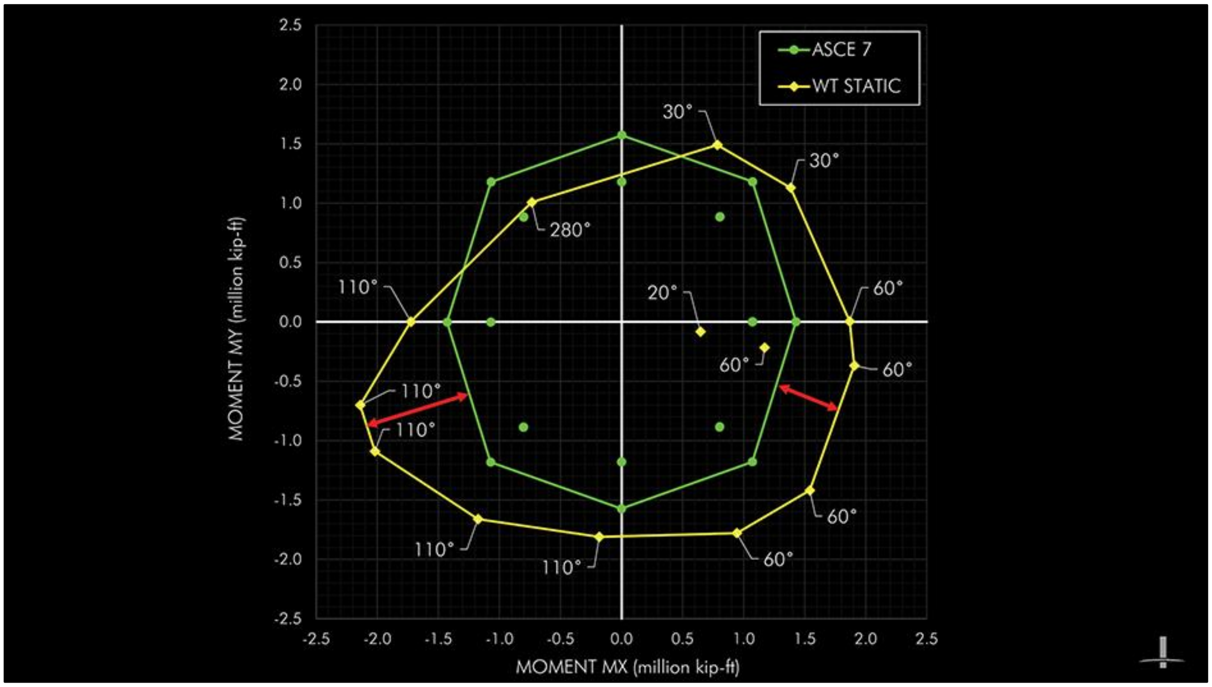
Wind Direction (°)
Y,y'
Z
up
X,x'


ASCE 7
WT STATIC
MOMENT MY (million kip-ft)
MOMENT MX (million kip-ft)
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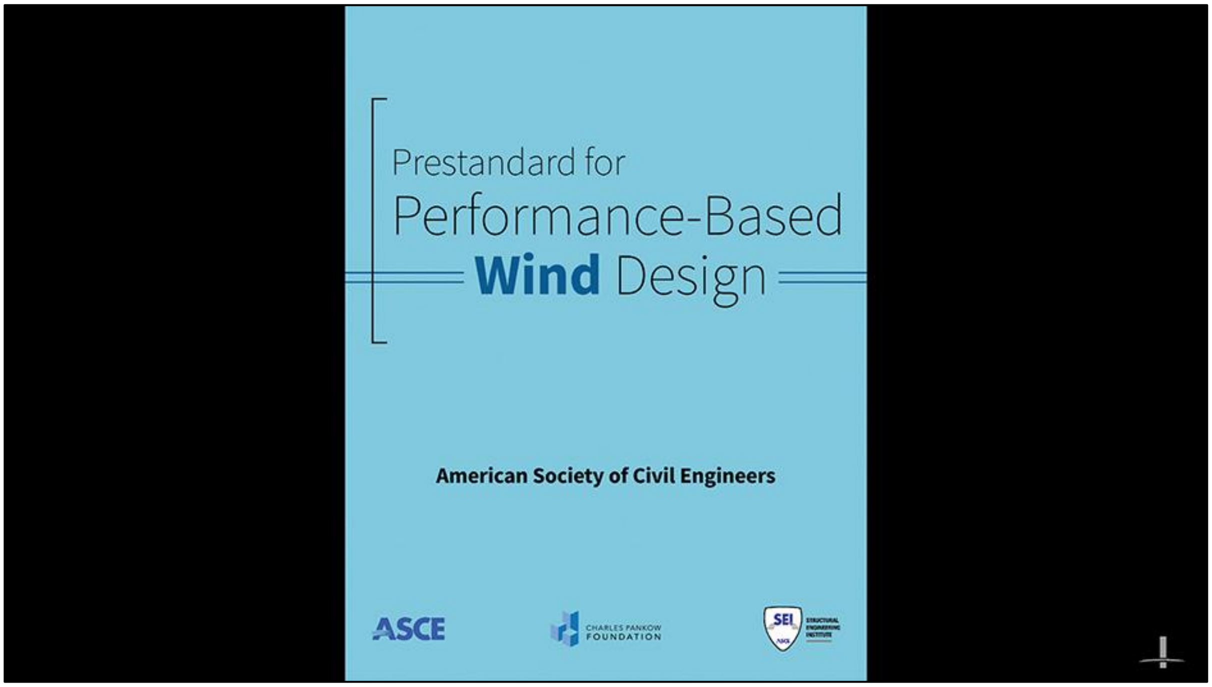
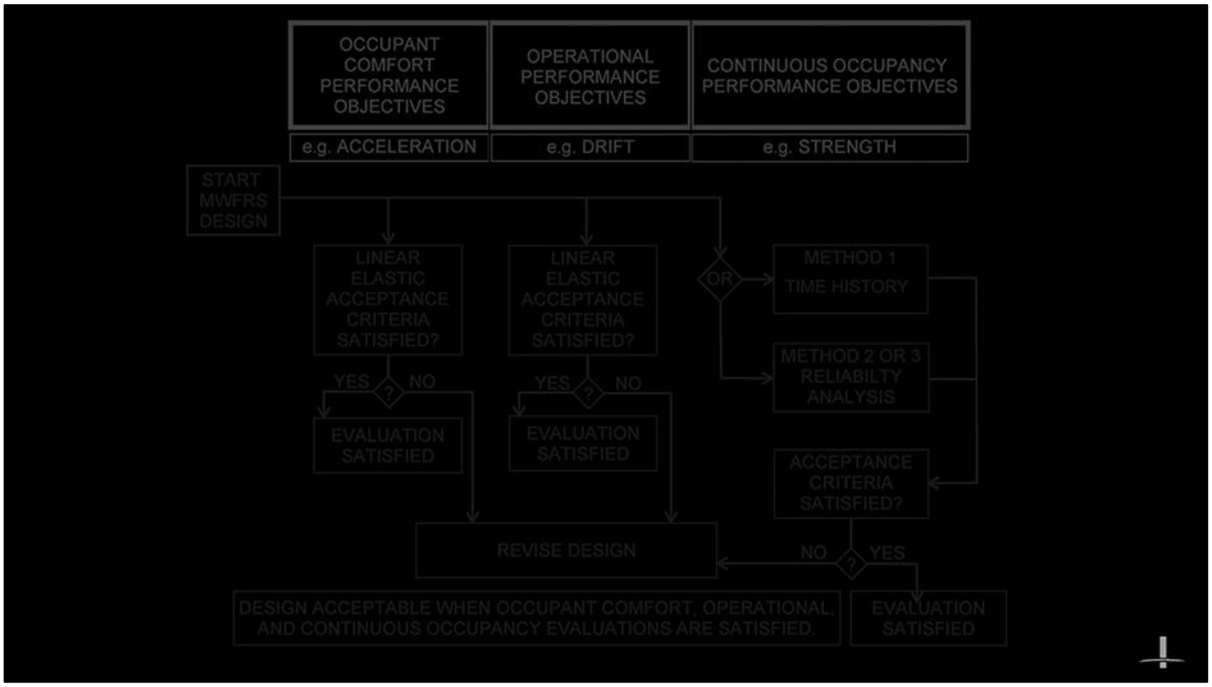
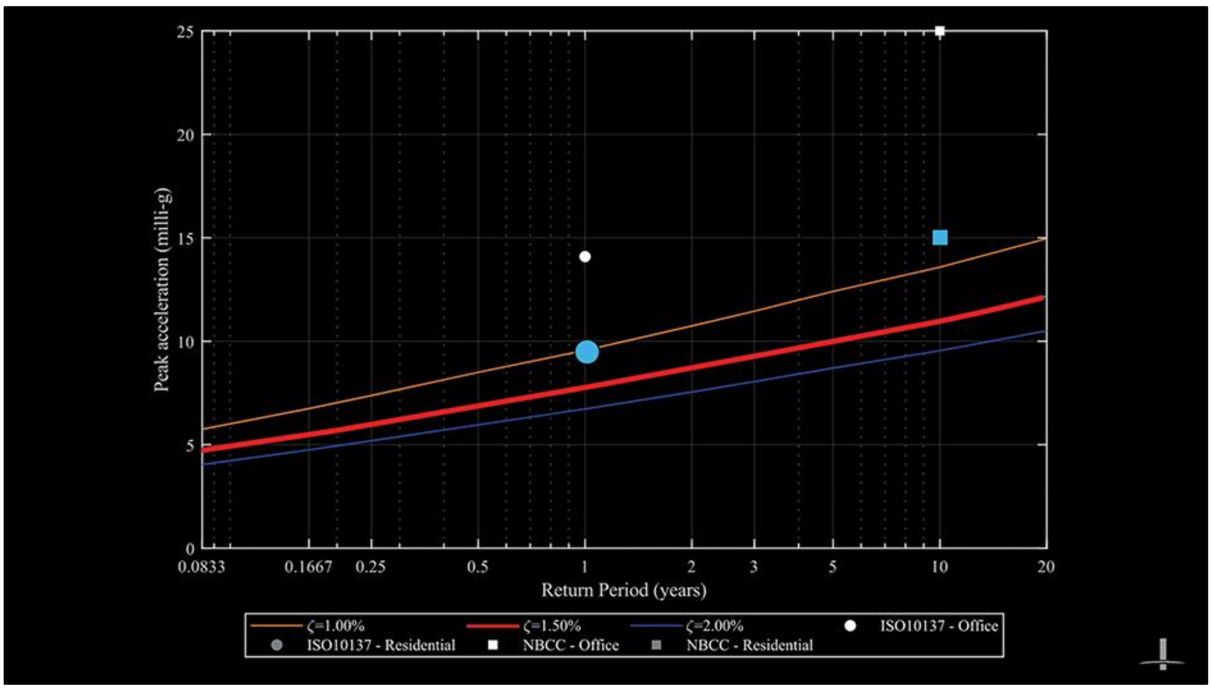
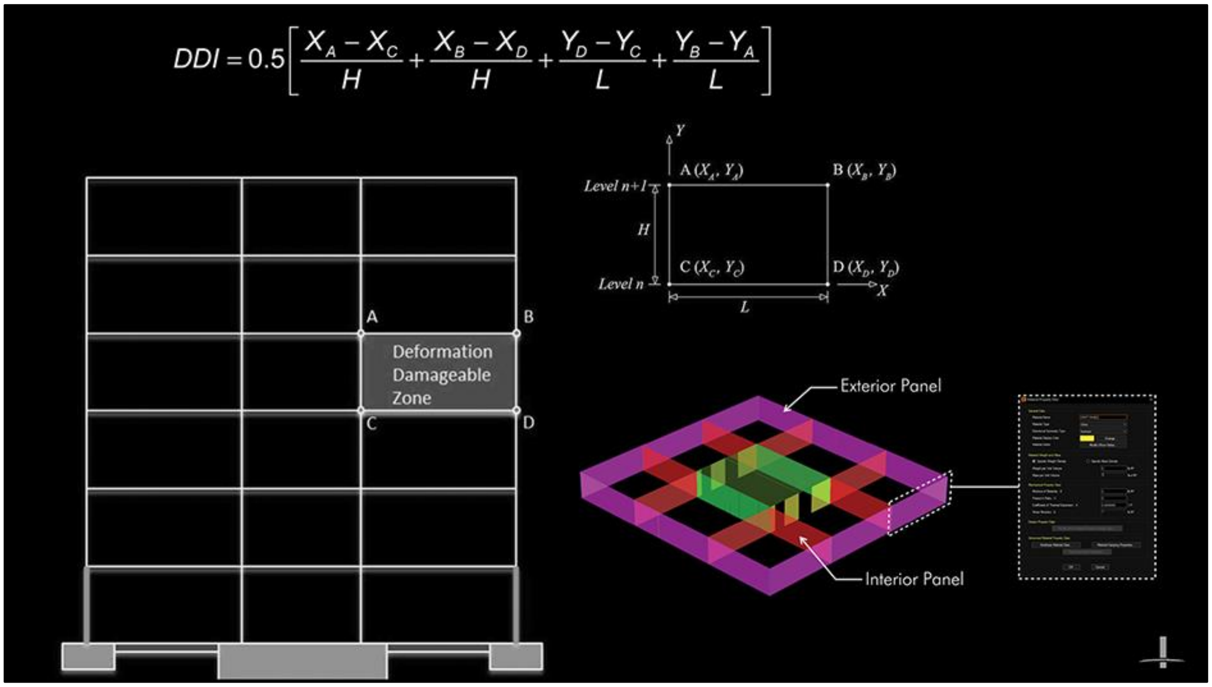
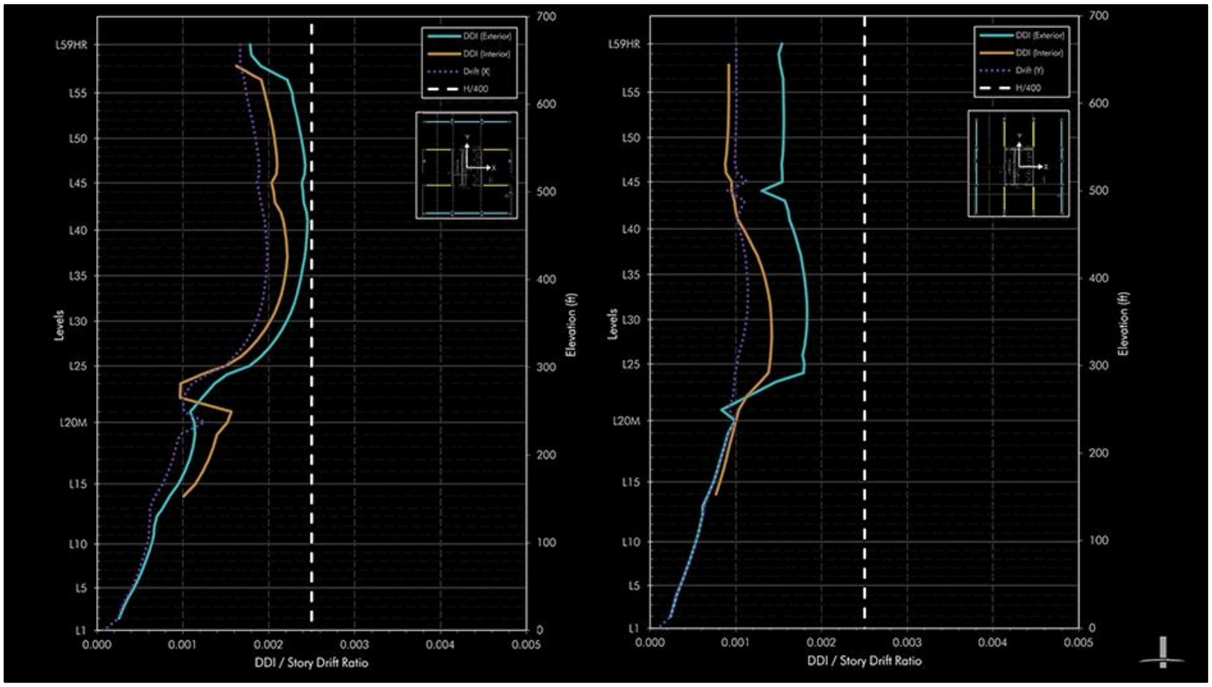
60°
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5

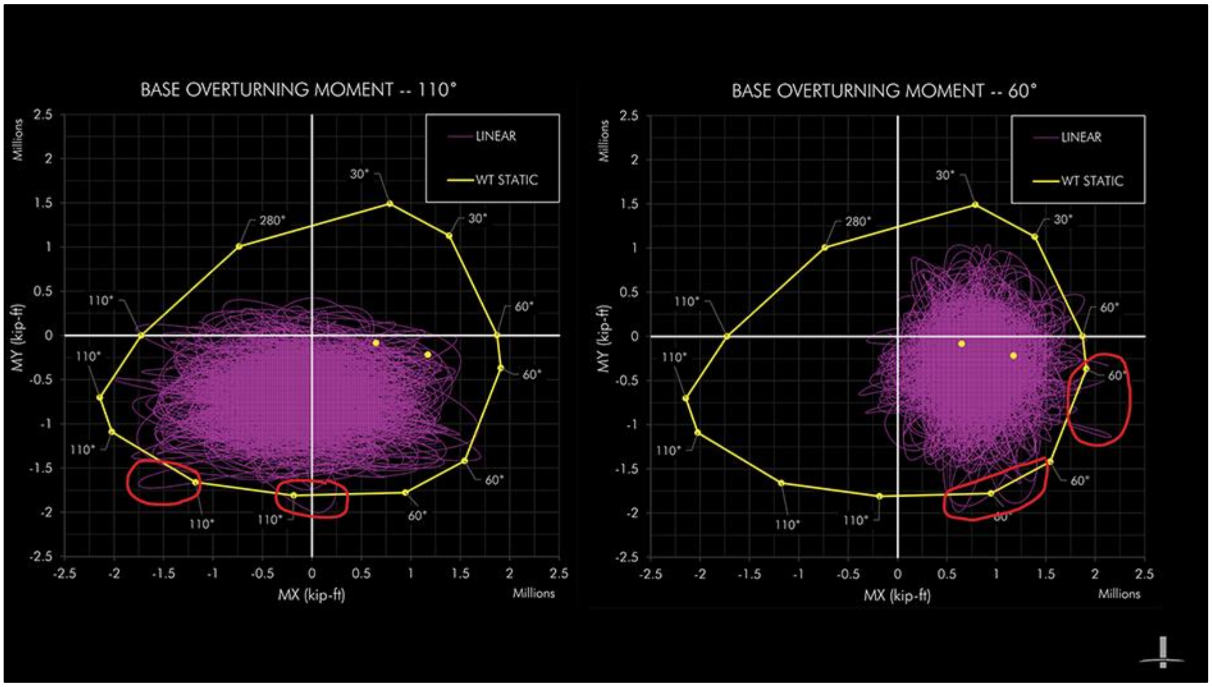

Prestandard for
Performance-Based
Wind Design
American Society of Civil Engineers
ASCE
CHARLES PANKOW FOUNDATION
SEI

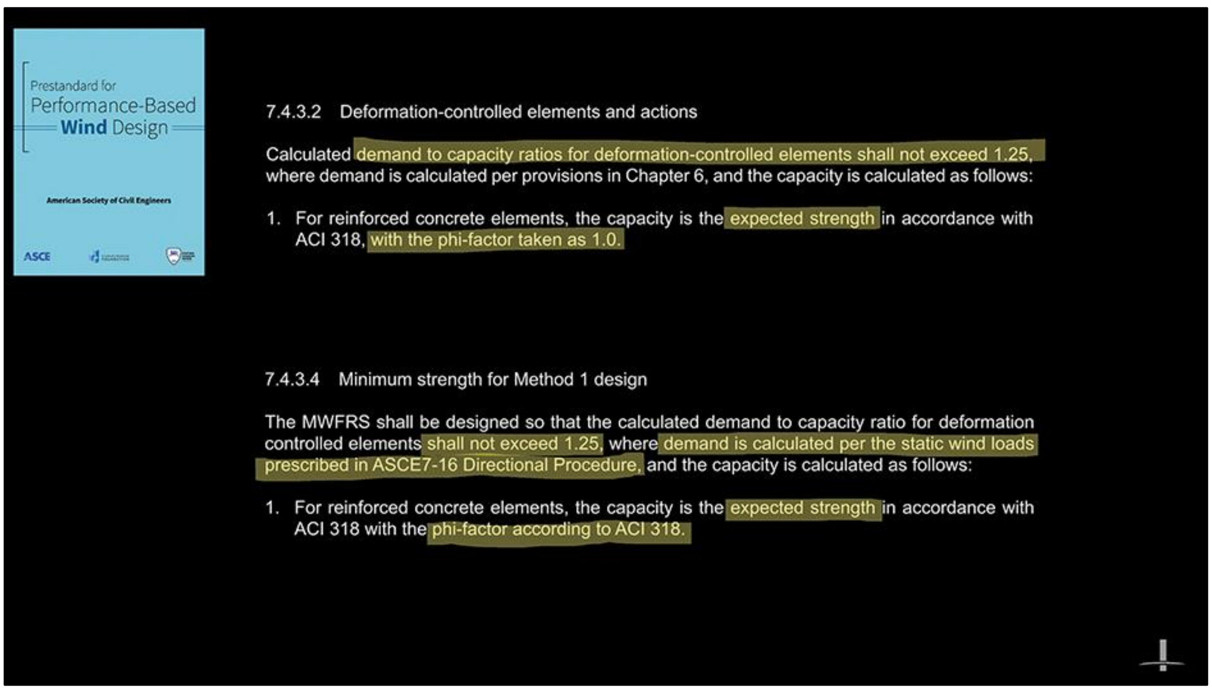

OCCUPANT COMFORT PERFORMANCE OBJECTIVES
OPERATIONAL PERFORMANCE OBJECTIVES
CONTINUOUS OCCUPANCY PERFORMANCE OBJECTIVES
e.g. ACCELERATION
e.g. DRIFT
e.g. STRENGTH
START MWFRS DESIGN
LINEAR ELASTIC ACCEPTANCE CRITERIA SATISFIED?
LINEAR ELASTIC ACCEPTANCE CRITERIA SATISFIED?
OR
METHOD 1 TIME HISTORY
METHOD 2 OR 3 RELIABILTY ANALYSIS
YES
NO
YES
NO
EVALUATION SATISFIED
EVALUATION SATISFIED
ACCEPTANCE CRITERIA SATISFIED?
REVISE DESIGN
NO
YES
DESIGN ACCEPTABLE WHEN OCCUPANT COMFORT, OPERATIONAL, AND CONTINUOUS OCCUPANCY EVALUATIONS ARE SATISFIED.
EVALUATION SATISFIED


Peak acceleration (milli-g)
0
5
10
15
20
25
0.0833
0.1667
0.25
0.5
1
2
3
5
10
20
Return Period (years)
ζ=1.00%
ζ=1.50%
ζ=2.00%
ISO10137 - Office
ISO10137 - Residential
NBCC - Office
NBCC - Residential


$DDI = 0.5\left[\frac{X_A - X_C}{H} + \frac{X_B - X_D}{H} + \frac{Y_D - Y_C}{L} + \frac{Y_B - Y_A}{L}\right]$
A
B
Deformation Damageable Zone
C
D
Y
A (X_A, Y_A)
B (X_B, Y_B)
Level n+1
H
C (X_C, Y_C)
D (X_D, Y_D)
Level n
X
L
Exterior Panel
Interior Panel


DDI (Exterior)
DDI (Interior)
Drift (X)
H/400
Levels
Elevation (ft)
DDI / Story Drift Ratio
DDI (Exterior)
DDI (Interior)
Drift (Y)
H/400
Levels
Elevation (ft)
DDI / Story Drift Ratio


BASE OVERTURNING MOMENT -- 110°
BASE OVERTURNING MOMENT -- 60°
LINEAR
WT STATIC
MY (kip-ft)
MX (kip-ft)
Millions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American Society of Civil Engineers
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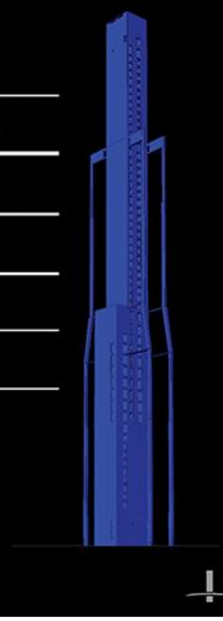
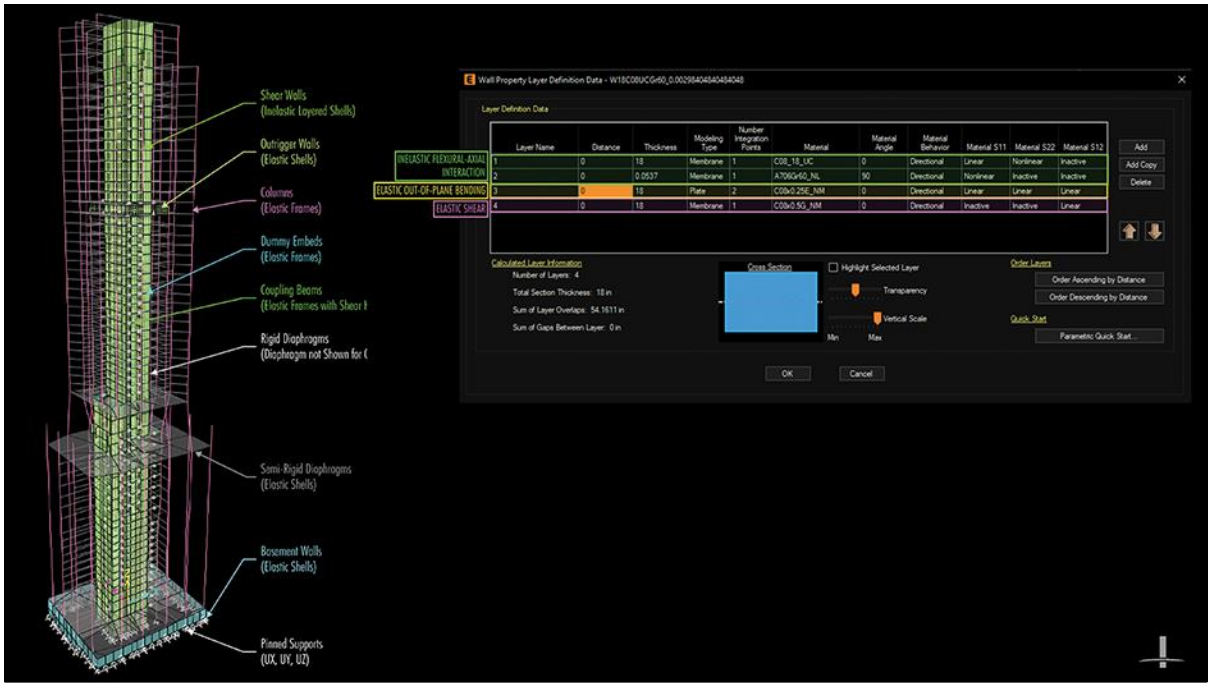
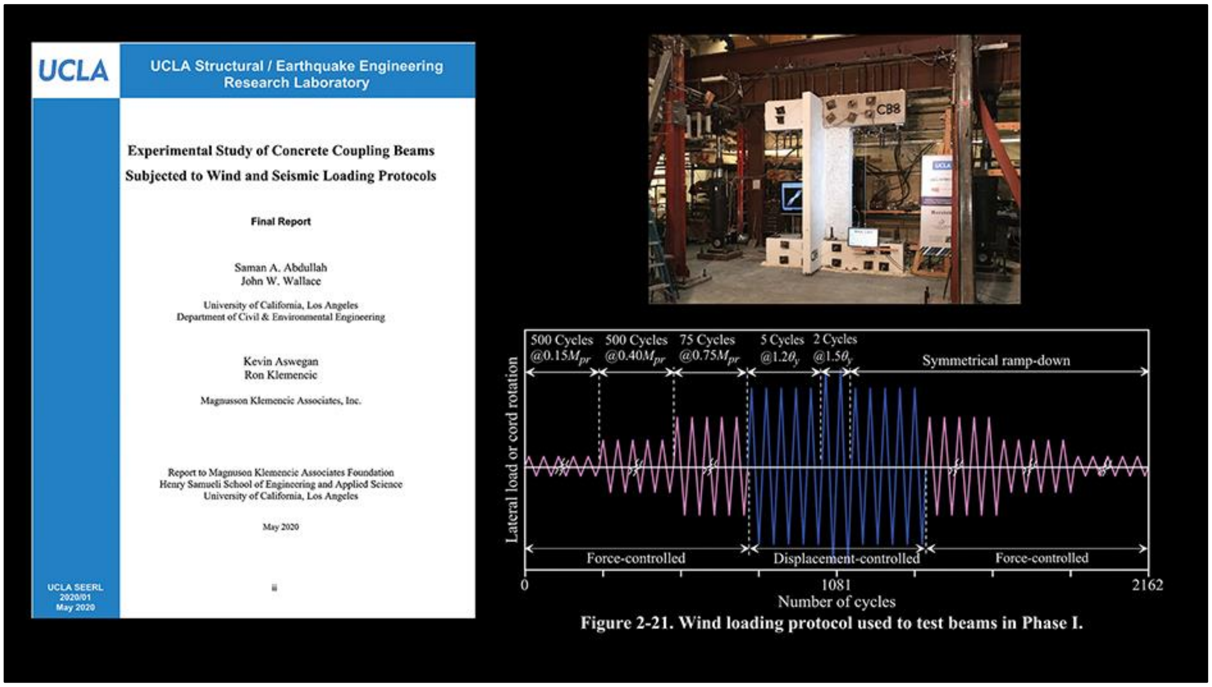
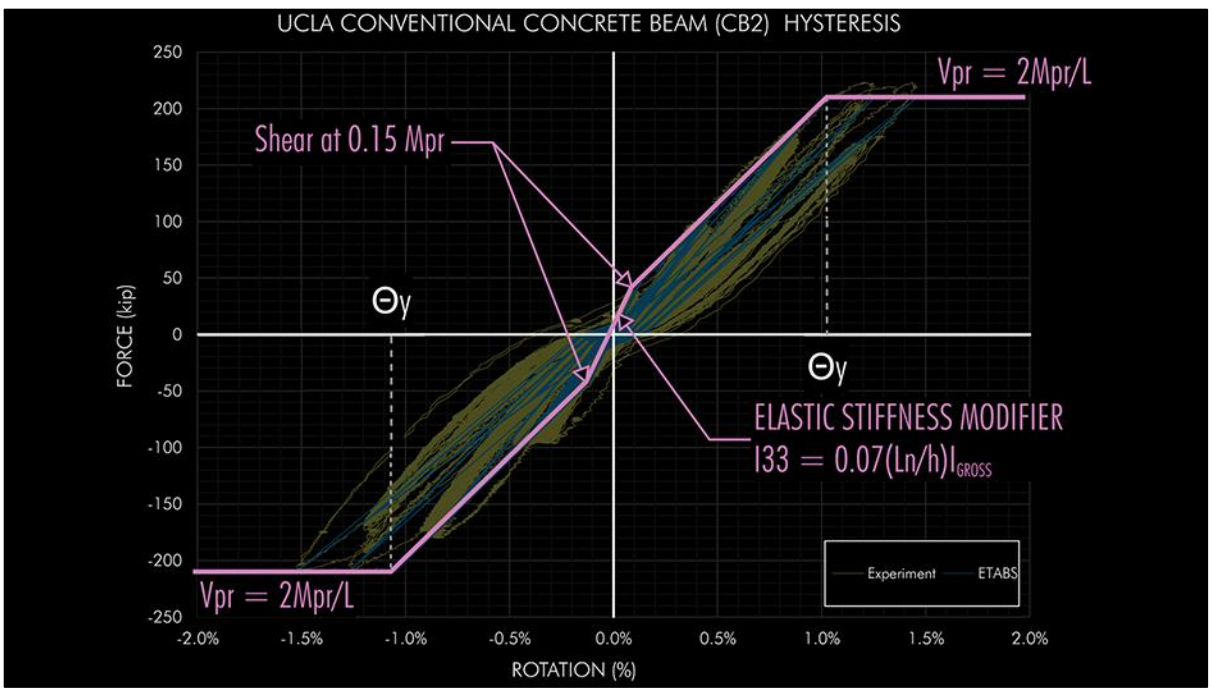
7.4.3.2 Deformation-controlled elements and actions
Calculated demand to capacity ratios for deformation-controlled elements shall not exceed 1.25, where demand is calculated per provisions in Chapter 6, and the capacity is calculated as follows:
1. For reinforced concrete elements, the capacity is the expected strength in accordance with ACI 318, with the phi-factor taken as 1.0.
7.4.3.4 Minimum strength for Method 1 design
The MWFRS shall be designed so that the calculated demand to capacity ratio for deformation controlled elements shall not exceed 1.25, where demand is calculated per the static wind loads prescribed in ASCE7-16 Directional Procedure, and the capacity is calculated as follows:
1. For reinforced concrete elements, the capacity is the expected strength in accordance with ACI 318 with the phi-factor according to ACI 318.

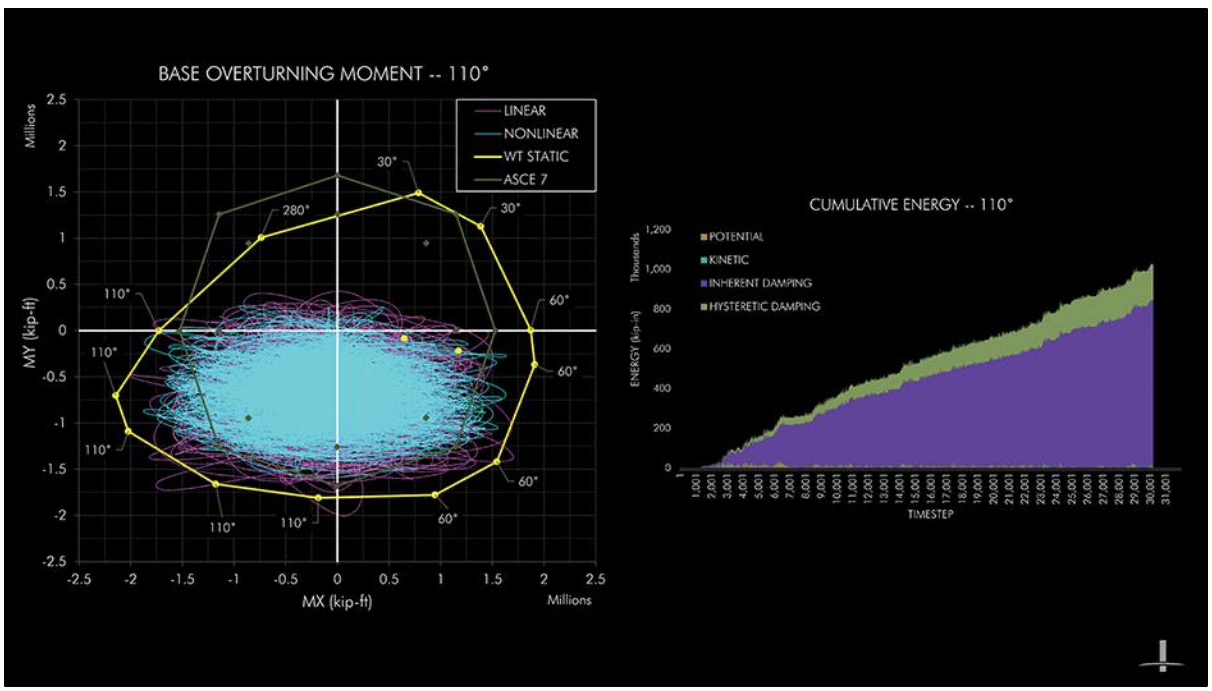
	Category	
Member Action	**Deformation-Controlled**	**Force-Controlled**
Shear wall shear		x
Shear wall flexural-axial interaction	x	
Coupling beam flexure	x	
Coupling beam shear		x

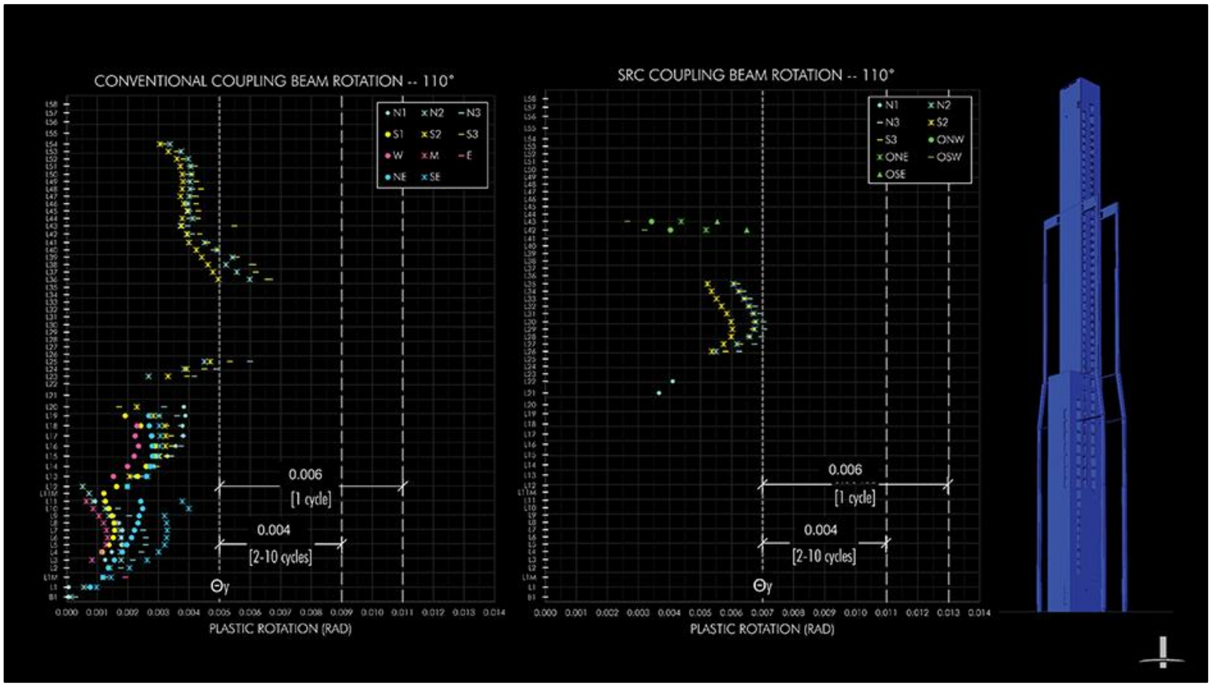


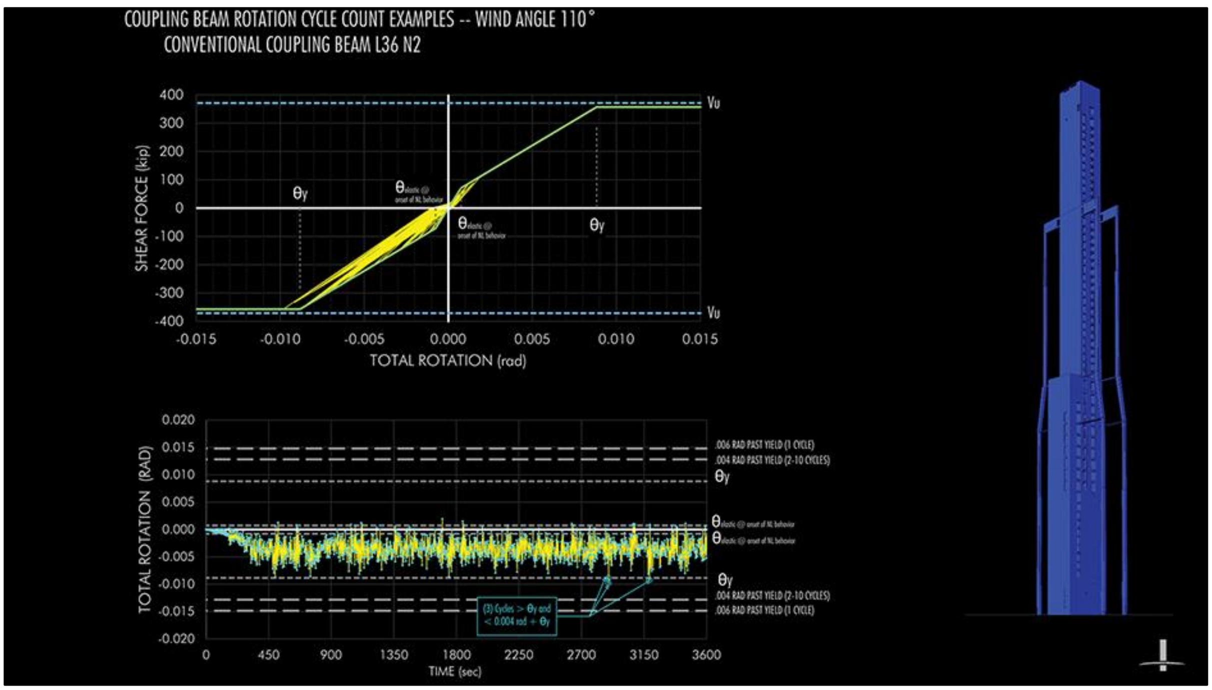


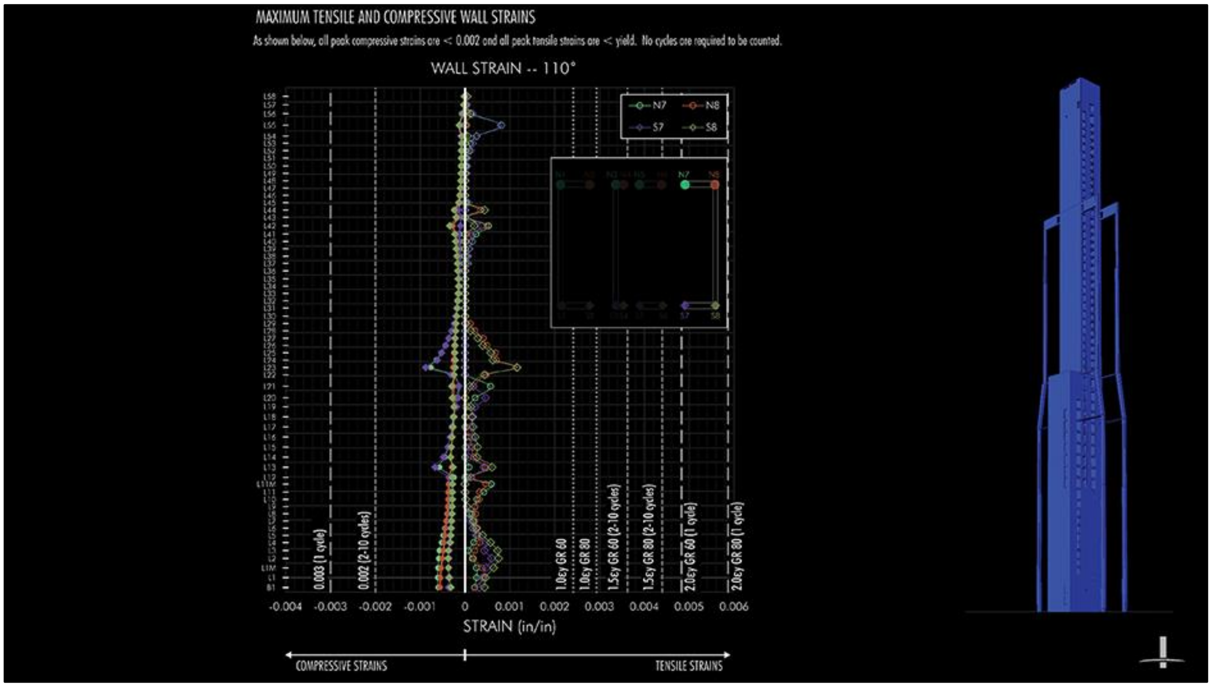

UCLA
UCLA Structural / Earthquake Engineering Research Laboratory
Experimental Study of Concrete Coupling Beams Subjected to Wind and Seismic Loading Protocols
Final Report
Saman A. Abdullah
John W. Wallace
University of California, Los Angeles
Department of Civil & Environmental Engineering
Kevin Aswegan
Ron Klemencic
Magnusson Klemencic Associates, Inc.
Report to Magnuson Klemencic Associates Foundation
Henry Samueli School of Engineering and Applied Science
University of California, Los Angeles
May 2020
ii
UCLA SEERL
2020/01
May 2020
CB8
500 Cycles @0.15M_{pr}
500 Cycles @0.40M_{pr}
75 Cycles @0.75M_{pr}
5 Cycles @1.2θ_y
2 Cycles @1.5θ_y
Symmetrical ramp-down
Lateral load or cord rotation
Force-controlled
Displacement-controlled
Force-controlled
0
1081
2162
Number of cycles
Figure 2-21. Wind loading protocol used to test beams in Phase I.


UCLA CONVENTIONAL CONCRETE BEAM (CB2) HYSTERESIS
Vpr = 2Mpr/L
Shear at 0.15 Mpr
Θy
Θy
ELASTIC STIFFNESS MODIFIER
I33 = 0.07(Ln/h)I_{GROSS}
Vpr = 2Mpr/L
Experiment
ETABS
FORCE (kip)
250
200
150
100
50
0
-50
-100
-150
-200
-250
-2.0%
-1.5%
-1.0%
-0.5%
0.0%
0.5%
1.0%
1.5%
2.0%
ROTATION (%)

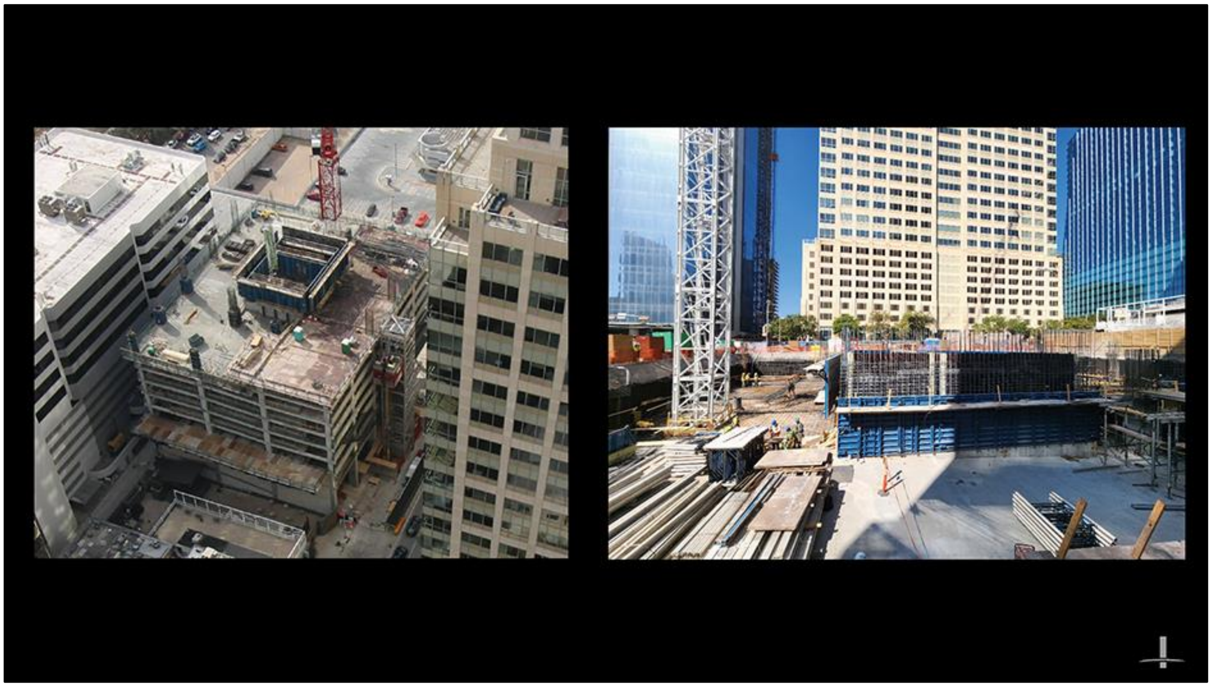

BASE OVERTURNING MOMENT -- 110°
LINEAR
NONLINEAR
WT STATIC
ASCE 7
MY (kip-ft)
Millions
MX (kip-ft)
Millions
30°
280°
60°
110°
CUMULATIVE ENERGY -- 110°
POTENTIAL
KINETIC
INHERENT DAMPING
HYSTERETIC DAMPING
ENERGY (kip-in)
Thousands
TIMESTEP


CONVENTIONAL COUPLING BEAM ROTATION -- 110°
SRC COUPLING BEAM ROTATION -- 110°
0.006
[1 cycle]
0.004
[2-10 cycles]
Θy
PLASTIC ROTATION (RAD)

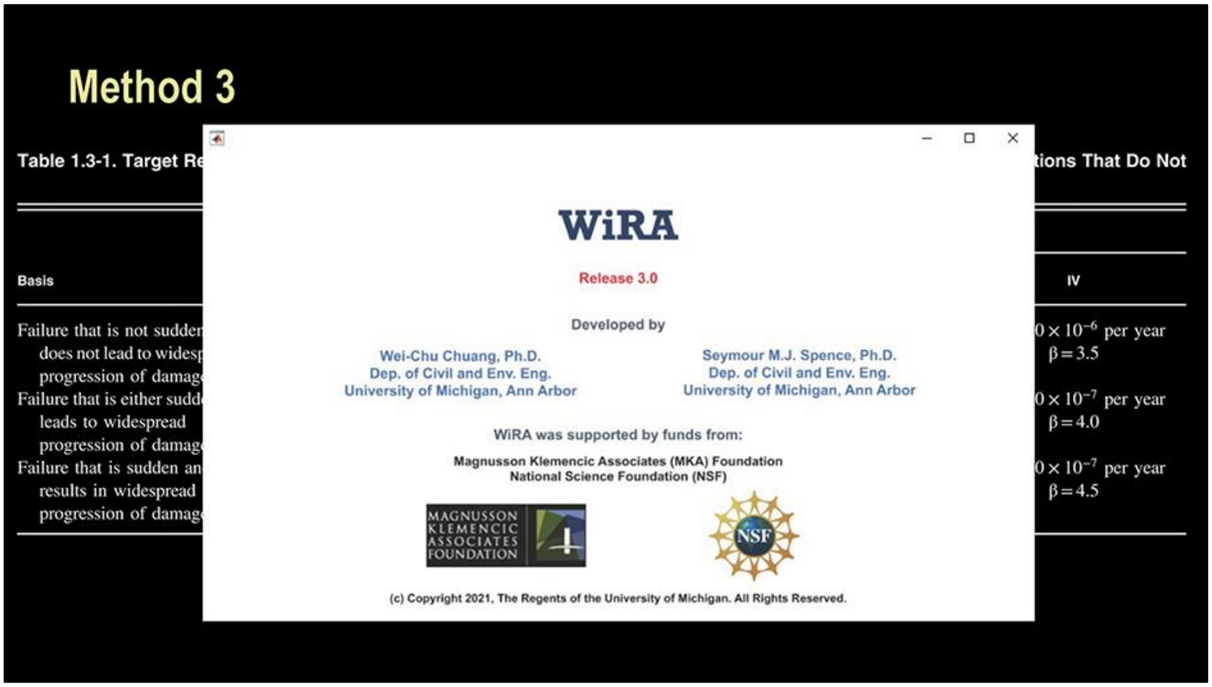

COUPLING BEAM ROTATION CYCLE COUNT EXAMPLES -- WIND ANGLE 110°
CONVENTIONAL COUPLING BEAM L36 N2
SHEAR FORCE (kip)
TOTAL ROTATION (rad)
Vu
θy
TOTAL ROTATION (RAD)
TIME (sec)
.006 RAD PAST YIELD (1 CYCLE)
.004 RAD PAST YIELD (2-10 CYCLES)


MAXIMUM TENSILE AND COMPRESSIVE WALL STRAINS
As shown below, all peak compressive strains are < 0.002 and all peak tensile strains are < yield. No cycles are required to be counted.
WALL STRAIN -- 110°
N7
N8
S7
S8
0.003 (1 cycle)
0.002 (2-10 cycles)
1.0εy GR 60
1.0εy GR 80
1.5εy GR 60 (2-10 cycles)
1.5εy GR 80 (2-10 cycles)
2.0εy GR 60 (1 cycle)
2.0εy GR 80 (1 cycle)
-0.004 -0.003 -0.002 -0.001 0 0.001 0.002 0.003 0.004 0.005 0.006
STRAIN (in/in)
COMPRESSIVE STRAINS
TENSILE STRAINS


Material Savings
20 TRUCKS OF REBAR (350 TONS)
10 TRUCKS OF STEEL
(125 TONS)
200 CONCRETE TRUCKS (1,800
CUBIC YARDS)
5% STRUCTURAL COST REDUCTION




THE CONSTRUCTION RESOURCE
ENR
Engineering News-Record
enr.com
INSIDE:
THE TOP
PROFESSIONAL
SERVICES FIRMS
WIND SIMULATION FOR
321 WEST 6TH STREET
AUSTIN
PART ONE OF A SERIES
BUILDING A LOWER CARBON FUTURE
WINDS OF CHANGE
TRAILBLAZERS LEAD THE WAY TOWARD A PARADIGM SHIFT IN SKYSCRAPER WIND DESIGN
THAT REDUCES MATERIALS, COST AND EMBODIED CARBON
(P. 20)


Method 3
Table 1.3-1. Target Re
tions That Do Not
Basis
IV
Failure that is not sudden does not lead to widesp progression of damag
Failure that is either sudd leads to widespread progression of damag
Failure that is sudden an results in widespread progression of damag
0 × 10⁻⁶ per year β = 3.5
0 × 10⁻⁷ per year β = 4.0
0 × 10⁻⁷ per year β = 4.5
WiRA
Release 3.0
Developed by
Wei-Chu Chuang, Ph.D.
Dep. of Civil and Env. Eng.
University of Michigan, Ann Arbor
Seymour M.J. Spence, Ph.D.
Dep. of Civil and Env. Eng.
University of Michigan, Ann Arbor
WiRA was supported by funds from:
Magnusson Klemencic Associates (MKA) Foundation
National Science Foundation (NSF)
MAGNUSSON KLEMENCIC ASSOCIATES FOUNDATION
NSF
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RESEARCH
ASCE/SEI
Prestandard for
Performance-Based
Wind Design
V1.1
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University at Buffalo
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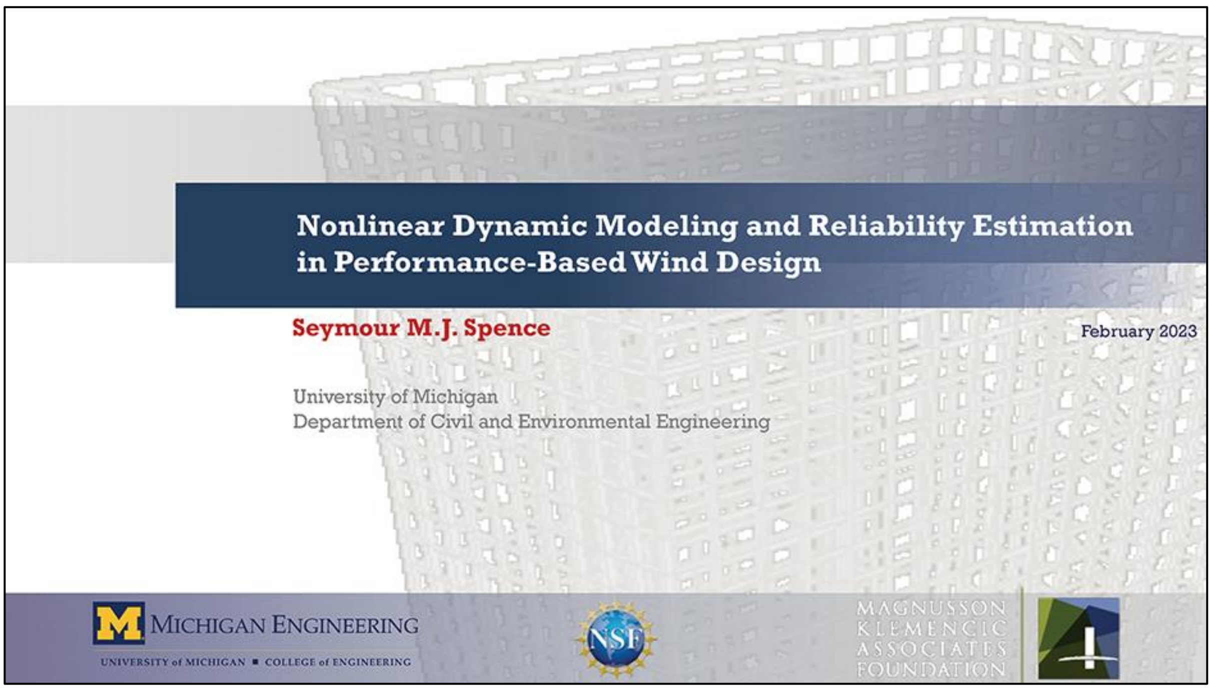
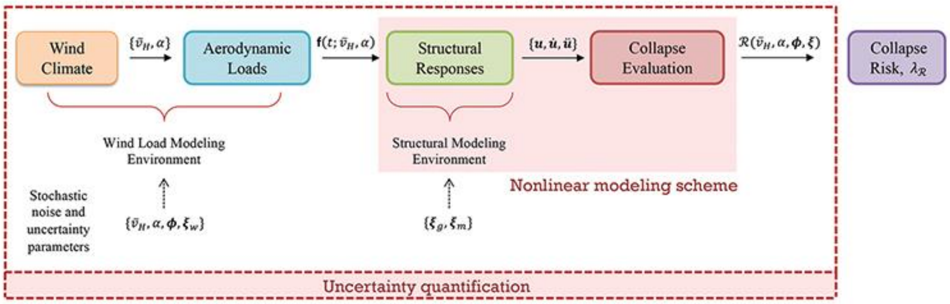

Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design
Seymour M.J. Spence
February 2023
University of Michigan
Department of Civil and Environmental Engineering
MICHIGAN ENGINEERING
UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING
NSF
MAGNUSSON KLEMENCIC ASSOCIATES FOUNDATION

Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design

PERFORMANCE-BASED WIND ENGINEERING

Reliability (or annual rate of exceedance/failure probability) estimation:

$$\lambda_{\mathcal{R}} = \int_{\alpha}\int_{\bar{v}_H} G(\mathcal{R}|\alpha, \bar{v}_H)|dG(\alpha|\bar{v}_H)||d\lambda(\bar{v}_H)| \Longrightarrow \beta_T = \Phi^{-1}[(1 - P^{a}_{f_{\mathcal{R}}})^T]$$



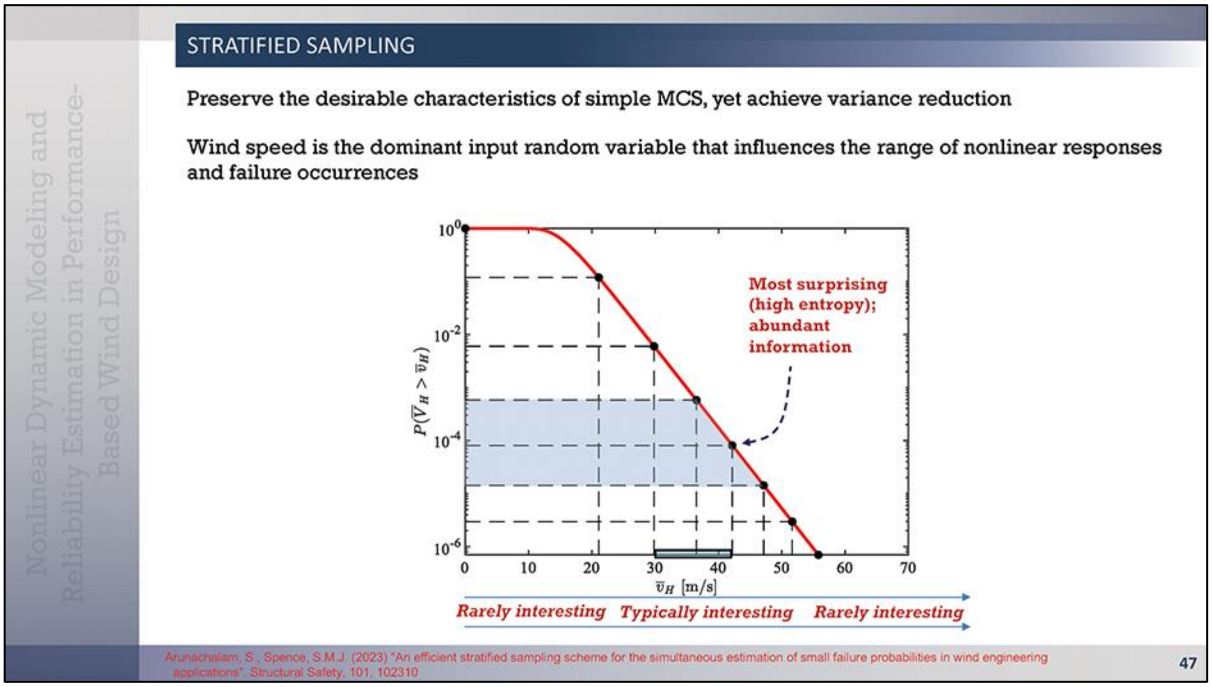
Arunachalam, S., Spence, S.M.J. (2022) "Reliability-based collapse assessment of wind excited steel structures within the setting of performance-based wind engineering". *Journal of Structural Engineering*, Journal of Structural Engineering, 148(9), 04022132

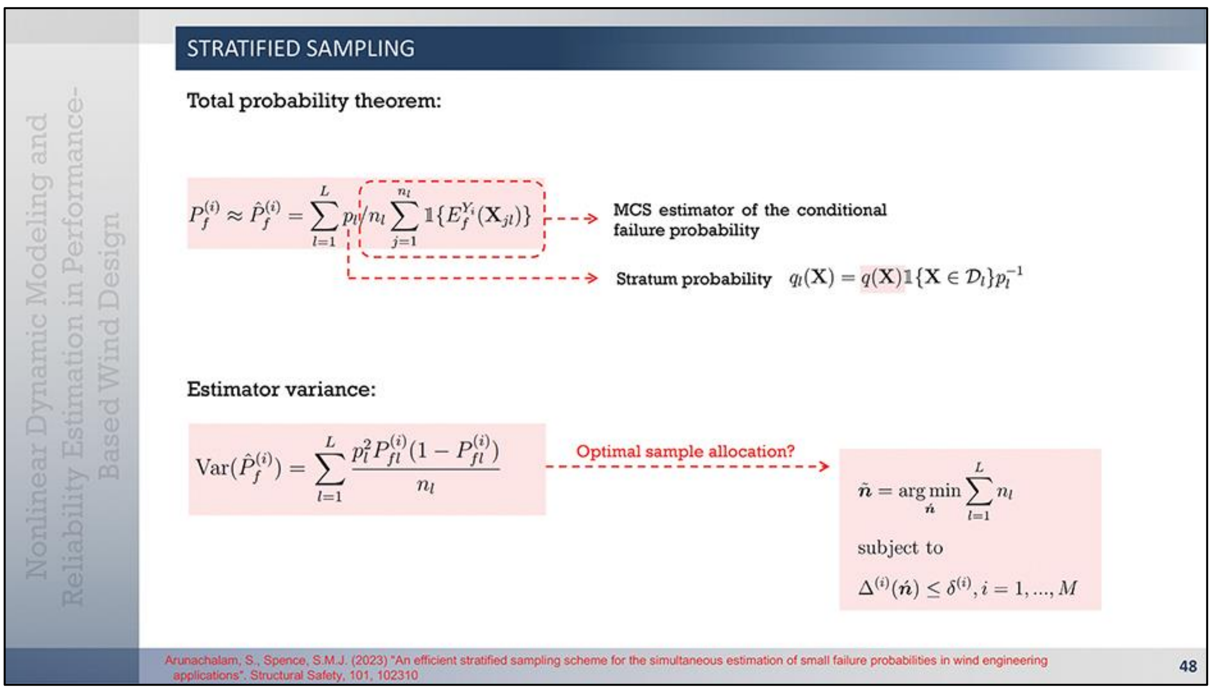
45

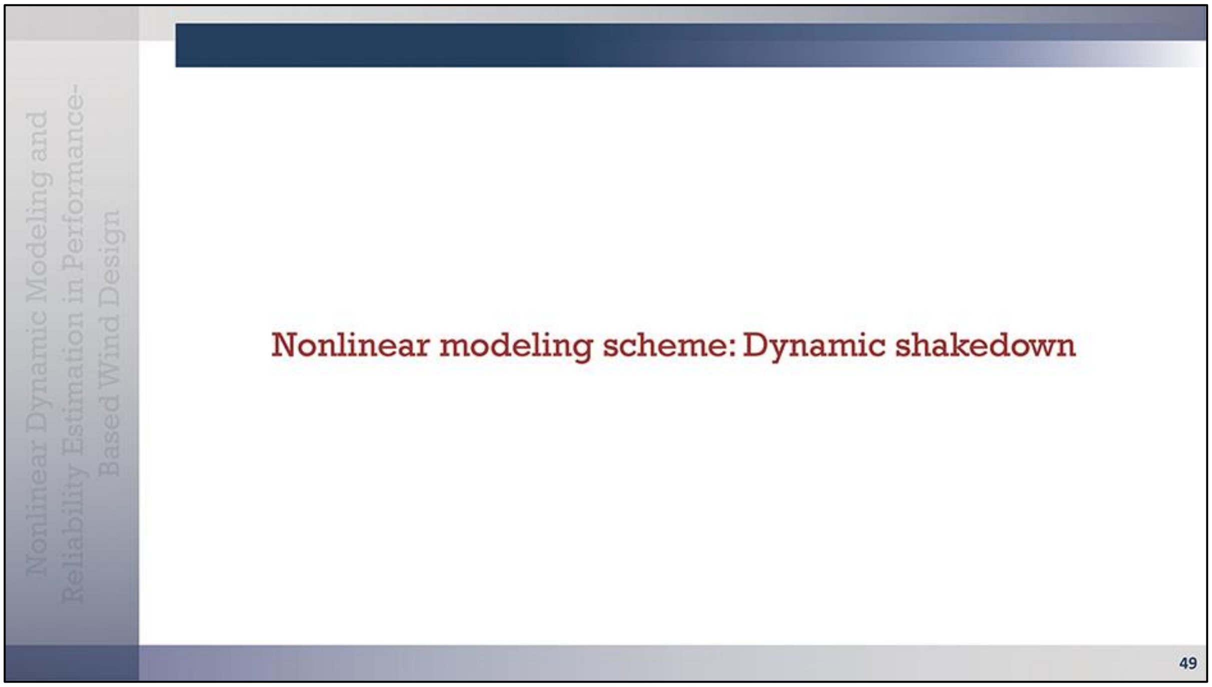
Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design

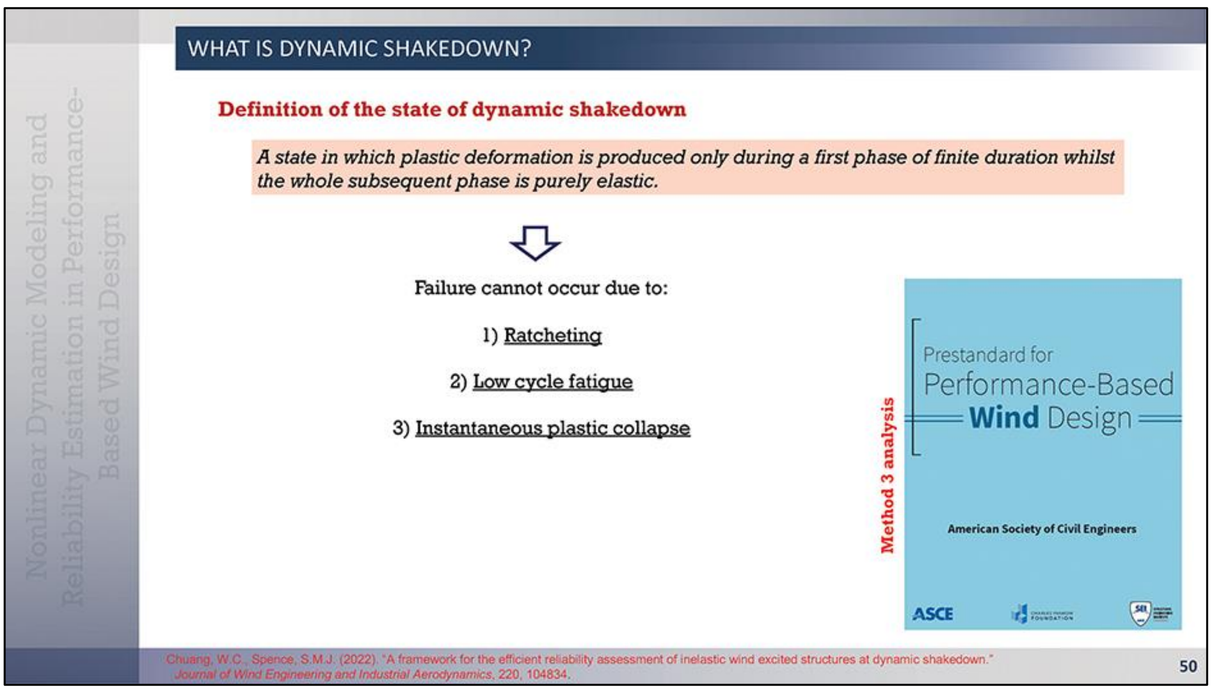
Uncertainty quantification

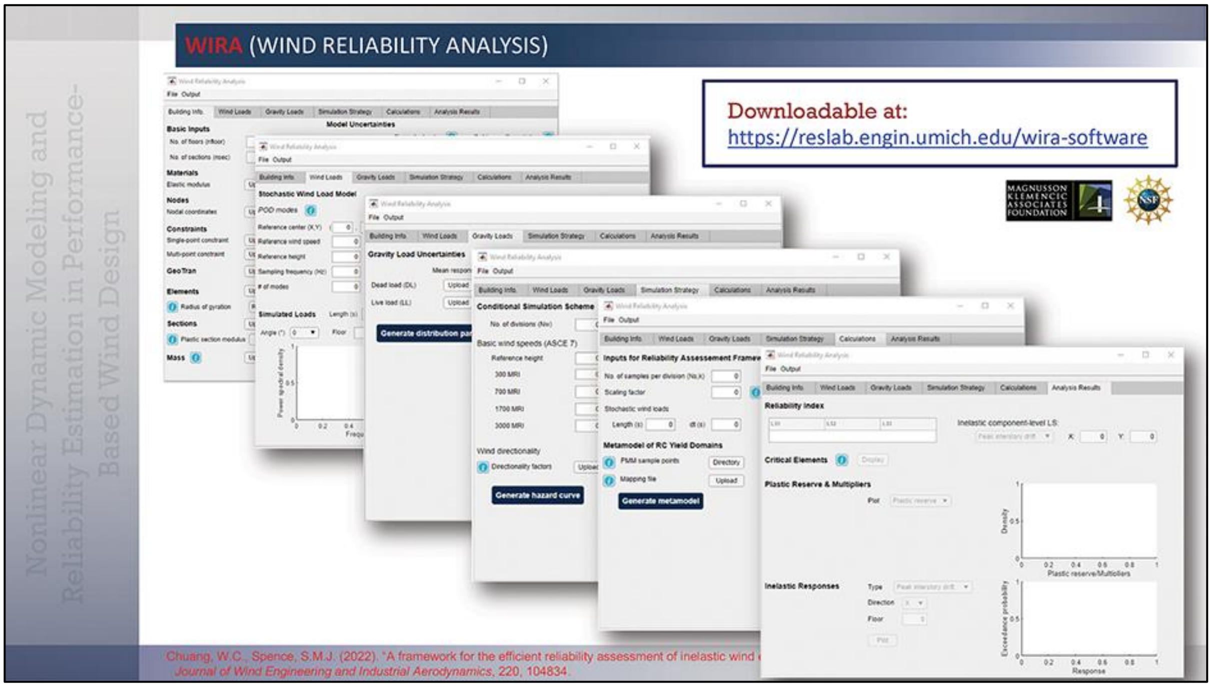
46

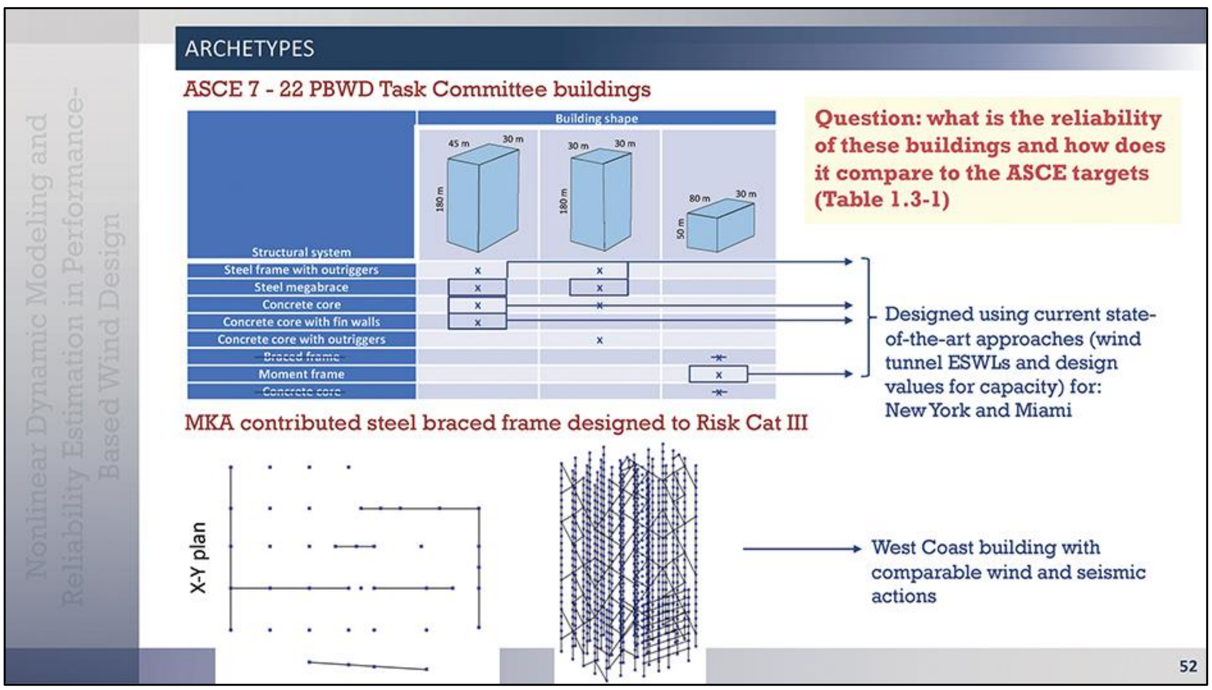

STRATIFIED SAMPLING
Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design
Preserve the desirable characteristics of simple MCS, yet achieve variance reduction
Wind speed is the dominant input random variable that influences the range of nonlinear responses and failure occurrences
$P(\overline{V}_H > \overline{v}_H)$
10^0
10^{-2}
10^{-4}
10^{-6}
0 10 20 30 40 50 60 70
$\overline{v}_H$ [m/s]
Most surprising (high entropy); abundant information
Rarely interesting
Typically interesting
Rarely interesting
Arunachalam, S., Spence, S.M.J. (2023) "An efficient stratified sampling scheme for the simultaneous estimation of small failure probabilities in wind engineering applications", Structural Safety, 101, 102310
47

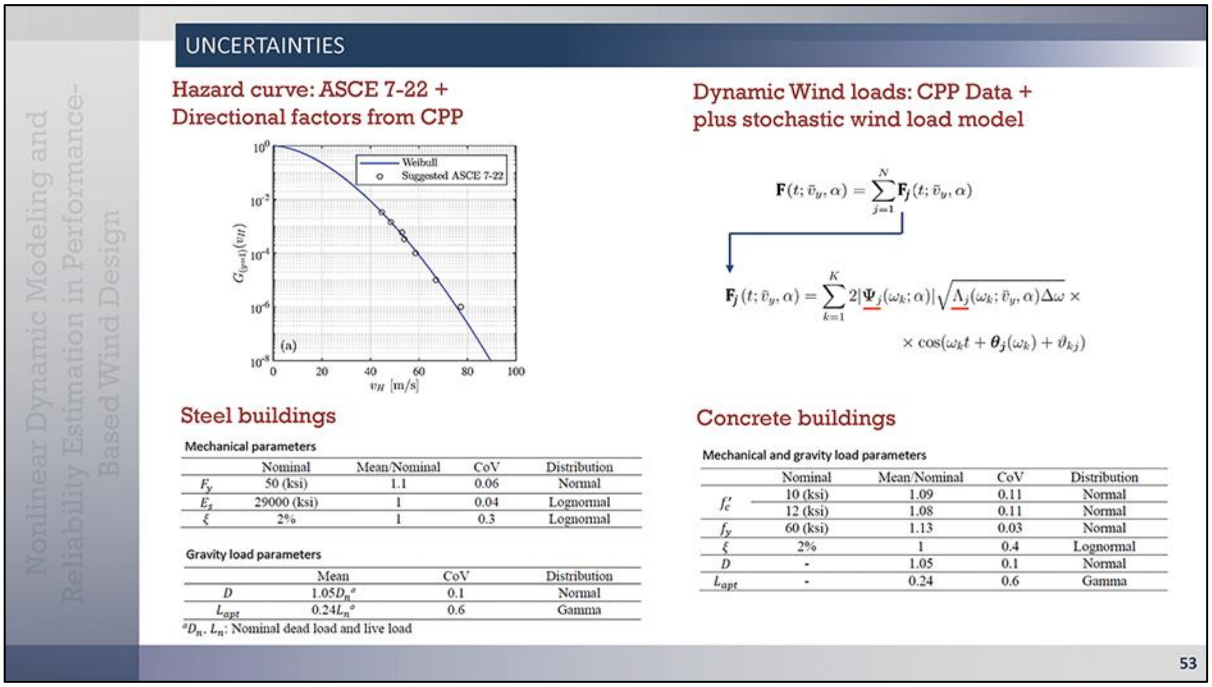

STRATIFIED SAMPLING
Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design
Total probability theorem:
$P_f^{(i)} \approx \hat{P}_f^{(i)} = \sum_{l=1}^{L} p_l / n_l \sum_{j=1}^{n_l} \mathbb{1}\{E_f^{Y_i}(\mathbf{X}_{jl})\}$
MCS estimator of the conditional failure probability
Stratum probability $q_l(\mathbf{X}) = q(\mathbf{X})\mathbb{1}\{\mathbf{X} \in \mathcal{D}_l\}p_l^{-1}$
Estimator variance:
$\mathrm{Var}(\hat{P}_f^{(i)}) = \sum_{l=1}^{L} \frac{p_l^2 P_{fl}^{(i)}(1 - P_{fl}^{(i)})}{n_l}$
Optimal sample allocation?
$\tilde{\boldsymbol{n}} = \arg\min_{\acute{\boldsymbol{n}}} \sum_{l=1}^{L} n_l$
subject to
$\Delta^{(i)}(\acute{\boldsymbol{n}}) \le \delta^{(i)}, i = 1, \ldots, M$
Arunachalam, S., Spence, S.M.J. (2023) "An efficient stratified sampling scheme for the simultaneous estimation of small failure probabilities in wind engineering applications", Structural Safety, 101, 102310
48


Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design
Nonlinear modeling scheme: Dynamic shakedown
49


Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design
WHAT IS DYNAMIC SHAKEDOWN?
Definition of the state of dynamic shakedown
A state in which plastic deformation is produced only during a first phase of finite duration whilst the whole subsequent phase is purely elastic.
Failure cannot occur due to:
1) Ratcheting
2) Low cycle fatigue
3) Instantaneous plastic collapse
Method 3 analysis
Prestandard for Performance-Based Wind Design
American Society of Civil Engineers
ASCE
Chuang, W.C., Spence, S.M.J. (2022). "A framework for the efficient reliability assessment of inelastic wind excited structures at dynamic shakedown." Journal of Wind Engineering and Industrial Aerodynamics, 220, 104834.
50


Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design
WIRA (WIND RELIABILITY ANALYSIS)
Downloadable at:
https://reslab.engin.umich.edu/wira-software
Chuang, W.C., Spence, S.M.J. (2022). "A framework for the efficient reliability assessment of inelastic wind
Journal of Wind Engineering and Industrial Aerodynamics, 220, 104834.


Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design
ARCHETYPES
ASCE 7 - 22 PBWD Task Committee buildings
Building shape
Structural system
Steel frame with outriggers
Steel megabrace
Concrete core
Concrete core with fin walls
Concrete core with outriggers
Braced frame
Moment frame
Concrete core
Question: what is the reliability of these buildings and how does it compare to the ASCE targets (Table 1.3-1)
Designed using current state-of-the-art approaches (wind tunnel ESWLs and design values for capacity) for: New York and Miami
MKA contributed steel braced frame designed to Risk Cat III
X-Y plan
West Coast building with comparable wind and seismic actions
52


Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design
UNCERTAINTIES
Hazard curve: ASCE 7-22 + Directional factors from CPP
Weibull
Suggested ASCE 7-22
$G_{(y=1)}(v_H)$
(a)
v_H [m/s]
Dynamic Wind loads: CPP Data + plus stochastic wind load model
$$\mathbf{F}(t;\bar{v}_y,\alpha)=\sum_{j=1}^{N}\mathbf{F}_j(t;\bar{v}_y,\alpha)$$
$$\mathbf{F}_j(t;\bar{v}_y,\alpha)=\sum_{k=1}^{K}2|\mathbf{\Psi}_j(\omega_k;\alpha)|\sqrt{\Lambda_j(\omega_k;\bar{v}_y,\alpha)\Delta\omega}\times$$
$$\times\cos(\omega_k t+\boldsymbol{\theta}_j(\omega_k)+\vartheta_{kj})$$
Steel buildings
Mechanical parameters

	Nominal	Mean/Nominal	CoV	Distribution
F_y	50 (ksi)	1.1	0.06	Normal
E_s	29000 (ksi)	1	0.04	Lognormal
ξ	2%	1	0.3	Lognormal

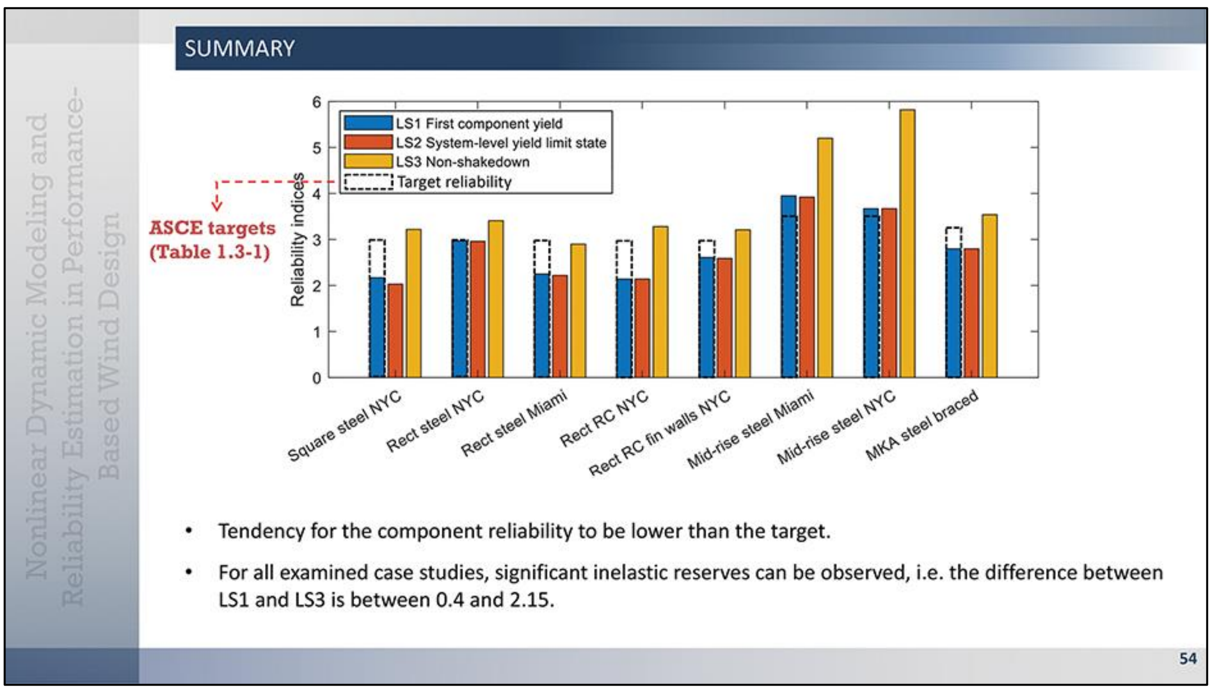
Gravity load parameters

	Mean	CoV	Distribution
D	$1.05D_n$[a]	0.1	Normal
L_{apt}	$0.24L_n$[a]	0.6	Gamma

[a] D_n, L_n: Nominal dead load and live load
Concrete buildings
Mechanical and gravity load parameters

	Nominal	Mean/Nominal	CoV	Distribution
f_c'	10 (ksi)	1.09	0.11	Normal
	12 (ksi)	1.08	0.11	Normal
f_y	60 (ksi)	1.13	0.03	Normal
ξ	2%	1	0.4	Lognormal
D	-	1.05	0.1	Normal
L_{apt}	-	0.24	0.6	Gamma

53


Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design
SUMMARY
LS1 First component yield
LS2 System-level yield limit state
LS3 Non-shakedown
Target reliability
ASCE targets (Table 1.3-1)
Reliability indices
Square steel NYC
Rect steel NYC
Rect steel Miami
Rect RC NYC
Rect RC fin walls NYC
Mid-rise steel Miami
Mid-rise steel NYC
MKA steel braced
• Tendency for the component reliability to be lower than the target.
• For all examined case studies, significant inelastic reserves can be observed, i.e. the difference between LS1 and LS3 is between 0.4 and 2.15.
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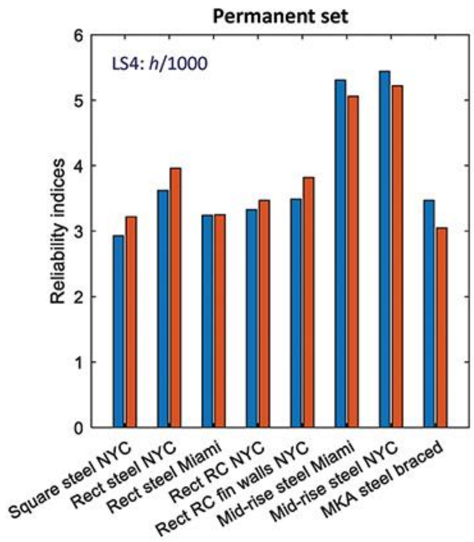
Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design

SUMMARY



Importantly, reliabilities associated with residual drift (permanent set) were seen to be consistent in both principal response directions and generally greater than the target component reliability

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Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design

Nonlinear modeling scheme: High-fidelity approaches

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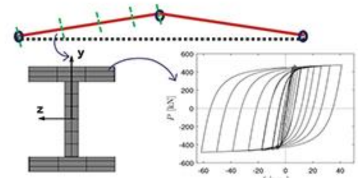
Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design

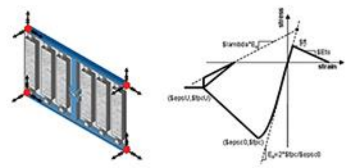
HIGH-FIDELITY STRUCTURAL MODELING

Nonlinear Structural Modeling (in OpenSees)

1) Fiber-based models that capture the **complex hysteretic behavior** of steel (including reinforcing) and concrete
2) **Low-cycle fatigue and potential fiber fracture** captured by damage index parameter: *Fatigue* model wrapped around *Steel02/SteelMPF* in OpenSees
3) Each compression member modeled using two inelastic elements with random initial camber to trigger **flexural buckling**
4) **Corotational formulation** for the geometric nonlinear effects
5) **Shell elements** with macro fibers for shear wall modeling
6) **Nonlinear Rayleigh damping** model
7) **Explicit or implicit** direct dynamic integration schemes:

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{f}_D(\dot{\mathbf{u}}(t), \mathbf{u}(t)) + \mathbf{f}_r(\mathbf{u}(t)) = \mathbf{f}(t; \bar{v}_H, \alpha)$$





Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design

CASE STUDY 1 - OVERVIEW

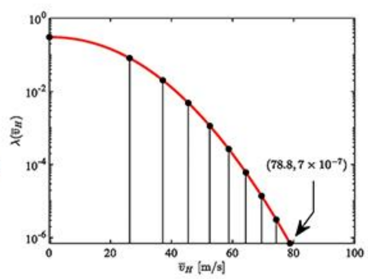
Description

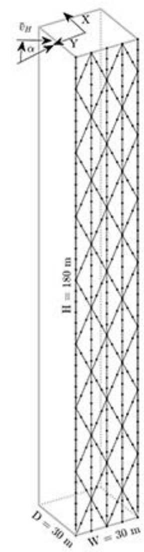
- 45-story building in New York City
  - Mega-braced steel frame
  - W14 sections for columns and braces
  - Rigid diaphragm
- Limit States
  - System first yield
  - Component first yield
  - Component fracture
  - Component buckling
  - System collapse
- Wind load model
  - Weibull distribution for $F_{\bar{v}_H}$
  - CPP wind tunnel data
  - 1-hr duration, 300 s ramp up and ramp down portions, 200s free vibration

Structural model uncertainties, ξ_m

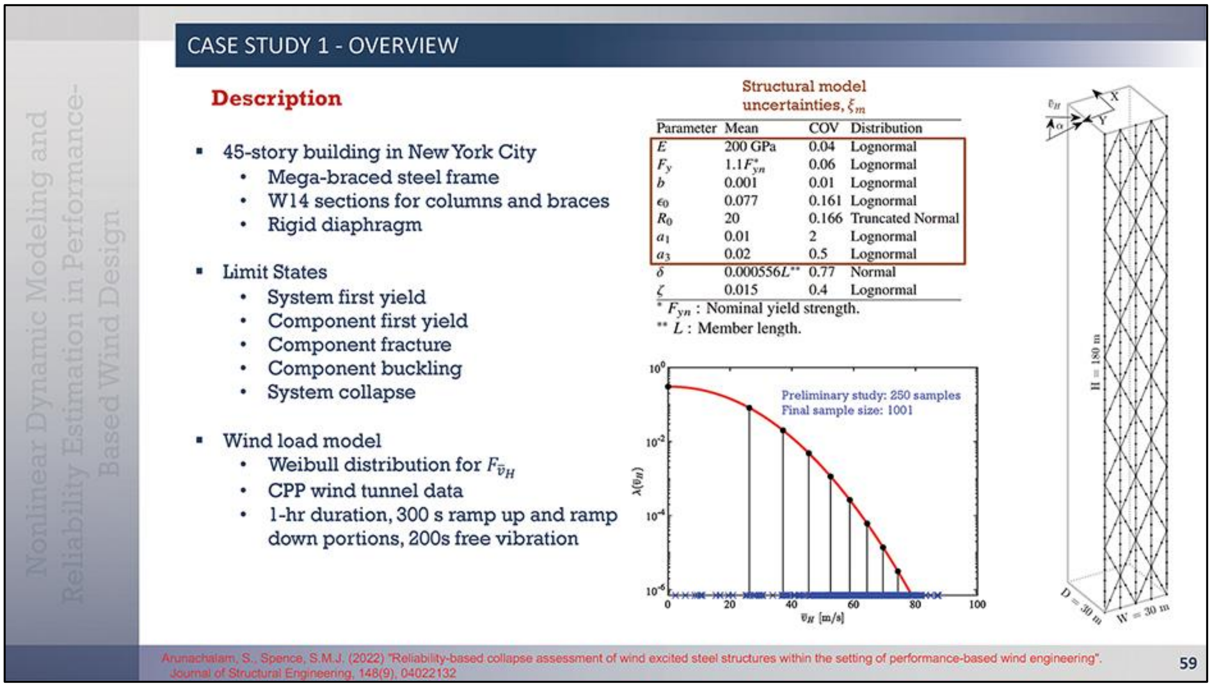
Parameter	Mean	COV	Distribution
E	200 GPa	0.04	Lognormal
F_y	$1.1F^*_{yn}$	0.06	Lognormal
b	0.001	0.01	Lognormal
ϵ_0	0.077	0.161	Lognormal
R_0	20	0.166	Truncated Normal
a_1	0.01	2	Lognormal
a_3	0.02	0.5	Lognormal
δ	$0.000556L^{**}$	0.77	Normal
ζ	0.015	0.4	Lognormal

* F_{yn} : Nominal yield strength.
** L : Member length.





Arunachalam, S., Spence, S.M.J. (2022) "Reliability-based collapse assessment of wind excited steel structures within the setting of performance-based wind engineering". Journal of Structural Engineering, 148(9), 04022132


CASE STUDY 1 - OVERVIEW
Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design
Description
45-story building in New York City
Mega-braced steel frame
W14 sections for columns and braces
Rigid diaphragm
Limit States
System first yield
Component first yield
Component fracture
Component buckling
System collapse
Wind load model
Weibull distribution for $F_{\bar{v}_H}$
CPP wind tunnel data
1-hr duration, 300 s ramp up and ramp down portions, 200s free vibration
Structural model uncertainties, ξ_m
Parameter Mean COV Distribution
E 200 GPa 0.04 Lognormal
F_y $1.1F_{yn}^*$ 0.06 Lognormal
b 0.001 0.01 Lognormal
ϵ_0 0.077 0.161 Lognormal
R_0 20 0.166 Truncated Normal
a_1 0.01 2 Lognormal
a_3 0.02 0.5 Lognormal
δ $0.000556L^{**}$ 0.77 Normal
ζ 0.015 0.4 Lognormal
* F_{yn} : Nominal yield strength.
** L : Member length.
Preliminary study: 250 samples
Final sample size: 1001
$\lambda(\bar{v}_H)$
$\bar{v}_H$ [m/s]
H = 180 m
D = 30 m
W = 30 m
Arunachalam, S., Spence, S.M.J. (2022) "Reliability-based collapse assessment of wind excited steel structures within the setting of performance-based wind engineering". Journal of Structural Engineering, 148(9), 04022132
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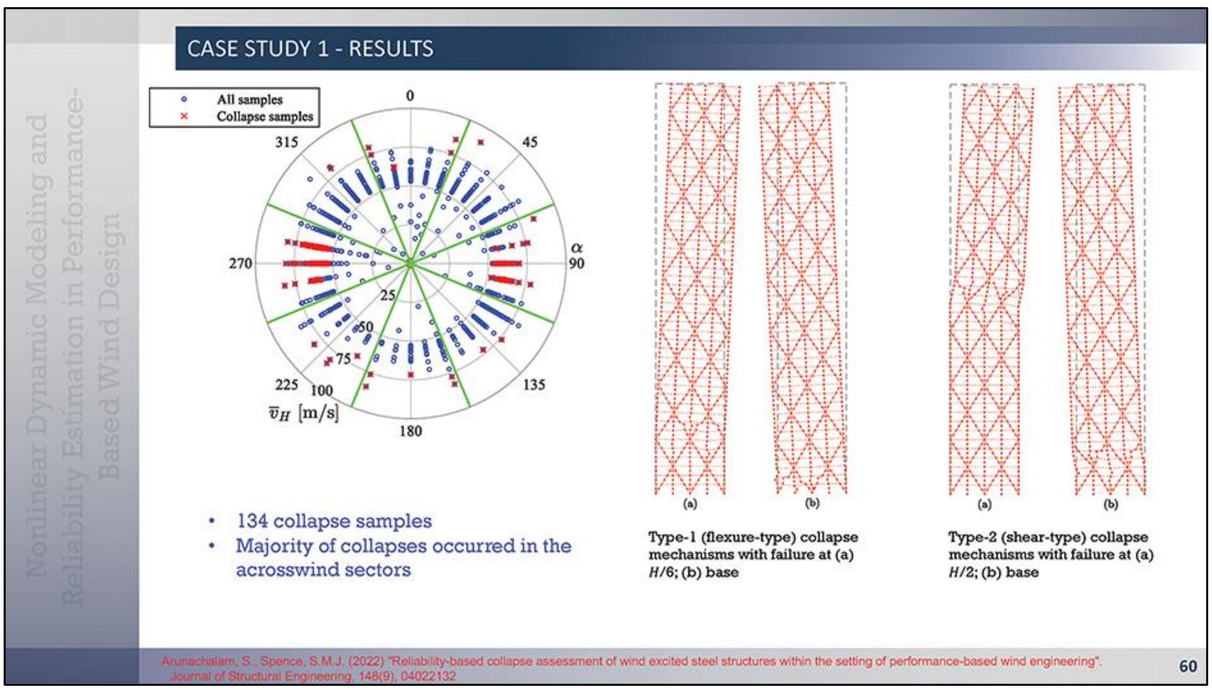
CASE STUDY 1 - RESULTS
Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design
All samples
Collapse samples
α
$\bar{v}_H$ [m/s]
134 collapse samples
Majority of collapses occurred in the acrosswind sectors
Type-1 (flexure-type) collapse mechanisms with failure at (a) $H/6$; (b) base
Type-2 (shear-type) collapse mechanisms with failure at (a) $H/2$; (b) base
Arunachalam, S., Spence, S.M.J. (2022) "Reliability-based collapse assessment of wind excited steel structures within the setting of performance-based wind engineering". Journal of Structural Engineering, 148(9), 04022132
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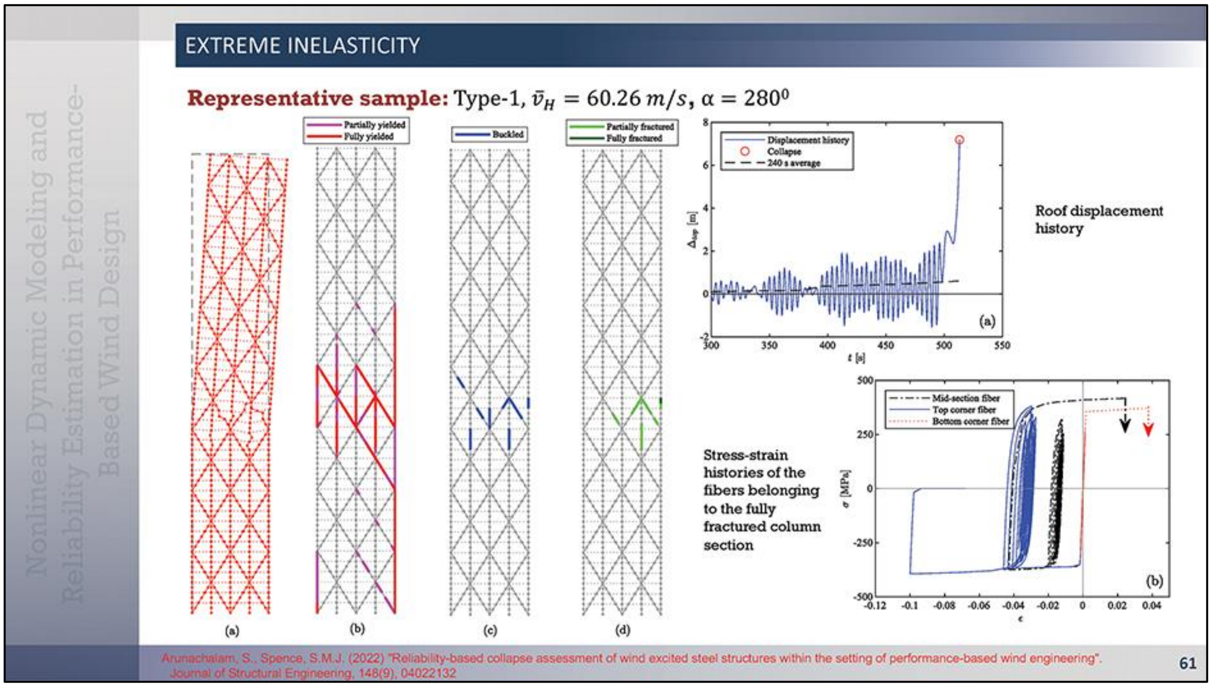


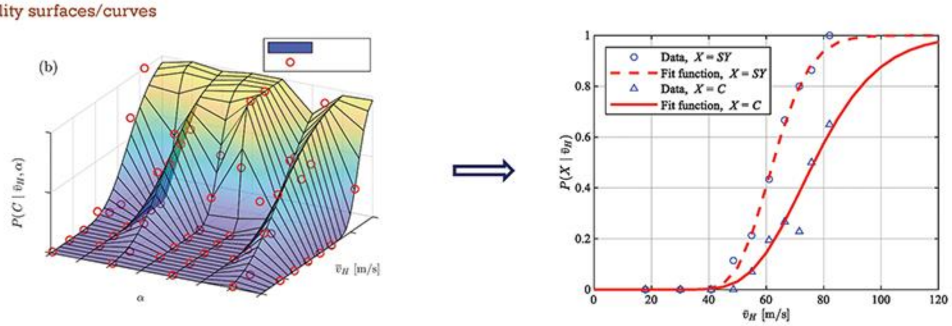
CASE STUDY 1 - RESULTS

Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design

Annual failure rates and 50 year reliability indices

Limit State	AER, $\nu\hat{P}_f$	COV($\nu\hat{P}_f$)	β_{50}
System collapse	1.18×10^{-4}	9.5%	2.52
Component first yield	5.64×10^{-4}	31.1%	1.91
System first yield	7.40×10^{-4}	26.9%	1.79
Component buckling	3.87×10^{-5}	17.9%	2.89
Component fracture	1.75×10^{-5}	26.5%	3.13

Fragility surfaces/curves



Arunachalam, S., Spence, S.M.J. (2022) "Reliability-based collapse assessment of wind excited steel structures within the setting of performance-based wind engineering". Journal of Structural Engineering, 148(9), 04022132

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Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design

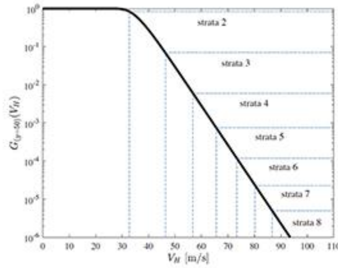
CASE STUDY 2

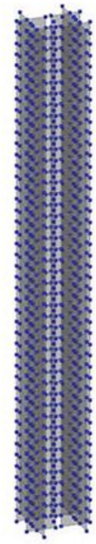
Description

- 45-story building in New York City
  - Reinforced concrete core system
  - Coupling beams at each floor
  - Rigid diaphragm
- Limit States
  - Concrete crushing
  - Concrete cracking
  - Rebar fracture
  - Rebar buckling
  - Rebar fatigue failure
  - System collapse
- Wind load model
  - Type 1 distribution for $F_{\bar{v}_H}$
  - CPP wind tunnel data
  - 1-hr duration, 300 s ramp up and ramp down portions, 200s free vibration

Summary of random variables for structural models

Parameter	Mean	COV	Distribution
f_c	f_{cn}	20%	Lognormal
ϵ_c	0.004	20%	Lognormal
f_u	f_{un}	20%	Lognormal
ϵ_u	0.02	20%	Lognormal
F_y	F_{yn}	10.6%	Beta
E_0	200Gpa	3.3%	Lognormal
b	0.02	20%	Lognormal
ϵ_0	0.077	16.1%	Lognormal
ϵ_{sh}	0.1	0.133%	Lognormal
ζ	ζ_n	30%	Lognormal





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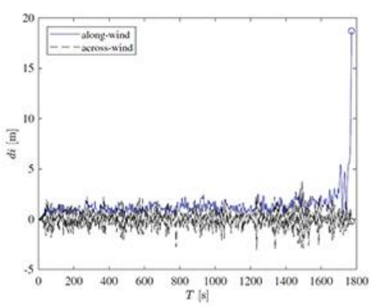
Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design

CASE STUDY 2



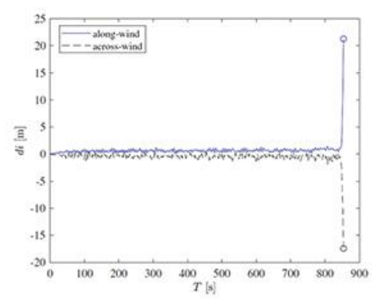


Table 6: Failure probabilities and reliability indices over 50 years

Limit States	Description	P_{f_R}	COV	β_{50}
LS1	system collapse	5.94×10^{-7}	20.02%	4.86
LS2	along-wind peak inter-story drift ratio > 1/50	9.71×10^{-7}	14.97%	4.76
LS3	across-wind peak inter-story drift ratio > 1/50	1.31×10^{-5}	39.18%	4.20
LS4	along-wind roof residual drift ratio> 1/1000	2.77×10^{-5}	24.45%	4.03
LS5	across-wind roof residual drift ratio > 1/1000	3.85×10^{-6}	23.98%	4.47
LS6	compressive fiber experiencing concrete crush/rebar buckling	2.16×10^{-7}	34.59%	5.05
LS7	tensile fiber experiencing rebar fracture	1.35×10^{-7}	44.12%	5.14

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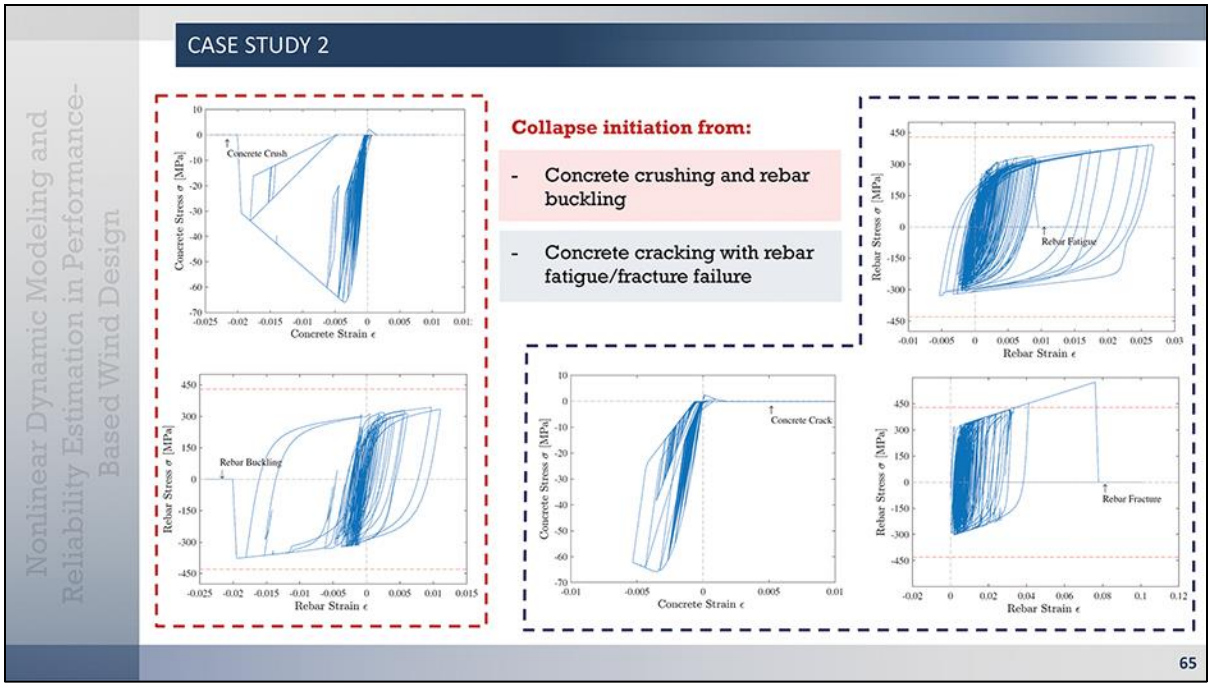
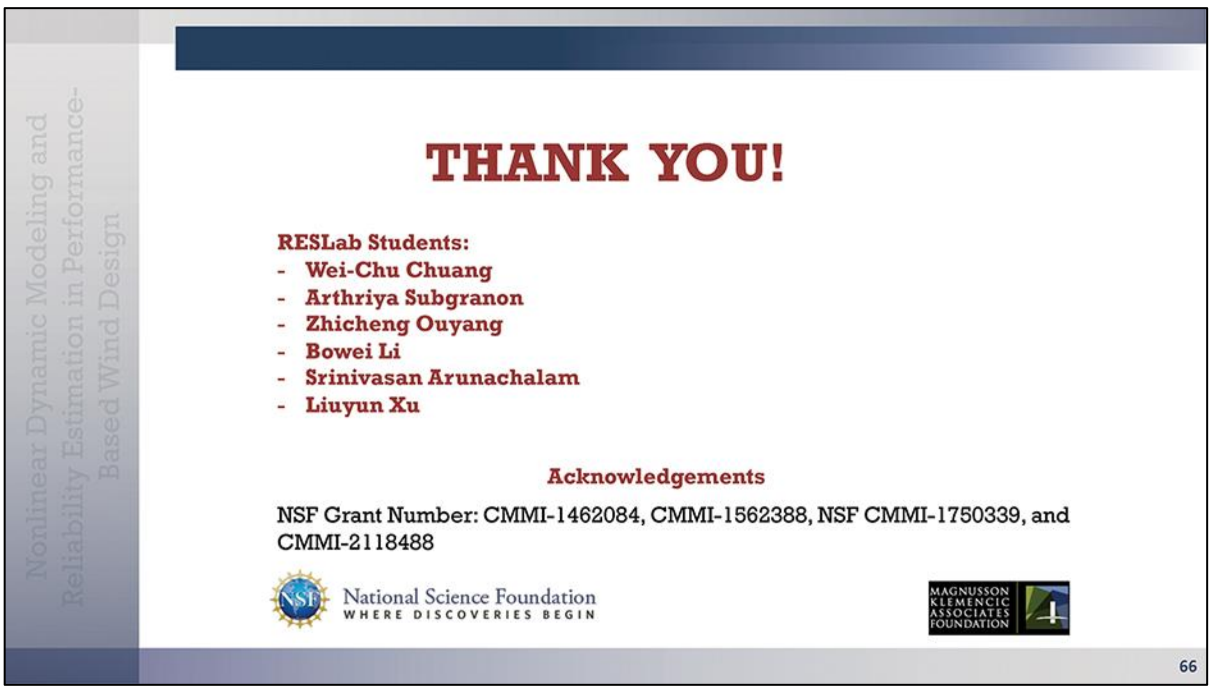

Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design
CASE STUDY 2
Collapse initiation from:
- Concrete crushing and rebar buckling
- Concrete cracking with rebar fatigue/fracture failure
Concrete Crush
Concrete Stress σ [MPa]
Concrete Strain ϵ
Rebar Buckling
Rebar Stress σ [MPa]
Rebar Strain ϵ
Rebar Fatigue
Concrete Crack
Rebar Fracture
65


Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design
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- Liuyun Xu
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National Science Foundation
WHERE DISCOVERIES BEGIN
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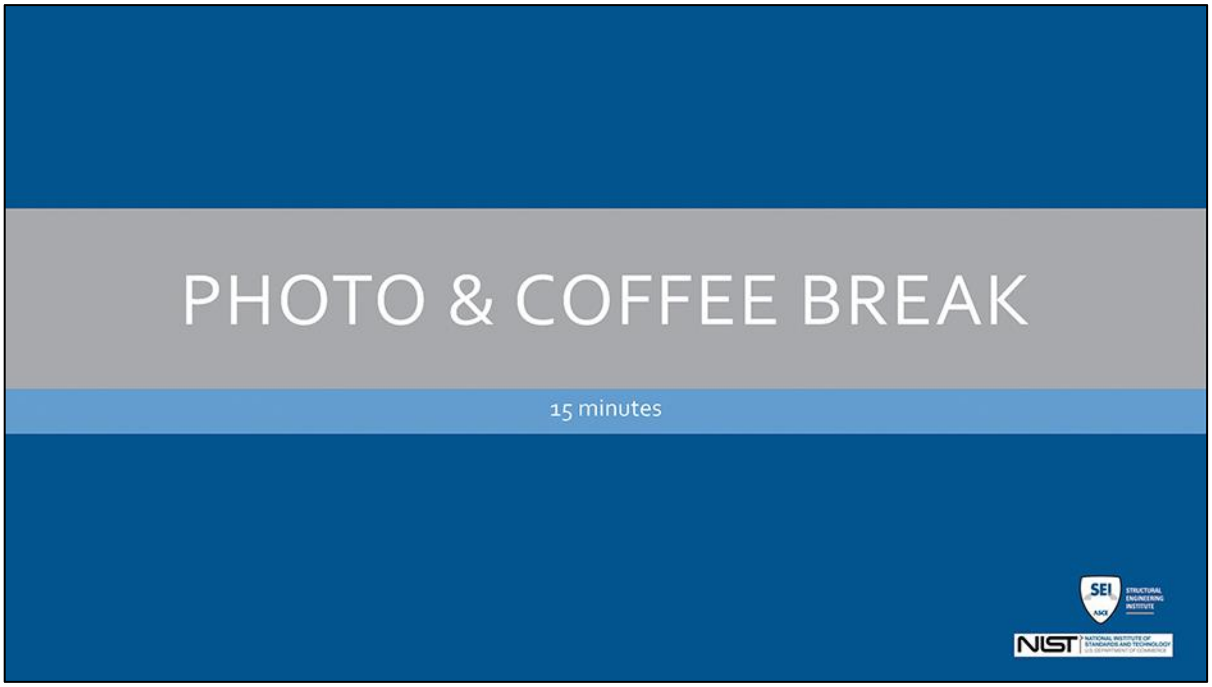
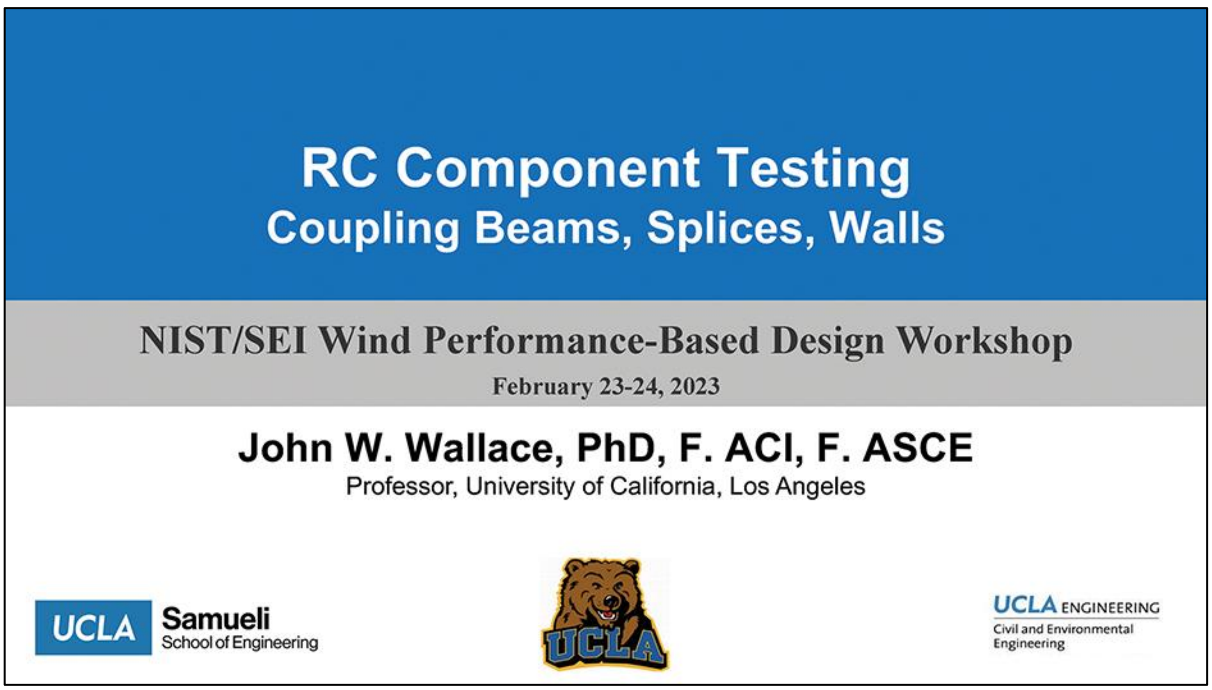


PHOTO & COFFEE BREAK
15 minutes
SEI STRUCTURAL ENGINEERING INSTITUTE
NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY


RC Component Testing
Coupling Beams, Splices, Walls
NIST/SEI Wind Performance-Based Design Workshop
February 23-24, 2023
John W. Wallace, PhD, F. ACI, F. ASCE
Professor, University of California, Los Angeles
UCLA Samueli School of Engineering
UCLA
UCLA ENGINEERING
Civil and Environmental Engineering

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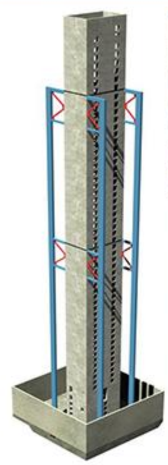
Performance-Based Wind Design

- **RC core wall buildings**
- **Economical**
  - **Low story heights**
  - **Open floor plans/views**
- **Efficient and Reliable lateral system**
  - **Large lateral stiffness and strength**
  - **Reliable yield mechanisms**
- **Research Issues**
  - **Well-defined and limited in scope**
  - **Coupling beam and wall plastic hinge detailing**
- **Very focused (limited) discussion today**



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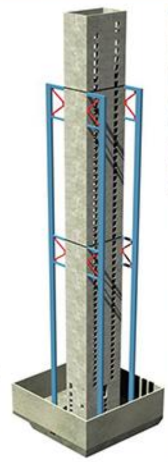
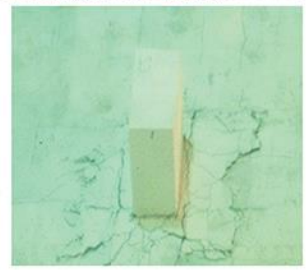
Research Topics Wind PBD: Components

- **Reinforced Concrete Link Beams**
  - RC, Steel RC (conventional reinforcement)
  - Reinforced with steel fibers
- **RC Shear Wall Performance**
  - Core walls (flanged wall cross sections)
  - Planar walls
- **Outrigger (intentional) Performance**
  - BRBs, beams, panels
- **Outrigger (gravity frame) Performance**
  - RC or PT slab column frames





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Research Objectives

- Coupling Beams & Walls
  - Requirements for modest levels of yielding
    - Capacity design (strength hierarchy)
    - Detailing: Transverse reinforcement (confinement/rebar buckling, anchorage/splices)
  - Load vs deformation behavior
    - stiffness degradation (cyclic), energy dissipation, strength loss (damage)
    - Modeling for nonlinear analysis
  - Damage (repairability)
  - Loading protocol (wind vs seismic vs gravity)
- Slab-Column Connections (gravity system)
  - Rotation capacity (w/o shear reinforcement) prior to punching failure
  - Damage (repair) and Loading protocol

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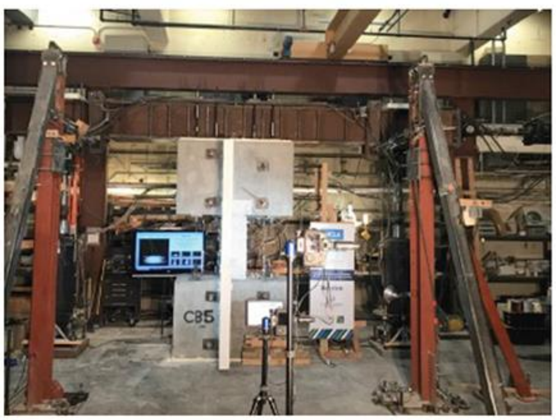
UCLA Coupling Beam Research



8 Test Beams	2/3 scale	Aspect Ratio	w/ and w/o slab	Loading Protocol

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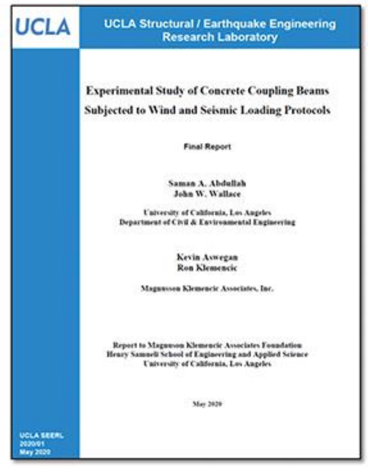
Reports & Journal Papers

- **Coupling Beams - Reports**
  - Experimental Study of Concrete Coupling Beams Subjected to Wind and Seismic Loading Protocols, UCLA SEERL Report 2020/01, May 2020, 276 pp.
  - Recommendations for Modeling of Reinforced Concrete Coupling Beams for Performance-Based Wind Design, UCLA SEERL Report 2022/01, 138 pp.
- **Coupling Beams – Journal Papers**
  - Abdullah SA, Aswegan K, Jaberansari, S, Klemencic RO, and Wallace JW, Performance of Coupling Beams Subjected to Simulated Wind Loading Protocols, ACI Structural Journal, 117(3), May 2020, pp 1-14. MS No. S-2019-203, 10.14359/51724555.
  - Abdullah SA, Aswegan K, Klemencic RO, and Wallace JW, Performance of Concrete Coupling Beams Subjected to Simulated Wind Loading Protocols – Phase II, ACI Structural Journal, 118(3), May 2021, pp 101-116. MS No. S-2020-105.R3, doi: 10.14359/51729356.
  - Abdullah SA, Aswegan K, Klemencic RO, and Wallace JW, Seismic Performance of Concrete Coupling Beams Subjected to Prior Nonlinear Wind Demands, Engineering Structures, 268 (2022), 114790, 17 pp.


UCLA
UCLA Structural / Earthquake Engineering Research Laboratory

Experimental Study of Concrete Coupling Beams Subjected to Wind and Seismic Loading Protocols

Final Report

Saman A. Abdullah
John W. Wallace
University of California, Los Angeles
Department of Civil & Environmental Engineering

Kevin Aswegan
Ron Klemencic
Magnusson Klemencic Associates, Inc.

Report to Magnusson Klemencic Associates Foundation
Henry Samueli School of Engineering and Applied Science
University of California, Los Angeles

May 2020

UCLA SEERL 2020/01 May 2020

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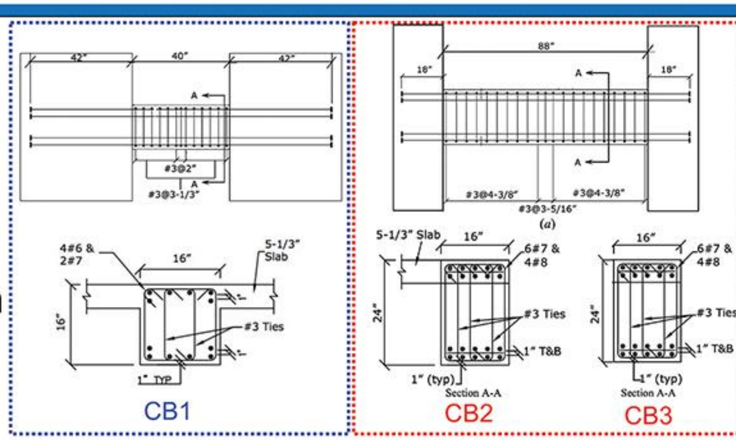
Phase I: RC Test Beams

- Demand
  - $V_u = 5\sqrt{f'_c}\, b_w d$
- Standard detailing
  - ACI 318-14 Ch.9
- No capacity design
  - $V_n \approx V_{@Mpr}$
  - $\phi V_n \approx V_u$



Standard detailing
Aspect ratio = 2.5
T-shaped slab

Standard detailing
Aspect ratio = 3.67
No vs. L-shaped slab

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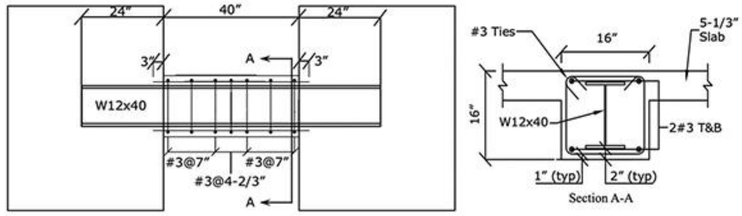
Phase II: 3 RC Beams + 1 SRC Beam

- Aspect ratio = 2.5
- Slab (both sides)
- Demand
  - $V_u = 5\sqrt{f'_c}\, b_w d$
- Standard detailing
  - ACI 318-14 Ch.9
  - AISC 360
- Connection capacity designed
- Rigid end blocks
  - UCLA Test
  - WSU (Motter) Tests



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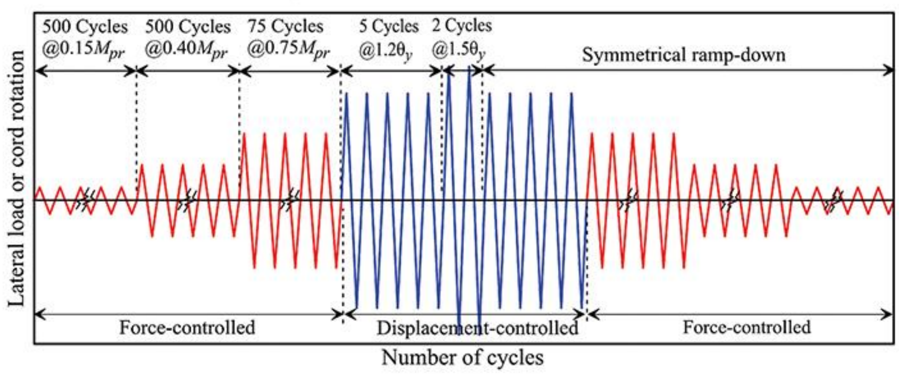
Loading Protocol Development (3/3)

- Consists of 2162 cycles
  - Building with 6s period (50-60 story) ≈ 3.5 hr storm
  - Took 7 to 10 days to test each beam



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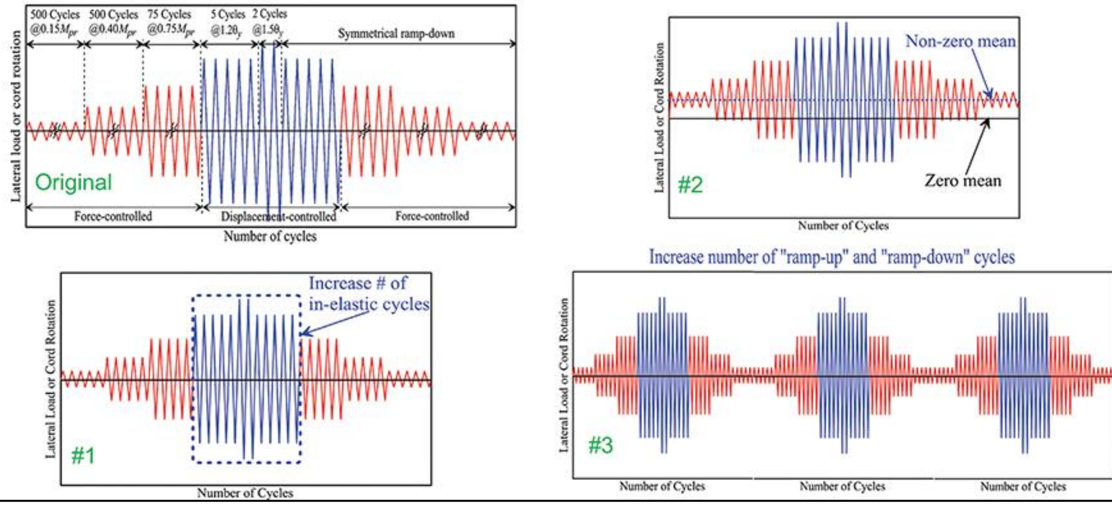
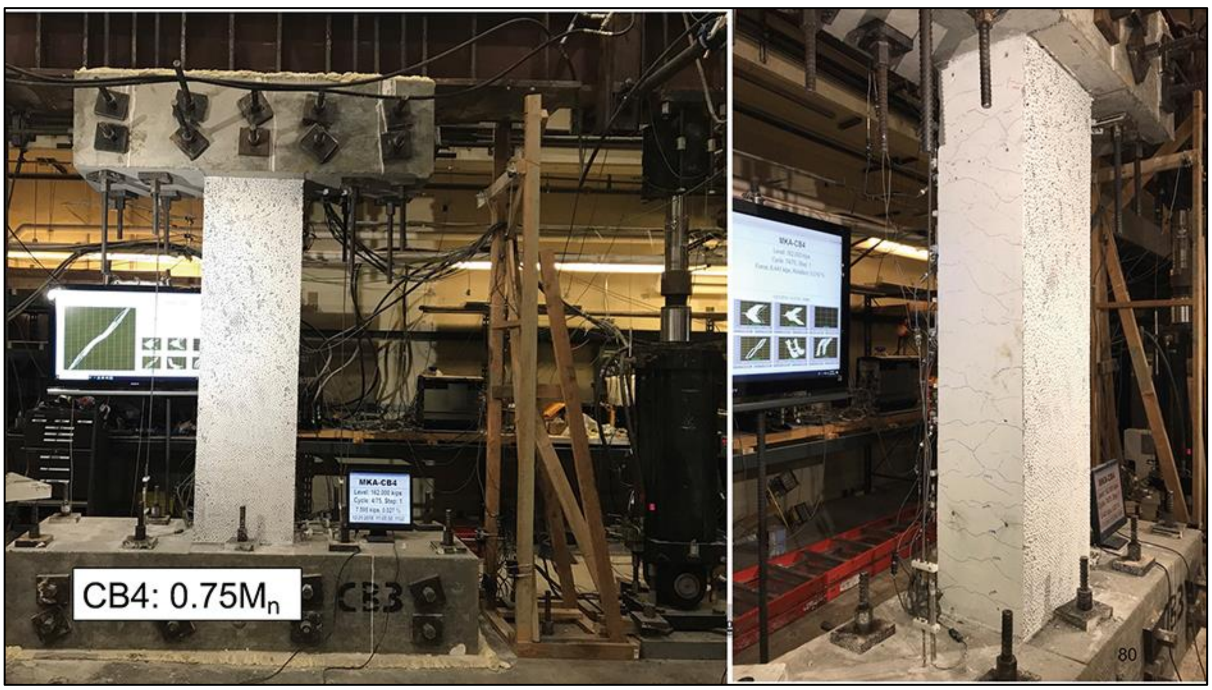
Phase II: Alternative Loadings Protocols

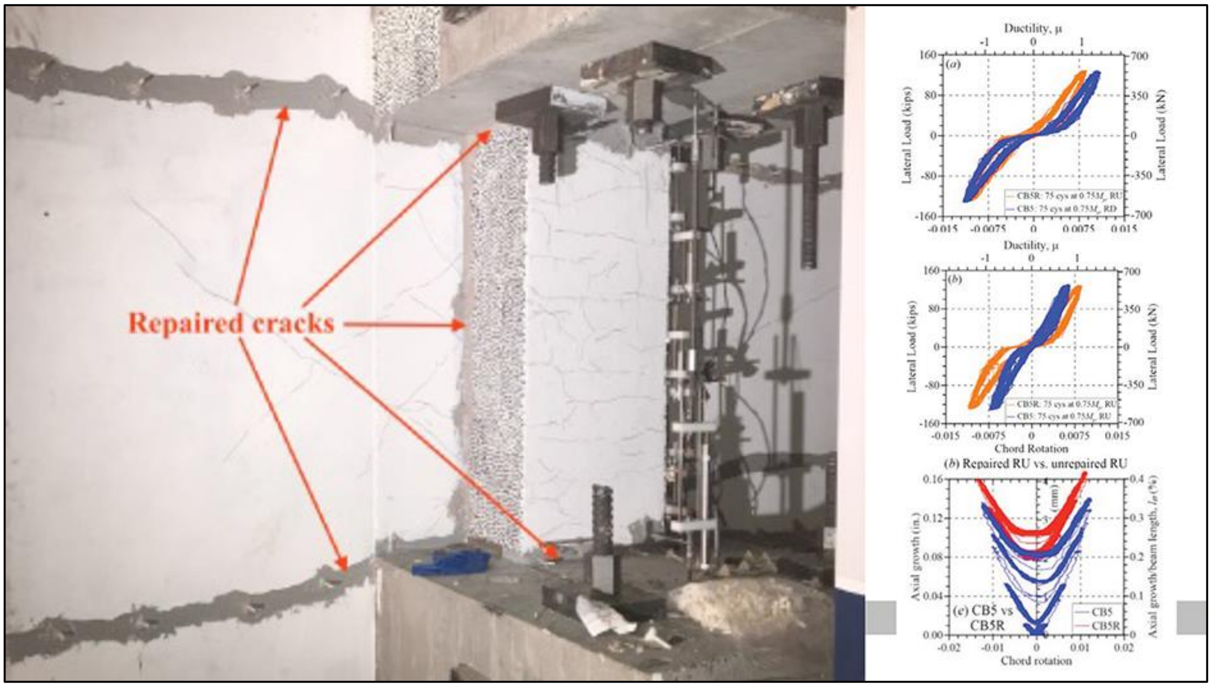
- Replicate three "standard" beams from Phase I



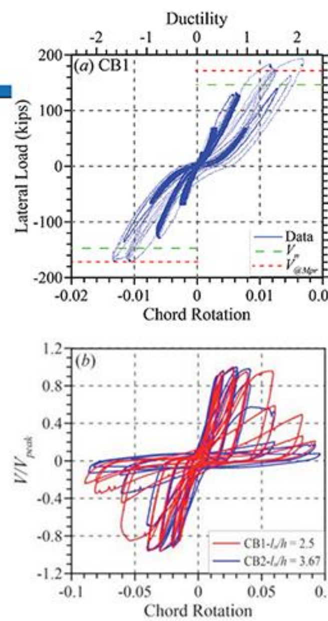



CB2: 1.5θ_y
MKA-CB2
81

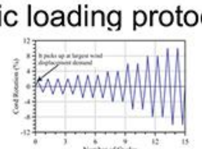

CB2: 2.0θ_y
MKA-CB2-
CB2
82



Summary



- Very modest damage for $\theta_{max}/\theta_y < 2.0$ (3.0)
  - Small residual rotations
  - Repair (epoxy) – not very effective (+15% stiffness)
- Pinching (> than for diagonal rebar)
- Aspect ratio (2.5 and 3.67)
  - Stiffness (l_n/h); otherwise, similar
- Strength loss (seismic loading protocol)
  - θ_{max}/θ_y = 5.3 to 8.0
  - θ_{max} = 4 to 6%



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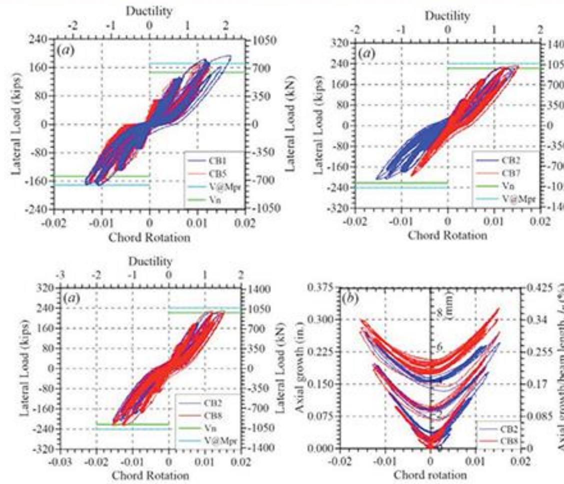
Summary

- Loading protocol
  - More inelastic cycles
  - Non-zero mean
  - Multiple loading protocols
    - Wind loading: Limited impact (more axial growth)
    - Seismic loading: Modestly reduced deformation capacity
- SRC Beam (1 beam; WSU)
  - Excellent performance



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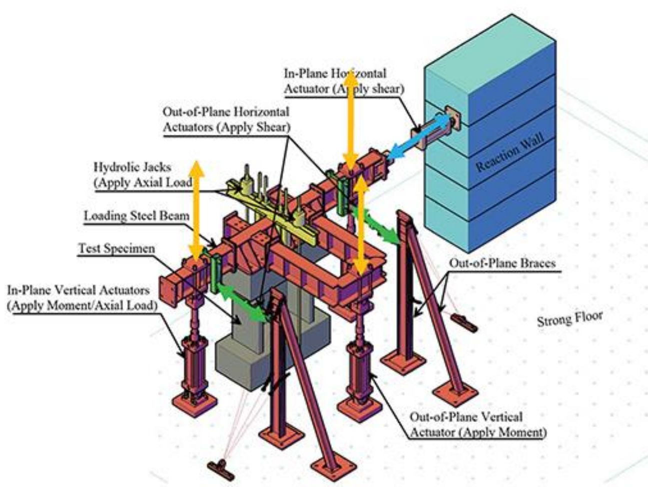
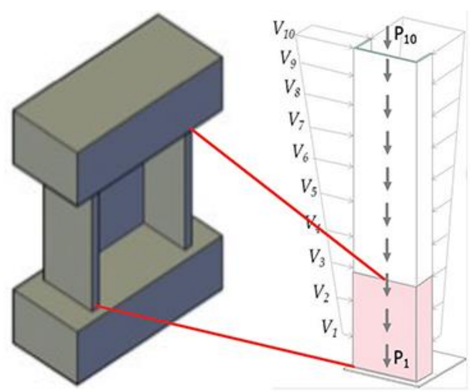
UCLA Wall Test Program





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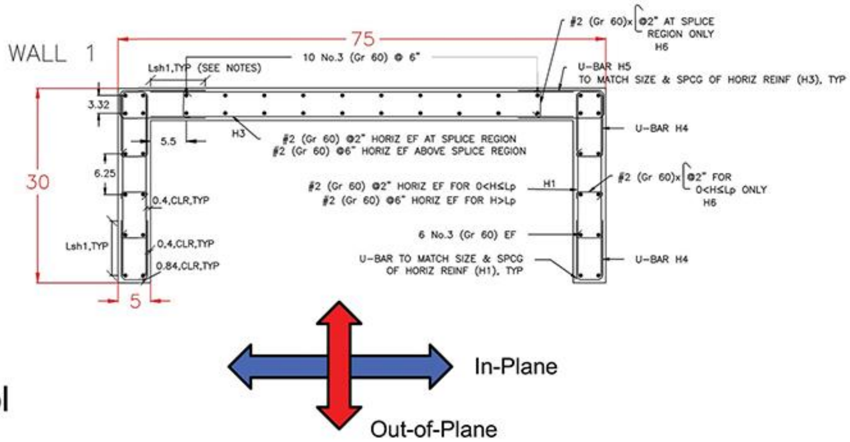
UCLA Wall Test Specimens

- $f'_{ce} \approx 8$ ksi
- Ordinary Detailing
- $P_u = 0.1A_g f'_c$ (constant)
- Biaxial Loading
  - $M_{pr,In\text{-}plane}$ + $0.5M_{pr,Out\text{-}of\text{-}plane}$
- Loading Protocol



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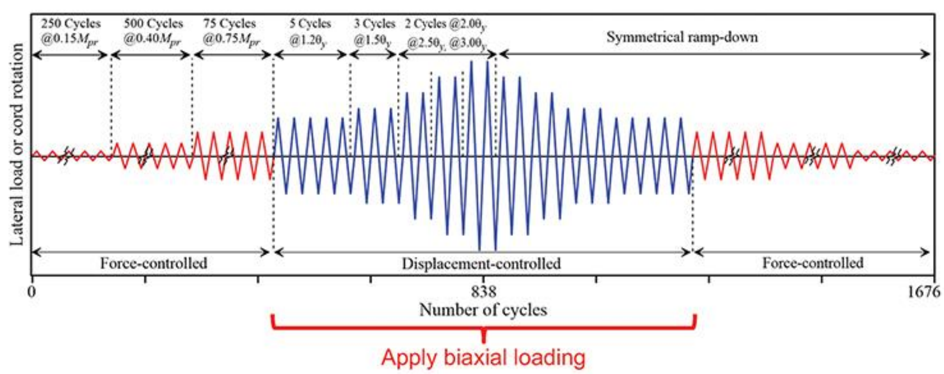
Loading Protocol

- 1650 elastic cycles (0.15, 0.40 and $0.75M_{pr,IP}$)
- Total of 26 inelastic cycles; Max ductility ratio of $3.0\Theta_y$



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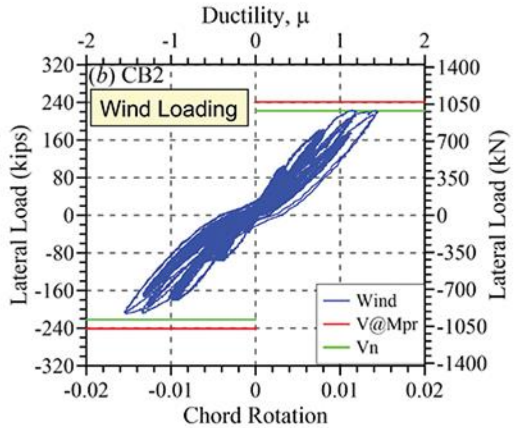
Shear Wall Wind-Related Performance Issues

- Lateral System (core wall)
  - Load vs Deformation behavior
    - Modeling parameters
  - Stiffness behavior/degradation
  - Unloading/Reloading (energy)
  - Strength loss (splices)
- Gravity System
  - Slab-column connections
- Lateral system
  - Outriggers
- Repair (stiffness)



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SPLICES

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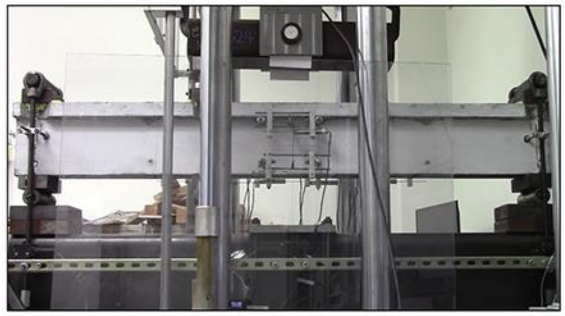
Wall Splice Behavior (fatigue)

- Literature Review
  - Pre-yield loading (fatigue)
  - Post-yield loading (seismic)
    - May reduce peak strength
    - Can significantly reduce deformation capacity
    - Tests reported in the literature had long splice lengths (relative to 318-19)
  - Only one test program using wind loading protocols with nonlinear demands (long splice lengths, well detailed)

UCLA Beam Tests



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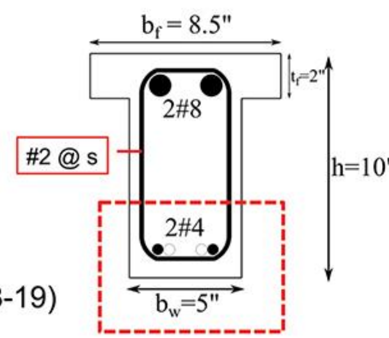
UCLA Beam Splice Tests

- **Splice region – Same as wall**
  - b_w = 5”
  - #4 longitudinal bars (spliced bottom bars)
  - c_b / d_b = 2.25
  - #2 stirrups
- **Splice details**
  - Splice length: l_d=12 in. (per §25.4.2.4 of ACI 318-19)
  - Stirrup spacing: s_{max} = 18 in. governs (full-scale)

    s_{max} = 6 in. for 1/3 scale C-shaped walls



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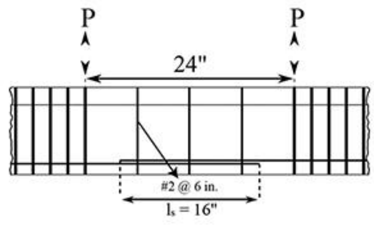
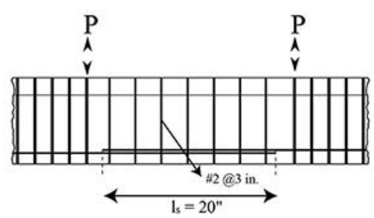
UCLA Beam Splice Tests

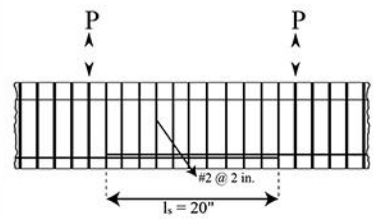
- **Beam 1**
  - Splice Length = 1.3*l_d
  - Stirrup spacing = 6in.



- **Beam 2**
  - Splice Length = 1.3*1.25*l_d
  - Stirrup spacing = 3in.



- **Beam 3**
  - Splice Length = 1.3*1.25*l_d
  - Stirrup spacing = 2in.



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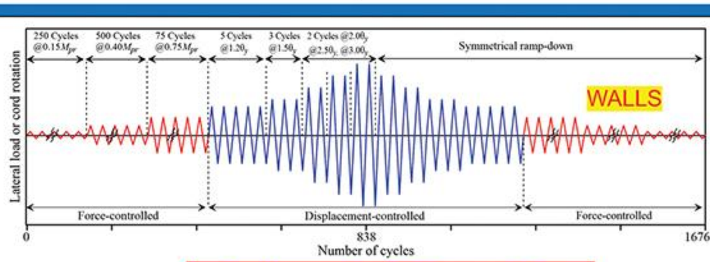
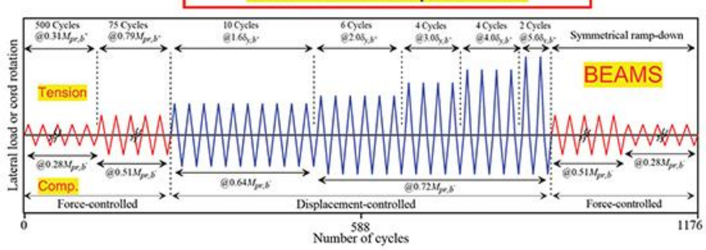
UCLA Beam Splice Tests: Loading Protocol



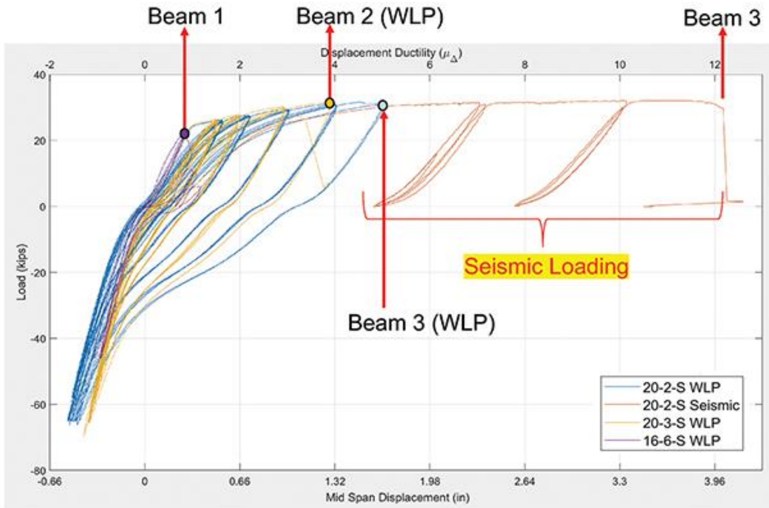
Apply same tensile & comp. strain demands to the spliced bars



Differences

- 250 cycles are not included (walls are under compression)
- Inelastic cycles in ramp-up only
- Constant compressive demands for the last 16 inelastic cycles

UCLA Beam Splice Tests: Results

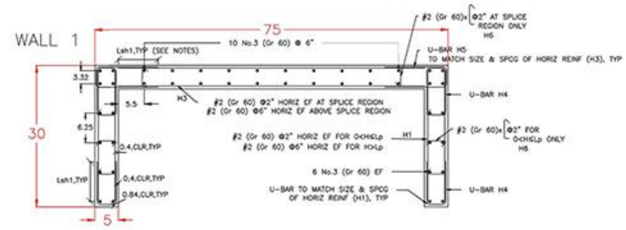


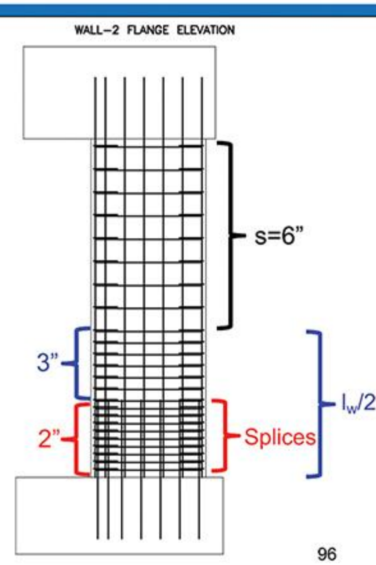
Failure Points:

1. **Beam 1 (s=6", ls=1.3*ld)**
   - At the 3rd cycle of 75 cycles @0.75M_{pr}
   - Before yield
   - Splice failure
2. **Beam 2 (s=3", ls=1.25*1.3*ld)**
   - At the 2nd cycle of 4 cycles @2.5Θy
   - WLP was not completed
   - Splice failure
3. **Beam 3 (s=2", ls=1.25*1.3*ld)**
   - WLP was completed
   - 2 cycles @7δy,b and @10δy,b applied
   - Failed @12δy,b
   - Bar rupture

UCLA Wall Tests: Splices

- Splice Length
  - $l_s = 1.25(1.3)\ l_d$
- Transverse reinforcement
  - U-bars and cross-ties @ 2" (splice)
  - U-bars and cross-ties @ 3" ($l_w/2$)





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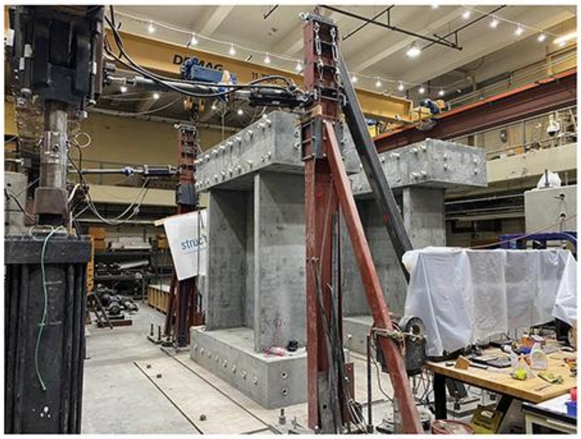
UCLA Test Program: Current Status



Wall Test Specimens (2) – Phase I

Large Beam Splice Tests (2)
#8 Spliced Bars

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Final Observation: Instrumentation

- LADBS requirements
  - Introduced in 2008
  - Typical tall building has 24 to 30 channels

Table 1. Minimum Number of Channels

Number of Stories Above Ground	Minimum Number of Channels
6 - 10	12
11 - 20	15
21 - 30	21
31 - 50	24
more than 50	30

  - Additional guidance in LATBSDC (2020)
  - Replicated in other jurisdictions

LA DBS DEPARTMENT OF BUILDING AND SAFETY

INFORMATION BULLETIN / PUBLIC - BUILDING CODE
REFERENCE NO.: LABC 1613.10.2 Effective: 01-01-2017
DOCUMENT NO.: P/BC 2017-117 Revised:
Previously Issued As: P/BC 2014-117

STRUCTURAL MONITORING EQUIPMENT IN BUILDINGS DESIGNED WITH NONLINEAR RESPONSE HISTORY PROCEDURE

SCOPE

These special standards for the installation and servicing of structural monitoring equipment shall apply only to new buildings designed in accordance with the nonlinear response history procedure of Chapter 16 of ASCE 7, "Seismic Response History Procedures" and required structural monitoring instrumentation per Section 1613.10.2 of the Los Angeles Building Code (LABC). The instrumentation requirements in this bulletin shall be used with the requirements in Information Bulletin P/BC 2017-048 for conventional high-rise buildings.

OVERVIEW

The primary objective of structural monitoring is to improve safety and reliability of infrastructure systems by providing data to improve computer modeling and enable damage detection for post-event condition assessment. Given the spectrum of structural systems used and response quantities of interest (acceleration, displacement, strain, rotation, pressure), the purpose of this bulletin is to provide comprehensive and flexible installation requirements for instrumentation to facilitate achieving these broad objectives. The instruments should be selected to provide the most useful data for post-event condition assessment. Variations in the instrumentation scheme for a given building type (e.g., steel moment frame) may be warranted to provide a broader range of data given the required relatively sparse instrumentation. An advantage of proper instrumentation to the building owner is that post event assessment may be expedited thru utilization of the data from the instrumentation meeting that described herein.

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THANK YOU
QUESTIONS?

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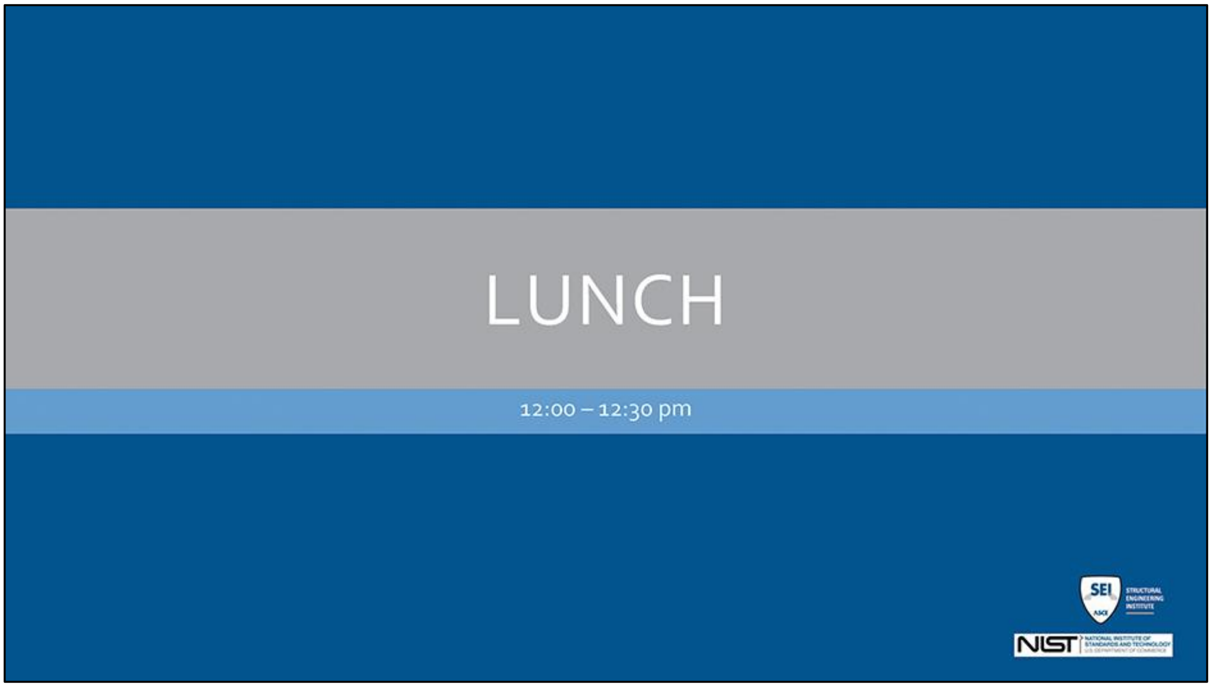
PANEL DISCUSSION

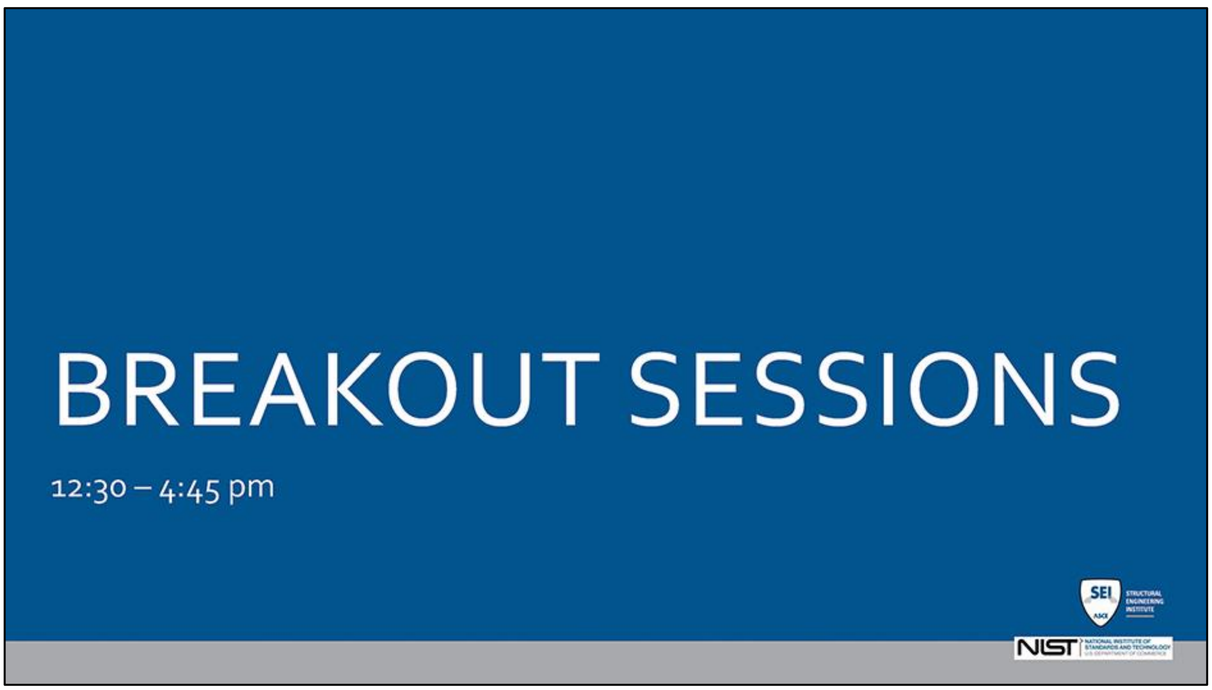
Moderator:

- Melissa Burton, Ph.D, C.Eng; Principal, Arup

Panelists:

- David Bott, P.E., S.E., AIA; Principal, Heintges
- Xinzhong Chen, Dr. Eng.; Professor, Texas Tech University
- Roy Denoon, Ph.D.; Principal, CPP Wind
- Mehedy Mashnad, Ph.D., P.E.; Principal; Walter P. Moore


LUNCH
12:00 – 12:30 pm


BREAKOUT SESSIONS
12:30 – 4:45 pm

GOALS FOR THURSDAY's BREAKOUT SESSION:

1. **State-of-the-Art**
   - Consensus on current State-of-Art
   - Identify current challenges

2. **Long Term Vision**
   - Consensus on Long Term Vision
   - Discussion of current gaps
   - Identify what is needed to get to the Ideal
   - How do we get there?

3. **Research**
   - Identify research needs
   - Prioritize

BREAKOUT SESSION Details:

BREAKOUT SESSION	MODERATOR	ROOM
Wind Climate Characteristics	Roy Denoon	Seabury & Smith
System Reliability	Seymour Spence	DMJM
Wind-Structure Interaction	Melissa Burton	CH2M Hill
Structural Analysis Techniques	Teng Wu	Cardinal
Design	Russell Larsen	Harris

SUMMARY & ADJOURN

4:45 – 5:00 pm

SEI-NIST PERFORMANCE BASED DESIGN WORKSHOP – DAY 2

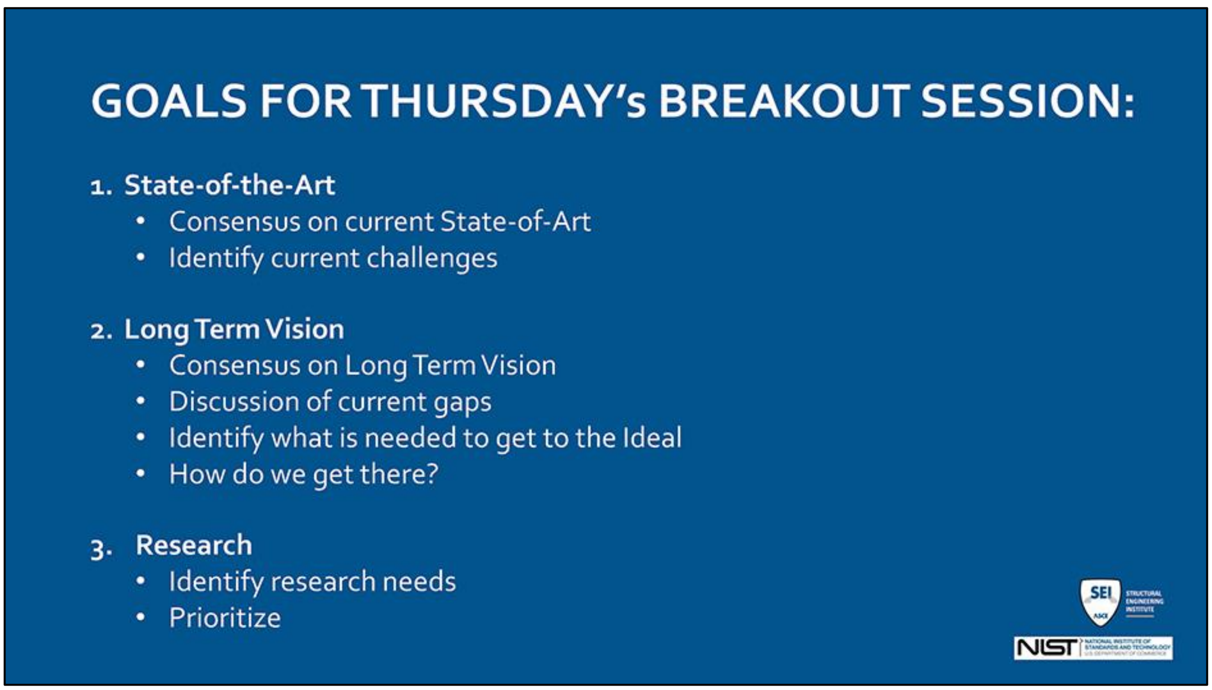
Feb. 23-24, 2023

American Society of Civil Engineers, Reston, Va.


WELCOME
8:00 – 8:15 am


GENERAL SESSION
Workshop Director:
Don Scott, P.E., S.E., F.SEI, F.ASCE
• Purpose – Report outs from each Breakout Group
• Goals – Prioritized Research Needs
• Agenda
• Digital Package
12:00pm-12:30pm – WORKING LUNCH PROVIDED
BREAKOUT SESSIONS
12:30pm-4:45pm – Five concurrent sessions (see descriptions below)
1. Wind climate characteristics – Moderator Roy Denoon
2. System reliability – Moderator Seymour Spence
3. Wind-structure interaction – Moderator Melissa Burton
4. Structural analysis techniques – Moderator Teng Wu
5. Design – Moderator Russell Larsen
2:30pm-2:45pm – COFFEE BREAK
4:45pm-5:00pm – Reconvene
Summary and Adjourn Day 1
Day 2: Fri., Feb. 24; 8:00am – 12:00pm Eastern
7:30am-8:00am – CONTINENTAL BREAKFAST PROVIDED
GENERAL SESSION
8:00am-8:15am – Welcome [ROOMS: CH2M, ASCE, S&S]
Purpose and Goals of Day 2
8:15am-11:45am – Report out and Prioritization
Breakout Session Report out: [30 mins EACH = 20 mins. + 10 mins Q&A]
1. Wind climate characteristics
2. Wind-structure interaction
3. System reliability
4. Structural analysis techniques
5. Design
10-minute COFFEE BREAK
Moderated Panel Discussion of WSC [30 mins.]
Prioritization of Research Needs [20 mins.]
11:45am-12:00pm – Conclusion
Summary and Adjourn Day 2
12:00-4:00pm – Workshop Steering Committee Meeting
David Bott P.E., S.E., AIA; Principal; Heintges
Xinzhong Chen, Dr. Eng.; Professor, Texas Tech University
Mark Lavery BEng, CEng, FIStructE; Director, BuroHappold
Chris Letchford, Professor and Department Head, Rensselaer Polytechnic Institute
[40 mins. = 30 mins PPT + 10 mins Q&A]


REPORT OUT &
PRIORITIZATION
8:15 am – 11:45 am


GOALS FOR THURSDAY's BREAKOUT SESSION:
1. State-of-the-Art
• Consensus on current State-of-Art
• Identify current challenges
2. Long Term Vision
• Consensus on Long Term Vision
• Discussion of current gaps
• Identify what is needed to get to the Ideal
• How do we get there?
3. Research
• Identify research needs
• Prioritize

WIND CLIMATE CHARACTERISTICS

Peter Vickery

WHAT ARE THE GOALS OF PBD?

- Different goals will require different data/methods/priorities. For example:
  - Reduce building materials costs / reduce embodied carbon
  - Reduce wind-induced structural damage and/or cladding damage / increase resilience
    - Does reducing damage / resulting debris / resulting rebuilding requirements actually reduce environmental impacts/embodied carbon more than reducing initial volumes of steel/concrete/other materials
  - Better seismic performance
  - Reduce water infiltration
  - Serviceability/occupant comfort
- What specific kinds of wind hazard characterisations do we need for Wind PBD ?
  - Current ASCE 7 gives a single nondirectional wind speed and tornado speed.
  - Need separate characteristics for different storm types (tropical, extratropical, thunderstorm, tornado, other?)
  - Need durations/time histories/peaks over threshold/duration over threshold to get accumulation of damage?

WINDSTORM TYPES

- Tropical Cyclones
  - Need more data for RMW and pressure wind relationship modelling (Hurricane Hunter Data)
  - Revisit hurricane boundary layer with more dropsondes
  - Air density
- Extratropical Storms –
  - Surface wind speed data driven models
    - Summary of the day (TD3210)
    - ISD 3505 – has multiple gusts and directions per day
- Thunderstorms
  - Poor knowledge of lateral extent of storms
  - Limited knowledge of vertical profiles
  - Limited knowledge of duration
  - Derechos vs. downbursts
- Tornadoes
  - Very limited knowledge of tornado wind structure
  - Significance of multi-vortex tornadoes?
- Others

MISSING HAZARD MODELS

- Climate Change Effects
  - Some confidence with tropical cyclones
  - Some confidence with extratropical storms
  - Not much for thunderstorms and tornadoes
  - Need to translate outputs from climate models to engineering requirements (wind speed)
- Combined wind/rain/hail models
  - Combined wind-rain maps
  - Combined wind-hail maps

TRANSLATION OF WIND DATA TO SITE

- Harris and Deaves/ESDU used for all storm types even though developed for extratropical storms.
- Meteorological modelling (WRF, etc.)

OTHER STUFF

- Lifetime exceedances of threshold – accumulated damage
- Which storms govern which design objective?
- How to deal with thunderstorms in the wind tunnel
- Large full scale field experiments to look at Deaves/Harris model and thunderstorms
  - Derechos vs. downbursts
  - Spatial and temporal characteristics of derechos
  - Are vertical profiles different in derechos and downbursts?
- Topographic Effects
  - More experimental data needed
  - Need CFD models

ABILITY TO PREDICT EXTREME EVENTS

- Probability distributions
  - Type I probably fine
  - Use superstations to define tails
- How to combine hazard/responses?
- How to strike a balance between complexity of structural analysis and number of wind time histories.

SIGNIFICANCE OF STORM TYPE FOR LOADS

- How to prioritize research needs
  - Most at risk buildings
  - Buildings amenable to PBD?
  - West coast PBD might have different goals than East and Gulf Coast PBD
- Use savings from reduced steel and put towards BETTER CLADDING
- What is the problem that needs to be solved
  - Water penetration

STATE OF THE ART FOR TESTING

- Tornados
  - Some knowledge of wind structure
  - Importance of pressure drop vs. wind loads
    - Thousands of combinations (size, r/RMW, translation speed, etc.)
  - CFD can help
    - Can get information on flow field anywhere in the tornado
    - CFD will be able to model loads – grid resolution problem
- Thunderstorms
  - Some knowledge of wind structure
  - CFD used to
    - get information on flow field anywhere in the tornado
    - CFD will be able to model loads – grid resolution problem
  - ABL tunnels can be configured to reproduce characteristics of thunderstorms
  - Can we model derechos – likely not yet. Need to get better understanding of the spatial and temporal characteristics. Likely different than downbursts.
  - Derechos likely longer lived than downbursts

RECOMMENDATIONS

1. Thunderstorm/Tornado characterisation (14)
2. Performance based multi-meteorological (wind/hail/rain) design (11)
3. Transferring non-ABL winds to practice in testing (10)
4. Risk mapping for different building stock types (3)
5. Redo Harris and Deaves model (2)
6. Extratropical simulations/climate modelling (2)

SYSTEM RELIABILITY

Luca Caracoglia

BREAKOUT SESSION Participants:

Moderator: Seymour Spence
Scribe: Srinivasan Arunachalam
Reporter: Luca Caracoglia
Participants:

- Michele Barbato
- Xinzhong Chen
- Do-Eun Choe
- Greg Deierlein
- Jeff Dragovich
- Terri McAllister
- Chris Raebel
- John Wallace

REPORT OUT:
SYSTEM RELIABILITY

1. SUMMARY of Current State-of-the-Art
   - Identify current challenges
2. SUMMARY of Long-Term Vision
   - Identify current gaps
   - Describe what is needed to get to the Ideal
3. PRIORITIZED Research Needs

SUMMARY: CURRENT STATE-OF-ART (1/3)
--- SYSTEM RELIABILITY ---

- Three methods from ASCE Pre-Standard for PBWE of engineered systems
  - Method 1: basic analysis (*pseudo* prescriptive)
  - Method 2: conditional probability analysis assessment
  - Method 3: fully coupled reliability analysis
- Literature review (2007+)

a) Performance-based design adapting the PEER equation from seismic to wind

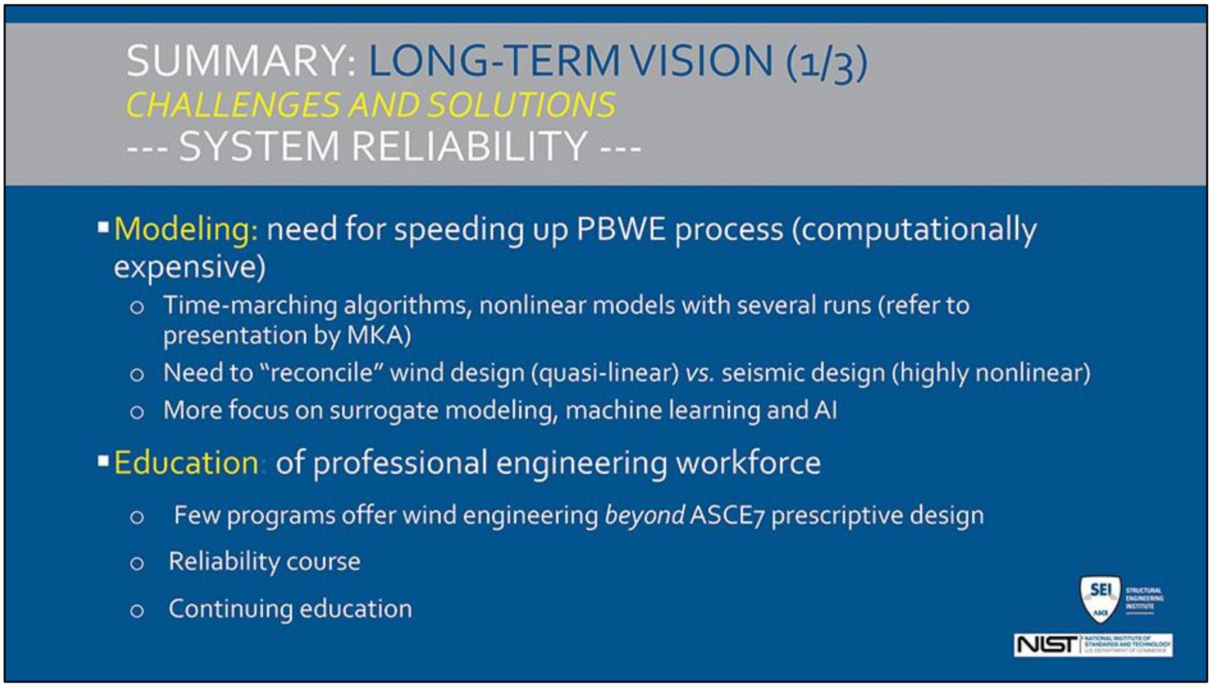
b) Recognize the need to consider two-way coupled system
   - From wind load to response, then to damage probability (on the envelope mainly, for tall building; failure for low-buildings)
   - For wind loads and response there is also a *feedback effect*, e.g., damage on façade induces water penetration; water damages the panel and modifies internal pressures. Pressure load changes (C&C mostly, but on occasion MWFRS)
   - A local problem (e.g., loss of a window panel) may affect the whole building

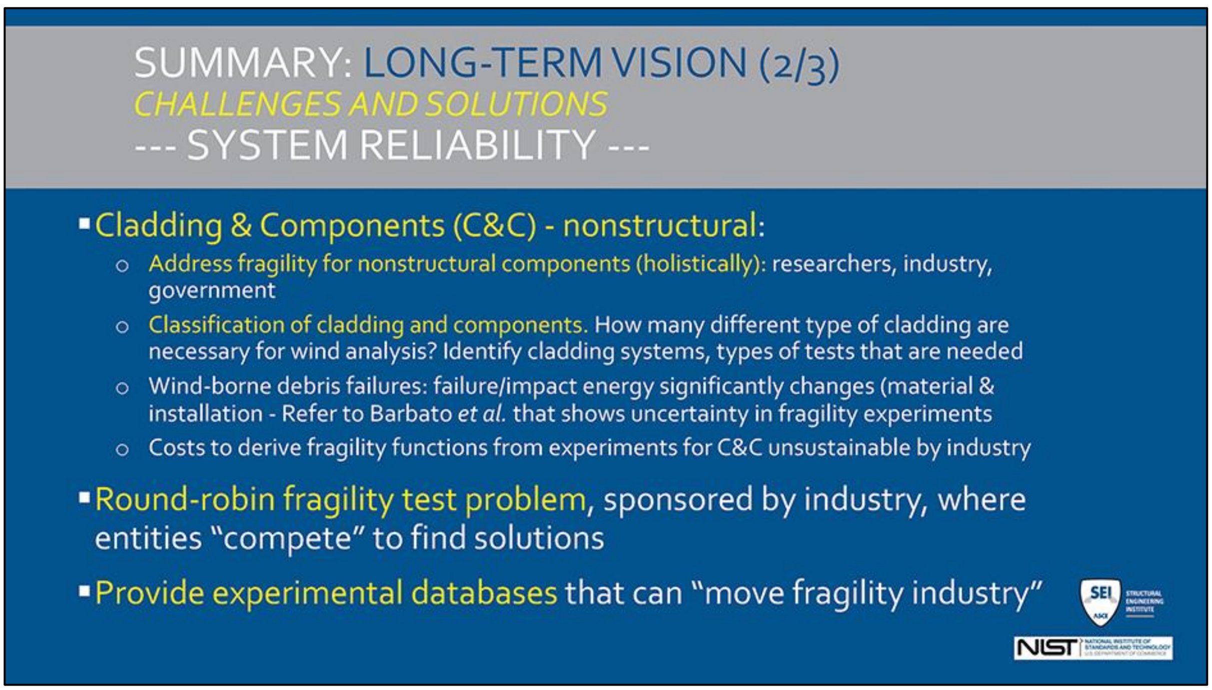
SUMMARY: CURRENT STATE-OF-ART (2/3) --- SYSTEM RELIABILITY ---

- Literature review (2007+) - *continued*
  - c) Fragility functions for structural & nonstructural components
    - EDP vs. fragility at the component level, Is FEMA P-58 applicable? No: earthquake is short-duration very intense; wind is persistent with several lower-level peaks
    - Classes of fragility functions: in seismic engineering the feedback is "local" at element level; in wind engineering fragility may trigger effects to other members (e.g., water penetration)
    - For low-rise buildings: the wind load changes with the progressive damage to the structure (roof structure collapses after breaking of a window)
    - For high-rise buildings: mainly nonstructural components, cladding systems, wind-borne debris
    - The engineer needs more structural fragility functions for wind analysis
  - d) Damage, losses and consequences (several methods proposed, problem understood)

SUMMARY: CURRENT STATE-OF-ART (3/3) --- SYSTEM RELIABILITY ---

- Literature review (2007+) - *continued*
  - e) Wind climate synoptic winds (well understood), hurricanes (well understood) but less understood for tornadoes & thunderstorms
  - f) Question: setting target performances that may be out of reach
    - Reliability question is important for cladding components: *what is the risk that we wish to take?*
    - *Problem*: testing on cladding is often standard but outdated (pass or fail test only, no probability) – every cladding type may be different and there is a lot of uncertainty


SUMMARY: LONG-TERM VISION (1/3)
CHALLENGES AND SOLUTIONS
--- SYSTEM RELIABILITY ---
Modeling: need for speeding up PBWE process (computationally expensive)
Time-marching algorithms, nonlinear models with several runs (refer to presentation by MKA)
Need to "reconcile" wind design (quasi-linear) vs. seismic design (highly nonlinear)
More focus on surrogate modeling, machine learning and AI
Education: of professional engineering workforce
Few programs offer wind engineering beyond ASCE7 prescriptive design
Reliability course
Continuing education


SUMMARY: LONG-TERM VISION (2/3)
CHALLENGES AND SOLUTIONS
--- SYSTEM RELIABILITY ---
Cladding & Components (C&C) - nonstructural:
Address fragility for nonstructural components (holistically): researchers, industry, government
Classification of cladding and components. How many different type of cladding are necessary for wind analysis? Identify cladding systems, types of tests that are needed
Wind-borne debris failures: failure/impact energy significantly changes (material & installation - Refer to Barbato et al. that shows uncertainty in fragility experiments
Costs to derive fragility functions from experiments for C&C unsustainable by industry
Round-robin fragility test problem, sponsored by industry, where entities "compete" to find solutions
Provide experimental databases that can "move fragility industry"

SUMMARY: LONG-TERM VISION (3/3)
CHALLENGES AND SOLUTIONS
--- SYSTEM RELIABILITY ---

- In tall buildings, unlike seismic design, mean drift controls the design
  - Avoid large inelastic behavior beyond yielding to occur → P-Δ effects cause progressive collapse
- Uncertainty in the loads probably more important than structural uncertainty
  - Uncertainly in structure can be on occasion neglected (yielding, structural damping) since reliability is almost the same (refer to studies by X. Chen *et al.*)
  - Large uncertainty is present because wind engineer is forced to make initial assumptions: e.g., wind field simplifications, homogeneous ABL profile *vs.* realistic wind profiles, directionality
  - Wind tunnel testing to assess wind loads:
    - ✓ If carefully performed, uncertainty in pressure load measurements (pressure coefficients C_p) can be controlled, except for peak pressures in C&C for low-rise, 3D buildings
    - ✓ Building shape effects: Reynolds number usually less relevant except for special structures
- Changing climate for structures designed for long lifetimes (Barbato *et al.*)

PRIORITIZED RESEARCH NEEDS:
--- SYSTEM RELIABILITY ---

1) Integrate performance between structural system and cladding ("feedback" modeling) & generate structural and non-structural damage functions, component-specific (cladding)

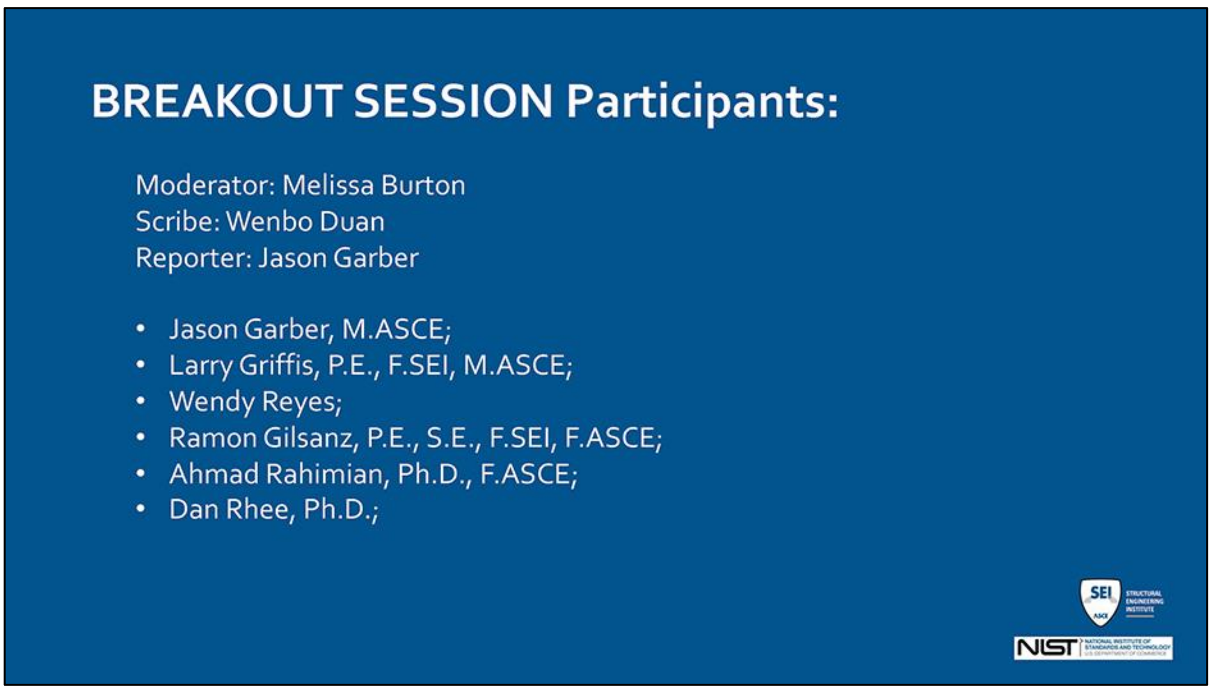
   1.a) Address special design needs through probability: debris, water penetration, progressive failure (window, roof, etc.), C&C testing (*not just pass/fail*)
2) Improve physics-informed, computationally efficient models for nonlinear analysis of wind response over long-period durations (surrogates, AI)
3) Characterize hazard and loads (loading uncertainty, assumptions, non-stationarity w/ climate change considerations, etc.) for both short and large return periods
4) Define probability-based and life-cycle cost metrics, limit state(s) of interest

   4.a) Consider damage, repair, recovery & account for impeding factors, e.g., delays damage/repair

   4.b) Differentiate PBWE needs for low-rise *vs.* high-rise buildings (MWFRS, C&C)

   4.c) "Organize" & "standardize" reliability targets (DCR, etc.) – benchmarking, ranges


WIND-STRUCTURE INTERACTION
Jason Garber
SEI STRUCTURAL ENGINEERING INSTITUTE
NIST


BREAKOUT SESSION Participants:
Moderator: Melissa Burton
Scribe: Wenbo Duan
Reporter: Jason Garber
• Jason Garber, M.ASCE;
• Larry Griffis, P.E., F.SEI, M.ASCE;
• Wendy Reyes;
• Ramon Gilsanz, P.E., S.E., F.SEI, F.ASCE;
• Ahmad Rahimian, Ph.D., F.ASCE;
• Dan Rhee, Ph.D.;
SEI STRUCTURAL ENGINEERING INSTITUTE
NIST

REPORT OUT: WIND- STRUCTURE INTERACTION

1. What is PBWD?

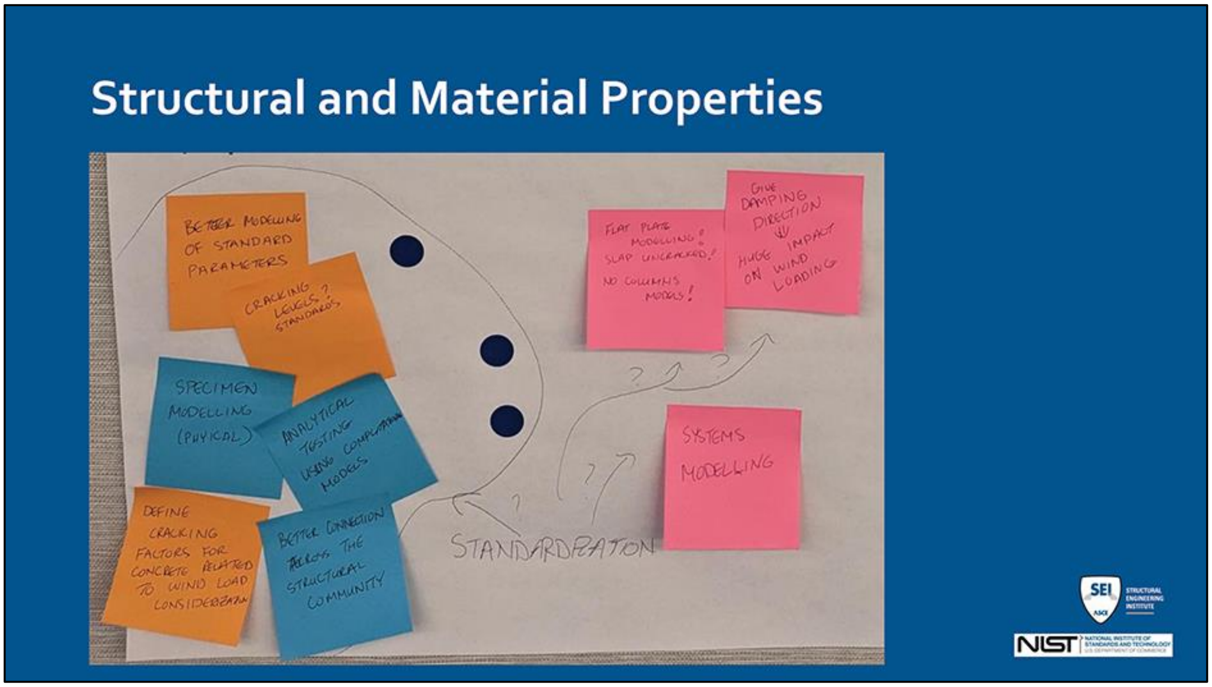
What is it?	What is it not?
Consideration across the design space	Step by step prescriptive methodology
Solution is nonprescriptive to achieve a performance goal	Something that you can employ without participation / collaboration of all stakeholders
More "accurate" approach to design loads (better definition of demand)	
More sustainable solution (it should be!)	Throwing mass at a building to solve dynamic issue
Conscious consideration of varying climatology	Only considering discrete points (RP's) in design
Incorporate climate change	
A refinement of existing practice (GOAL: that is adopted by all)	

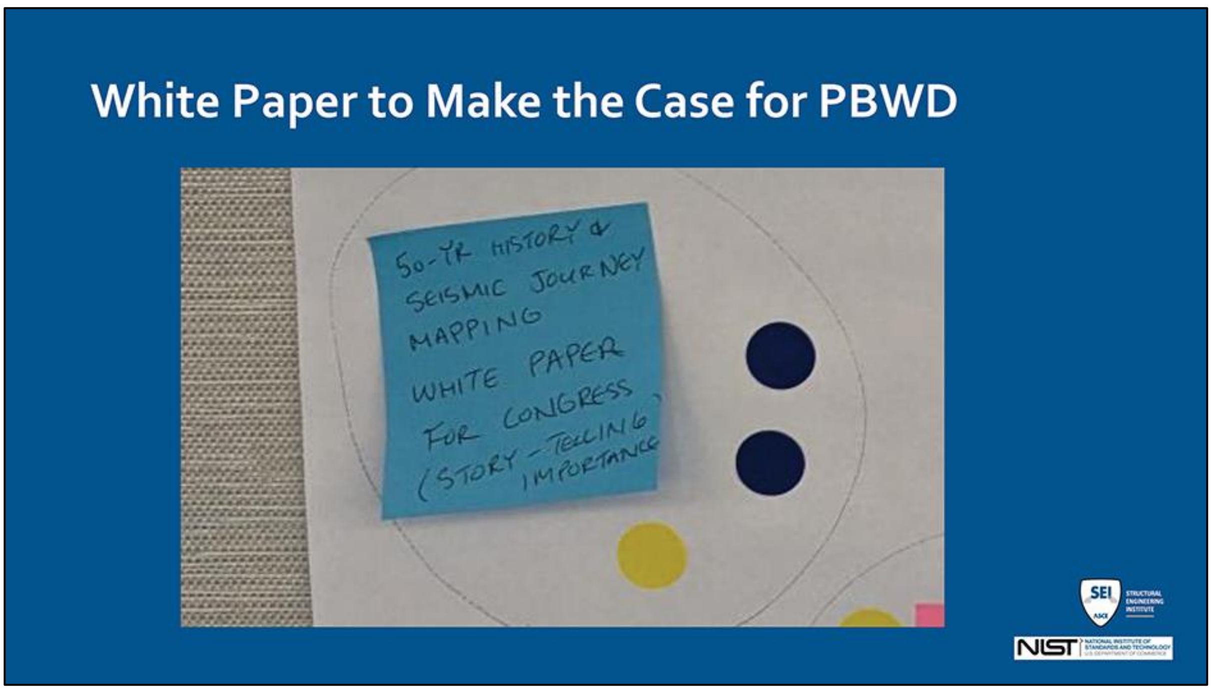
SUMMARY: CURRENT STATE-OF-ART --- WIND- STRUCTURE INTERACTION ---

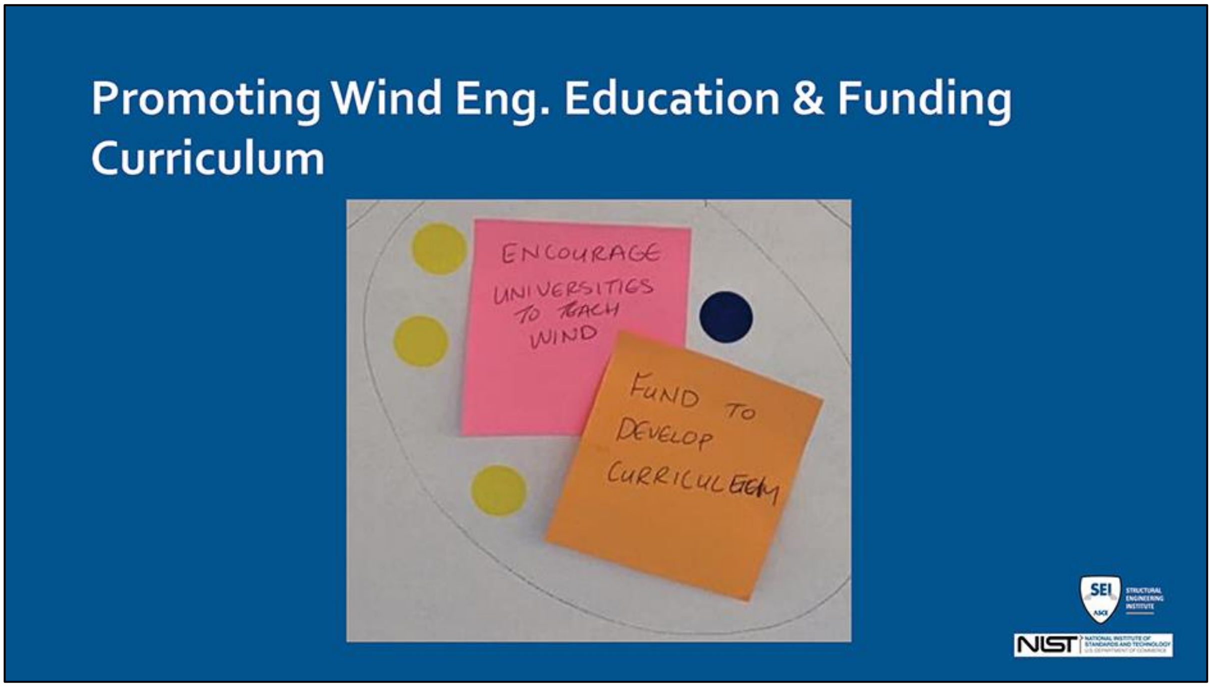
Current challenges:

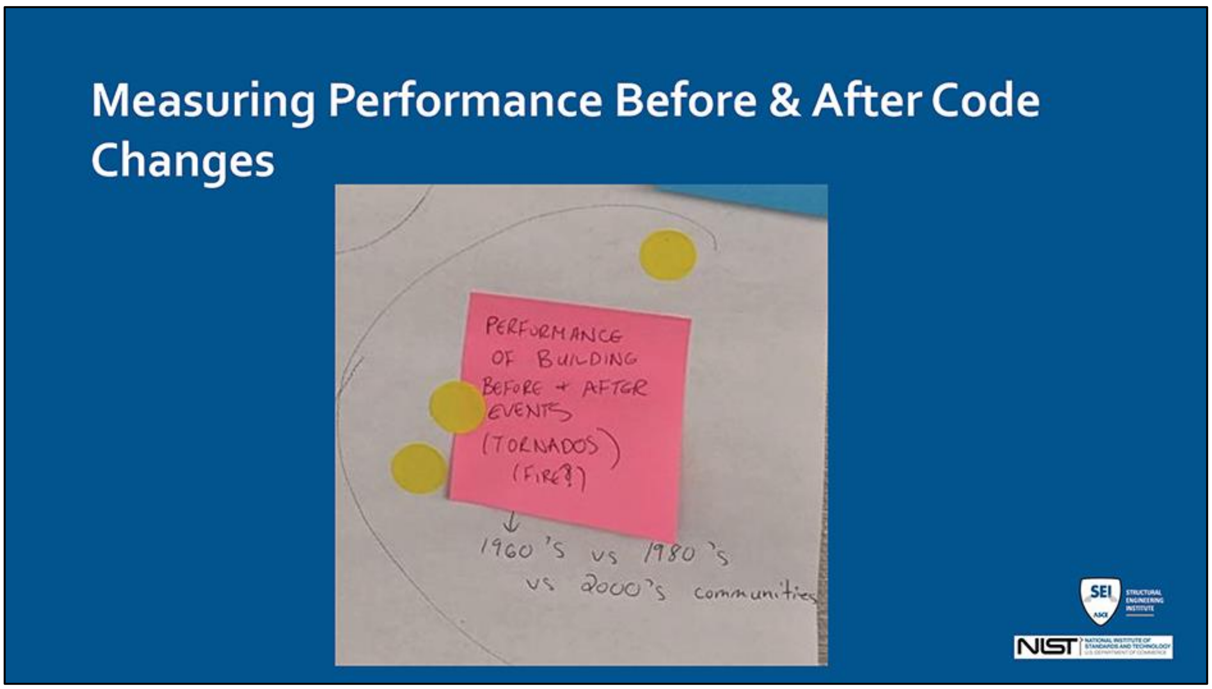
- Value proposition
- Adoption by many / all

Areas of Consideration
• Time of Peak Demand / Storm Duration
• Complex Structures
• Complex Surroundings
• Computational Requirements
• Required Suites / Progressive Storm after Storm Loading
• Addressing structures where most failures arise
• Load Application / Model + Load Interaction
• Modelling Implications / Structural Properties
• Wind Load Input
• Missing data from Existing Buildings / Monitoring

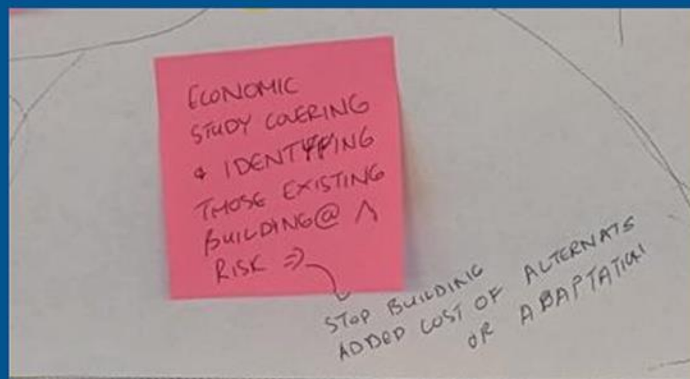

Structural and Material Properties
BETTER MODELLING OF STANDARD PARAMETERS
CRACKING LEVELS? STANDARDS
SPECIMEN MODELLING (PHYSICAL)
ANALYTICAL TESTING USING MODELS
DEFINE CRACKING FACTORS FOR CONCRETE RELATED TO WIND LOAD CONSIDERATION
BETTER CONNECTION ACROSS THE STRUCTURAL COMMUNITY
FLAT PLATE MODELLING! SLAB UNCRACKED! NO COLUMNS MODELS!
GIVE DAMPING DIRECTION HUGE IMPACT ON WIND LOADING
SYSTEMS MODELLING
STANDARDIZATION
SEI
NIST


White Paper to Make the Case for PBWD
50-YR HISTORY & SEISMIC JOURNEY MAPPING
WHITE PAPER FOR CONGRESS
(STORY-TELLING IMPORTANCE)
SEI
NIST

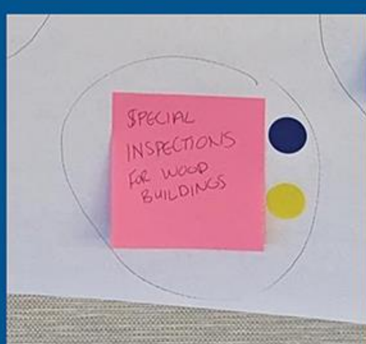

Promoting Wind Eng. Education & Funding Curriculum
ENCOURAGE UNIVERSITIES TO TEACH WIND
FUND TO DEVELOP CURRICULUM

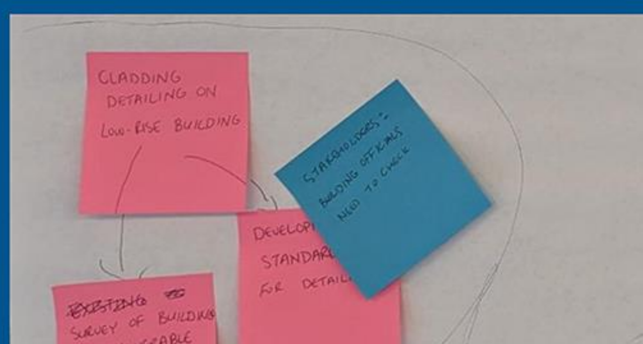

Measuring Performance Before & After Code Changes
PERFORMANCE OF BUILDING BEFORE + AFTER EVENTS (TORNADOS) (FIRE?)
1960's vs 1980's vs 2000's communities

Economic Study Identifying Existing Buildings @ Risk in Vulnerable Community

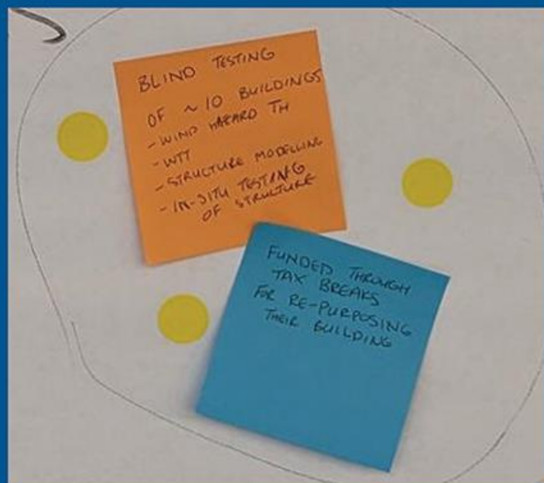


Policies Around Inspections & Approvals





Incentivized Existing Tall Building Surveys



STRUCTURAL ANALYSIS TECHNIQUES

Ricardo Medina

BREAKOUT SESSION Participants:

Moderator: Teng Wu
Scribe: Baichuan Deng
Reporter: Ricardo Medina

- Kevin Aswegan
- Jennifer Goupil
- Hitomitsu Kikitsu
- Viral Patel
- Donghun Yeo
- Scott Erickson
- Juan Paulino
- Marcos Martinez

SUMMARY: CURRENT STATE-OF-ART --- STRUCTURAL ANALYSIS TECHNIQUES ---

- DCR is 1.25 for deformation-controlled actions
- Limited research on design of loading protocols
- Data for model validation are essentially based on tests under seismic loading protocols
- Few physical tests are available under wind loading protocol
- Inherent damping is one of the most critical factors to be considered in wind analysis, but it is relatively poorly understood
- The static pushover is a natural extension of linear static analysis and can be used as a quick check of building performance under strength wind demands
- Extreme value theory is used for linear static analysis, and it is implemented in codes and standards
- Nonlinear response history analysis is good for general structures, with high demands on computational resources. Compared to black-box fast methods (e.g., machine learning), the engineering community prefers theory-based fast methods (e.g., shakedown)
- Lack of comprehensive validation at the system level
- Method 3 provides an efficient way to analyze structural performance

SUMMARY: LONG-TERM VISION
--- STRUCTURAL ANALYSIS TECHNIQUES ---

- Facilitate the implementation of analysis tools so that at least 80% of the practicing engineers can incorporate PBWD routinely
- Implementation of PBWD with the objective of supporting the resilience goals of the community.

PRIORITIZED RESEARCH NEEDS:
--- STRUCTURAL ANALYSIS TECHNIQUES ---

1. Confirmation of loading protocol
2. Lab tests of various components, e.g., slab-to-column connection, walls, steel joints, etc.
3. Guidance for selection of extreme values (peaks of peaks) in nonlinear response history analysis (e.g., in the analysis of force-controlled actions)
4. High-fidelity FEM models to calibrate component modeling along with available database
5. Testing beyond yielding to understand the effects of strong nonlinearity in wind-induced responses
6. Improved understanding and quantification of inherent damping
7. Leveraging the high efficiency of Method 3 to study various archetype buildings to facilitate its application in design
8. Static pushover for wind engineering to quickly evaluate nonlinear structural performance
9. Theory-guided data-driven approaches (e.g., knowledge-enhanced machine learning) for efficient nonlinear analysis
10. Full-scale structural response data
11. Improved understanding of the benefits of considering the nonlinear behavior of various foundation types.

DESIGN

Juliana Rochester

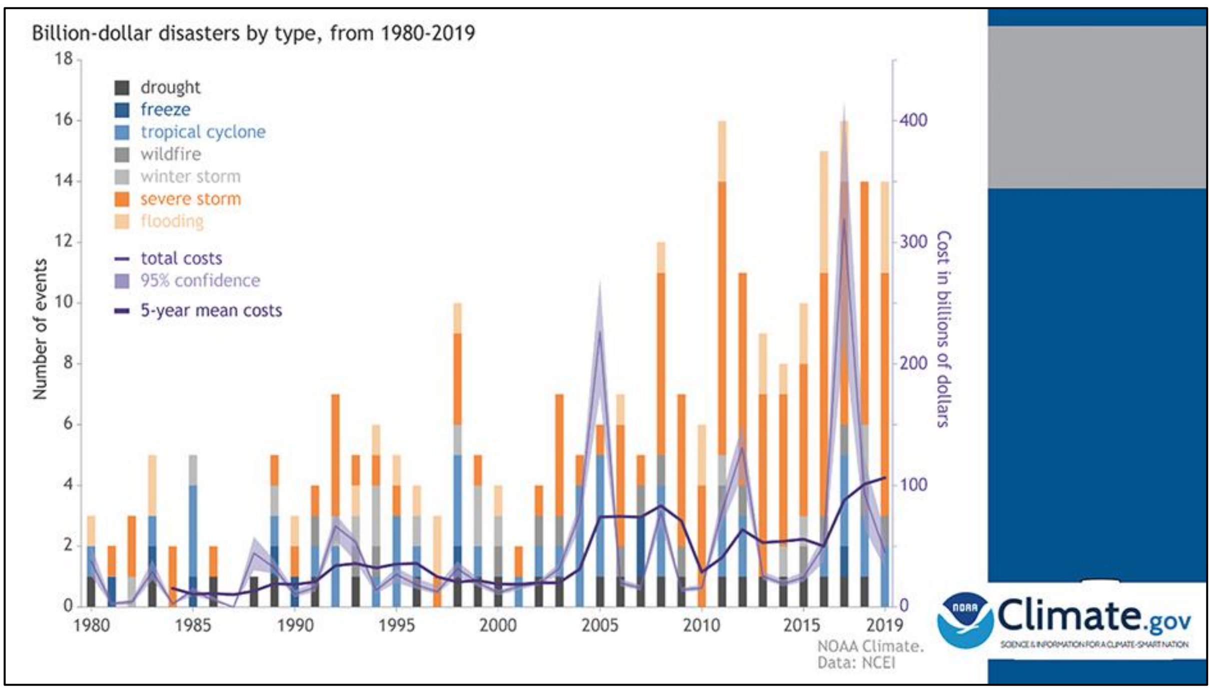
BREAKOUT SESSION Participants:

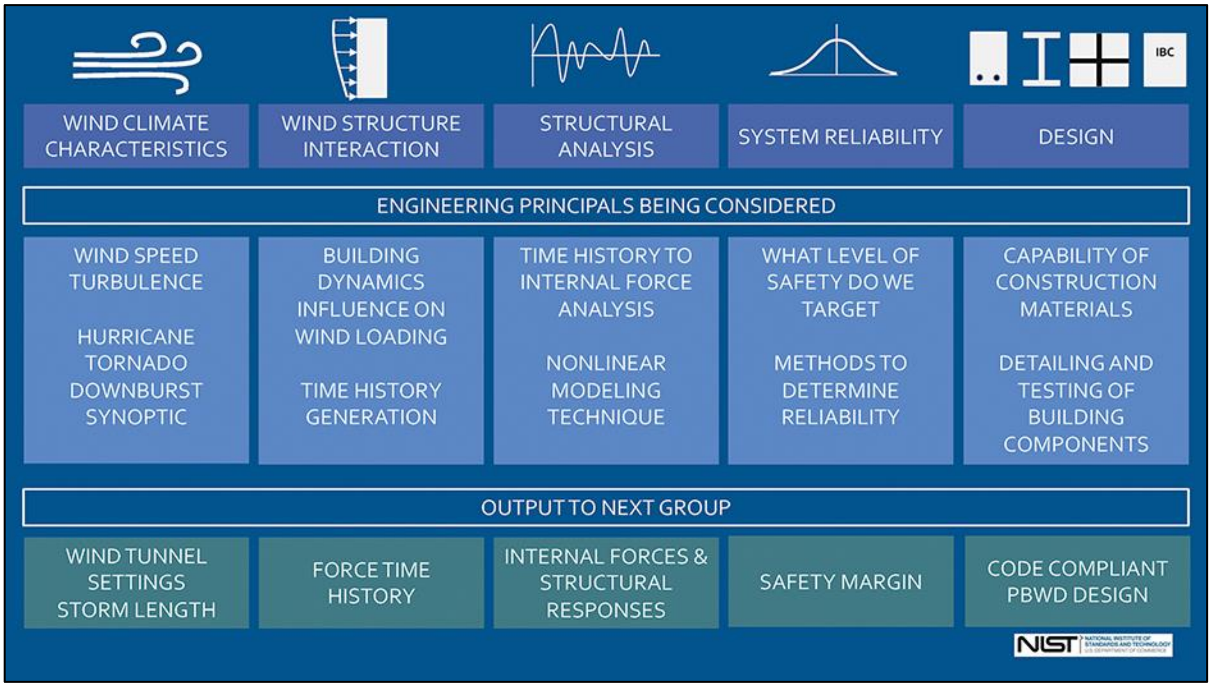
Moderator: Russell Larsen
Scribe: Juliana Rochester
Reporter: Juliana & Tom

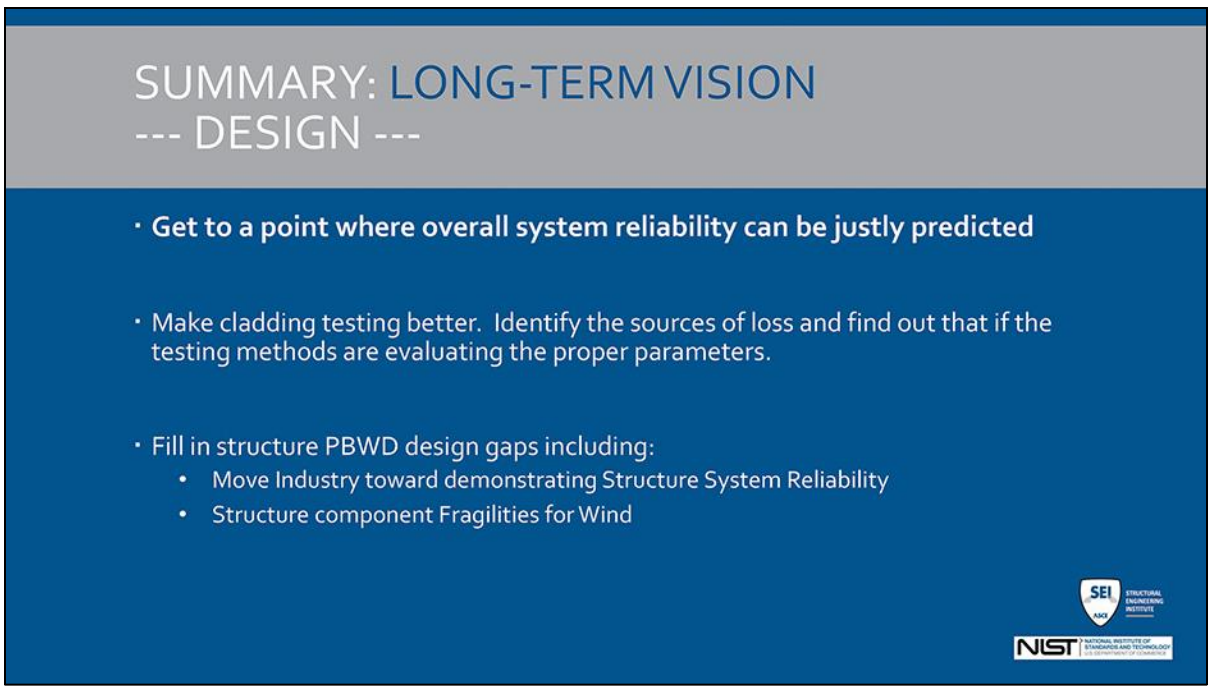
- Davit Bott
- Mehedy Mashnad
- Angela Mejorin
- Don Scott
- Tom Smith
- Pataya Scott
- Long Phan

SUMMARY: CURRENT STATE-OF-ART --- DESIGN ---

- Cladding, Impact, & Water Infiltration design expectations are *possibly* inadequate
- PBWD Prestandard v1.1 offers solutions to improve cladding and enhance MWFRS performance
- Inspection for envelope exists . . . But isn't detecting / covering enough
- Structural Concrete Testing going nicely… PBWD Steel Seems to Lag




WIND CLIMATE CHARACTERISTICS
WIND STRUCTURE INTERACTION
STRUCTURAL ANALYSIS
SYSTEM RELIABILITY
DESIGN
IBC
ENGINEERING PRINCIPALS BEING CONSIDERED
WIND SPEED TURBULENCE
HURRICANE TORNADO DOWNBURST SYNOPTIC
BUILDING DYNAMICS INFLUENCE ON WIND LOADING
TIME HISTORY GENERATION
TIME HISTORY TO INTERNAL FORCE ANALYSIS
NONLINEAR MODELING TECHNIQUE
WHAT LEVEL OF SAFETY DO WE TARGET
METHODS TO DETERMINE RELIABILITY
CAPABILITY OF CONSTRUCTION MATERIALS
DETAILING AND TESTING OF BUILDING COMPONENTS
OUTPUT TO NEXT GROUP
WIND TUNNEL SETTINGS STORM LENGTH
FORCE TIME HISTORY
INTERNAL FORCES & STRUCTURAL RESPONSES
SAFETY MARGIN
CODE COMPLIANT PBWD DESIGN
NIST


SUMMARY: LONG-TERM VISION
--- DESIGN ---
Get to a point where overall system reliability can be justly predicted
Make cladding testing better. Identify the sources of loss and find out that if the testing methods are evaluating the proper parameters.
Fill in structure PBWD design gaps including:
Move Industry toward demonstrating Structure System Reliability
Structure component Fragilities for Wind
SEI
NIST

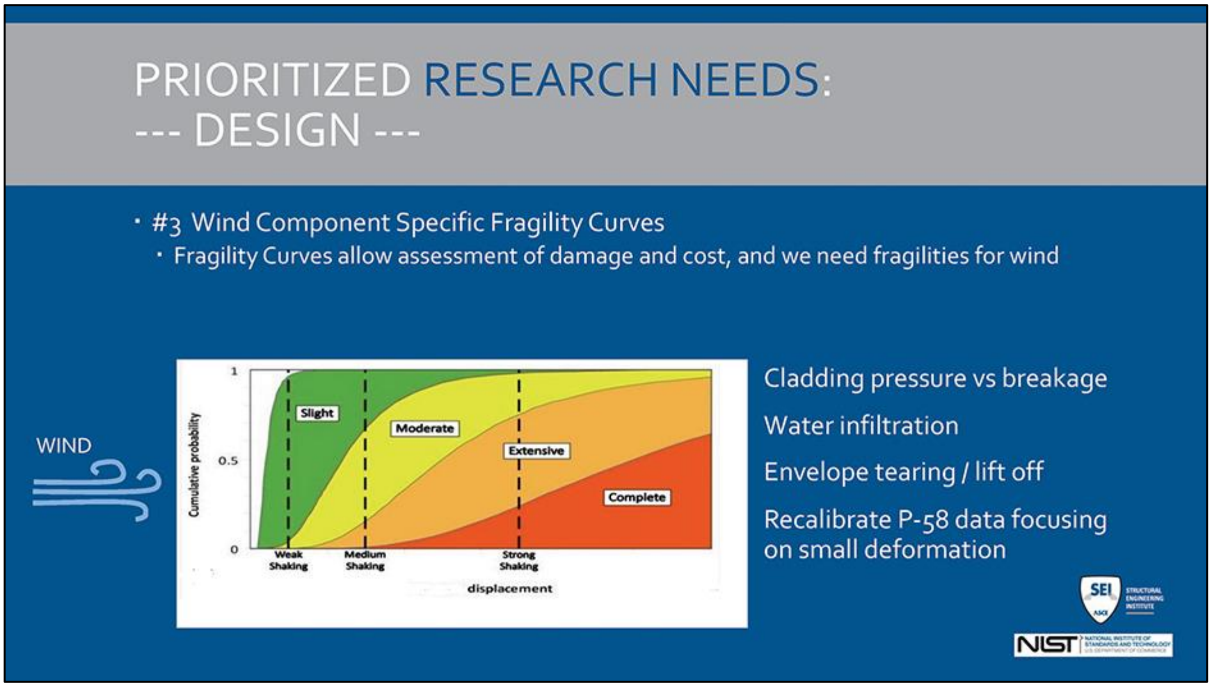
PRIORITIZED RESEARCH NEEDS:
--- DESIGN ---

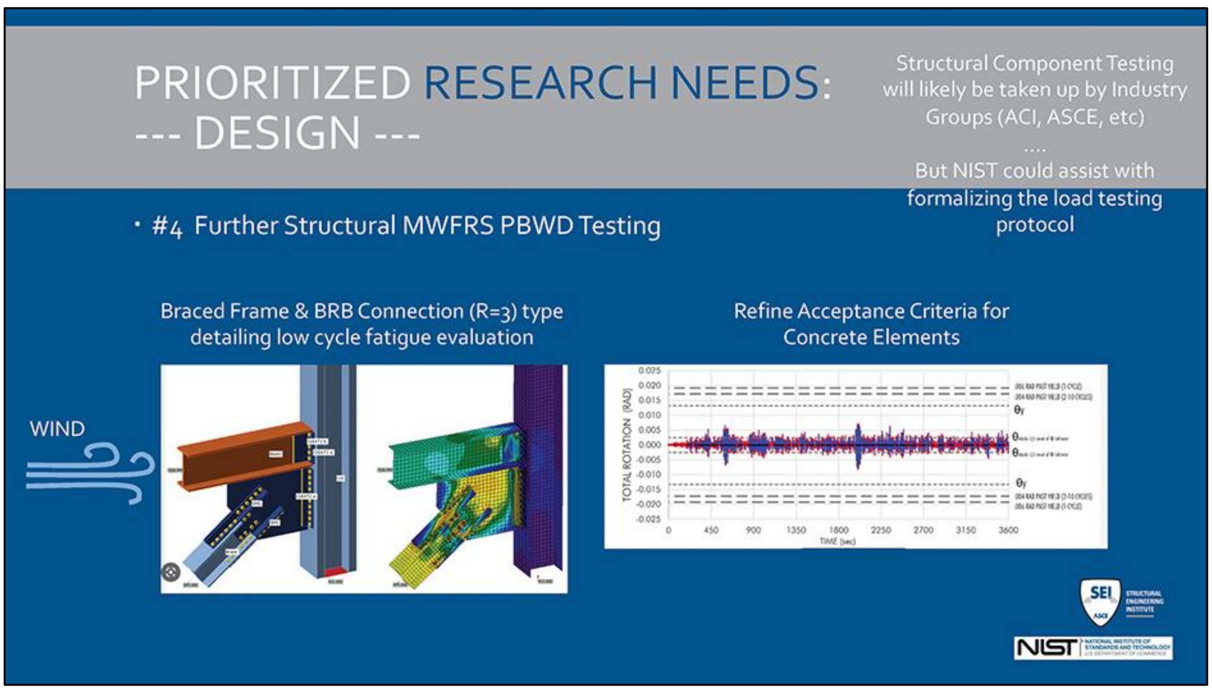
- #1 Re-Evaluation of Envelope Test Methods
  - Do Debris Impact tests evaluate the relevant performance parameters?
  - Do pressure & water infiltration tests actually evaluate the parameters needed to prove a design outcome?
  - Tests for wind and pressure of cladding may not recreate relevant demands on cladding system.
  - Effect of Aging of sealant and similar – and do tests pick this up.

PRIORITIZED RESEARCH NEEDS:
--- DESIGN ---

- #2 Field Diagnostic Tests for Envelope Component Integrity
  - Following #1 – where deficiencies in performance are found, and are not supported with inspection or verification tests, create evaluation metrics

This is an example of cladding adhesion that was not tested. (and the membrane was not installed correctly.)

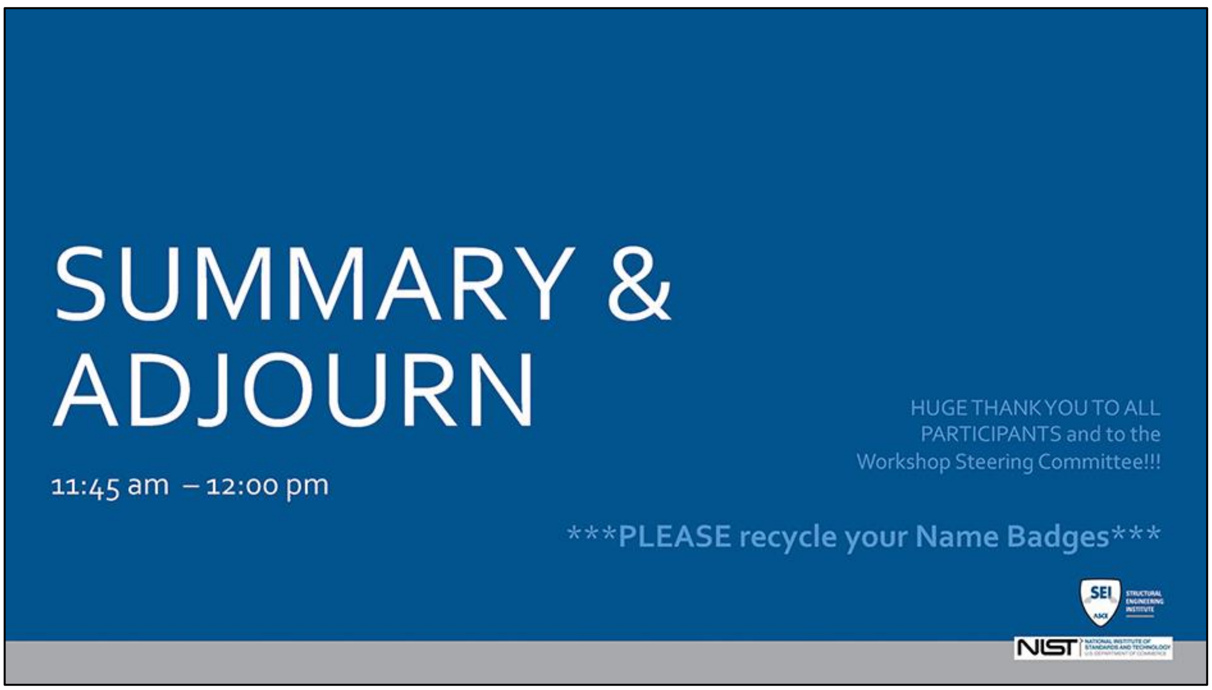

PRIORITIZED RESEARCH NEEDS:
--- DESIGN ---
#3 Wind Component Specific Fragility Curves
Fragility Curves allow assessment of damage and cost, and we need fragilities for wind
WIND
Cumulative probability
1
0.5
0
Slight
Moderate
Extensive
Complete
Weak Shaking
Medium Shaking
Strong Shaking
displacement
Cladding pressure vs breakage
Water infiltration
Envelope tearing / lift off
Recalibrate P-58 data focusing on small deformation
SEI
NIST


PRIORITIZED RESEARCH NEEDS:
--- DESIGN ---
Structural Component Testing will likely be taken up by Industry Groups (ACI, ASCE, etc)
....
But NIST could assist with formalizing the load testing protocol
#4 Further Structural MWFRS PBWD Testing
Braced Frame & BRB Connection (R=3) type detailing low cycle fatigue evaluation
Refine Acceptance Criteria for Concrete Elements
WIND
TOTAL ROTATION (RAD)
TIME (sec)
SEI
NIST


COFFEE BREAK
10 minutes


PANEL DISCUSSION – 30 MINUTES
Moderator:
Don Scott, P.E., S.E. – Workshop Director
Panelists: Workshop Steering Committee
• Roy Denoon, Ph.D., M.ASCE; Principal; CPP Wind
• Melissa Burton, Ph.D, C.Eng; Principal, Arup
• Seymour Spence, Ph.D., A.M.ASCE; Associate Professor; University of Michigan
• Teng Wu, Ph.D., M.ASCE; Associate Professor; University at Buffalo
• Russell Larsen, P.E., S.E., Aff.M.ASCE; Principal; MKA


PRIORITIZATION OF RESEARCH NEEDS
20 minutes


SUMMARY & ADJOURN
11:45 am – 12:00 pm
HUGE THANK YOU TO ALL PARTICIPANTS and to the Workshop Steering Committee!!!
PLEASE recycle your Name Badges

B.3. Workshop Participants

B.3.1. GENERAL SESSION Presenters

Don Scott, P.E., S.E., F.SEI, F.ASCE; Don Scott Consulting; Workshop Director
Long Phan, Ph.D., P.E., M.ASCE, F.ACI; Group Leader; NIST
Laura Champion, P.E., F.SEI, F.ASCE, Managing Director, SEI, and Global Partnerships; ASCE

B.3.2. BREAKOUT Participants

B.3.2.1. Wind Climate Characteristics

Moderator: Roy Denoon, Ph.D., M.ASCE; Senior Principal; CPP Wind Engineering Consultants
Scribe: Workamaw Warsido, Aff.M.ASCE; Senior Project Engineer; CPP Wind Engineering Consultants
Participants:

John Kilpatrick, Ph.D., P.Eng., M.ASCE; Principal; RWDI
Greg Kopp, Ph.D., P.E., M.ASCE; Professor; Western University
Frank Lombardo, Ph.D., EIT, Aff.M.ASCE; Assistant Professor; University of Illinois
Peter Vickery, Ph.D., P.E., F.SEI, F.ASCE; Peter J Vickery Consulting
Marc Levitan, Ph.D., Aff.M.ASCE; Lead Research Engineer; NIST
Antonio Zaldivar, Ph.D.; Graduate Structural Engineer, Walter P Moore
Brian Skourup, P.E., S.E., M.ASCE; EVS, Inc.
Jason Smart, P.E., M.ASCE; American Wood Council

B.3.2.2. System Reliability

Moderator: Seymour M.J. Spence, Ph.D., Aff.M.ASCE; Associate Professor; University of Michigan
Scribe: Srinivasan Arunachalam, S.M.ASCE; Graduate Student; University of Michigan
Participants

Michele Barbato, Ph.D., P.E., F.ASCE, F.SEI, F.EMI; Professor; University of California Davis
Luca Caracoglia, P.E., M.ASCE; Associate Professor; Northeastern University
Xinzhong Chen, M.ASCE; Professor; Texas Tech University
Greg Deirlein, Ph.D.; Professor; Stanford University
John Wallace, Ph.D.; Professor, University of California Los Angeles
Terri McAllister, Ph.D., P.E., F.SEI., Dist.M.ASCE; Group Leader/Program Manager; NIST
Chris Raebel, Ph.D., P.E., S.E., M.ASCE; American Institute of Steel Construction
Do-Eun Choe, Ph.D., P.E., M.ASCE; New Mexico State University
Jeff Dragovich, Ph.D., P.E., S.E., M.ASCE, F.ACI; Associate, DeSimone Consulting Engineers

B.3.2.3. Wind-Structure Interaction

Moderator: Melissa Burton, Ph.D., C.Eng., M.ASCE; Principal; Arup
Scribe: Wenbo Duan, Arup
Participants

Jason Garber, M.ASCE; Engineer; RWDI
Larry Griffis, P.E., F.SEI, M.ASCE; Senior Consultant; Walter P. Moore
Wendy Reyes; HDR Inc.
Ramon Gilsanz, P.E., S.E., F.SEI, F.ASCE; Partner, Gilsanz Murray Steficek LLP Engineers and Architects
Ahmad Rahimian, Ph.D., F.ASCE; WSP
Dan Rhee, Ph.D.; Research Engineer; NIST

B.3.2.4. Structural Analysis Techniques

Moderator: Teng Wu, Ph.D., M.ASCE; Associate Professor; University at Buffalo
Scribe: Baichuan Deng, S.M.ASCE; University at Buffalo
Participants

Kevin Aswegan, P.E., S.E., M.ASCE; Senior Associate, Magnusson Klemencic Associates
Scott Erickson, P.E., M.ASCE; Principal; DCI Engineers
Jennifer Goupil, P.E., F.SEI, F.ASCE; Managing Director Structural Engineering Institute and ASCE Chief Resilience Officer; Workshop Program Manager
Hitomitsu Kikitsu; National Institute for Land and Infrastructure Management
Ricardo A. Medina, Ph.D., P.E., M.ASCE; Engineering Mechanics & Infrastructure; Simpson Gumpertz & Heger
Viral Patel, P.E., S.E., M.ASCE; Design Director; Walter P. Moore
DongHun Yeo, Ph.D., P.E., M.ASCE; Research Structural Engineer; NIST
Marcos J. Martinez, Ph.D., P.E.; Desimone Consulting Engineers
Juan M. Paulino, P.E., S.E.; Buro Ehring Engineering

B.3.2.5. Design

Moderator: Russell Larsen, P.E., S.E., M.ASCE; Principal; MKA
Scribe: Juliana Rochester; P.E., M.ASCE; Senior Design Engineer, MKA
Participants

David Bott, P.E., S.E., AIA, M.ASCE; Principal; Heintges Consulting Architects & Engineers
Mehedy Mashnad, Ph.D., P.E.; Principal; Walter P. Moore
Angela Mejorin, Ph.D.; Western University-Canada
Don Scott, P.E., S.E., F.SEI, F.ASCE; Don Scott Consulting; Workshop Director
Tom Smith, R.A., F.SEI, M.ASCE; President; TLSmith Consulting, Inc.
Pataya Scott, Ph.D., EIT, Aff.M.ASCE; FEMA
Long Phan, Ph.D., P.E., M.ASCE, F.ACI; Group Leader; NIST

B.4. Workshop Reading List

B.4.3. Wind Climate Characteristics

- ASCE Prestandard for Performance-Based Wind Design (2019)

Additional Materials:
- ASCE/SEI Manual of Practice 143, *Design and Performance of Tall Buildings for Wind*
- ASCE 7-22, Chapters 1, 2, C1, and C2

B.4.4. System Reliability

- ASCE Prestandard for Performance-Based Wind Design (2019), Chapter 1 and Appendices 2 and 3

Additional Materials:
- Ghosn et al., Performance Indicators for Structural Systems and Infrastructure Networks
- Zhang et al., System-Based Design of Planar Steel Frames, I: Reliability Framework
- Zhang et al., System-Based Design of Planar Steel Frames, II: Reliability Results and Design Recommendations
- Arunachalam and Spence, Reliability-Based Collapse Assessments of Wind-Excited Steel Structures within Performance-Based Wind Engineering
- Ouyang and Spence, Performance-Based Wind-Induced Structural and Envelope Damage Assessment of Engineered Buildings through Nonlinear Dynamic Analysis
- Ouyang and Spence, A Performance-Based Wind Engineering Framework for Engineered Building Systems Subject to Hurricanes
- Chuang and Spence, A Framework for the Efficient Reliability Assessment of Inelastic Wind Excited Structures at Dynamic Shakedown
- Chuang and Spence, A Performance-Based Design Framework for the Integrated Collapse and Non-Collapse Assessment of Wind Excited Buildings

B.4.5. Wind-Structure Interaction

- ASCE Prestandard for Performance-Based Wind Design (2019)

Additional Materials:
- Serviceability Design of Tall Buildings under Wind Loads
- Council of Tall Buildings and Urban Habitat (CTBUH) Wind Tunnel Testing of High-Rise Buildings

B.4.6. Structural Analysis Techniques

- ASCE Prestandard for Performance-Based Wind Design (2019), especially Chapter 6 and Appendices A and B

- NIST GCR 17-917-46v1, Guidelines for Nonlinear Structural Analysis for Design of Buildings
- NIST GCR 17-917-46v2, Guidelines for Nonlinear Structural Analysis for Design of Buildings
- NIST GCR 17-917-46v3, Guidelines for Nonlinear Structural Analysis for Design of Buildings
- NIST GCR 17-917-45, Recommended Modeling Parameters and Acceptance Criteria for Nonlinear Analysis in Support of Seismic Evaluation, Retrofit, and Design
- PEER Tall Buildings Initiative Report, Case Studies of the Seismic Performance of Tall Buildings Designed by Alternative Means. Tall Buildings Initiative | Pacific Earthquake Engineering Research Center

Additional Materials:

- Huang and Chen (2022), Inelastic Performance of High-Rise Buildings to Simultaneous Actions of Alongwind and Crosswind Loads
- Mohammadi et al. (2019), Performance Assessment of an Existing 47-Story High-Rise Building under Extreme Wind Loads
- Preetha Hareendran et al. (2022), Performance-Based Wind Design of Tall Buildings Considering the Nonlinearity in Building Response
- Jeong et al. (2021), Performance-Based Wind Design of High-Rise Buildings Using Generated Time-History Wind Loads
- Wang and Wu (2022), Statistical Investigation of Wind Duration Using a Refined Hurricane Track Model

B.4.7. Design

- Guidelines for Wind Vulnerability Assessments of Existing Critical Facilities
- Main and Fritz, Database-Assisted Design for Wind: Concepts, Software, and Examples for Rigid and Flexible Buildings. 1 Database-Assisted Design (DAD) Approach

Additional Materials:

- A Performance-Based Wind Engineering Framework for Envelope Systems of Engineered Buildings Subject to Directional Wind and Rain Hazards
- Wind-Borne Debris Hazards, 9780784414965
- Aswegan et al. (2015), Recommended Procedures for Damage-Based Serviceability Design of Steel Buildings under Wind Loads
- Estimation of Wind-Driven Rain Intrusion through Building Envelope Defects and Breaches during Tropical Cyclones
- Griffis, Serviceability Limit States under Wind Loads
- Cui and Caracoglia, Performance-Based Wind Engineering of Tall Buildings Examining Life-Cycle Downtime and Multisource Wind Damage
- Arunachalam and Spence, Reliability-Based Collapse Assessment of Wind-Excited Steel Structures within Performance-Based Wind Engineering
- Johnson et al., Simulation of Rain Penetration and Associated Damage in Buildings within a Hurricane Vulnerability Model

- Chowdhury et al., Large-Scale Experimentation Using the 12-Fan Wall of Wind to Assess and Mitigate Hurricane Wind and Rain Impacts on Buildings and Infrastructure Systems
- Wolf and Griffith, Wind-Driven Rain as a Design Parameter

Appendix C. Workshop Research Needs Mapped to Program Elements

NIST is the lead agency in the U.S. Federal Government for the National Windstorm Impact Reduction Program (NWIRP), and Strategic Plan Item No. 4 for this program is to "Develop Performance-Based Design for Windstorm Hazards."

The following language is taken directly from the NWIRP Strategic Plan document. Priority research needs are added in bold font and brackets to indicate how these needs align with the program elements of the NIST NWIRP.

> The National Windstorm Impact Reduction Act Reauthorization of 2015 (Public Law 114-52), directed NWIRP to "support the development of performance-based engineering tools, and work with appropriate groups to promote commercial application of such tools, including wind-related model building codes, voluntary standards, and construction best practices." This strategic priority will engage the program agencies in performing basic and applied research that supports PBD development and in the knowledge transfer activities needed to support implementation.
>
> Existing national model building codes emphasize prescriptive wind and coastal design procedures that implicitly seek to minimize loss of life but do not adequately address minimizing direct or indirect economic losses **[Priority Research Need 10]**. Performance-based design (PBD) focuses on explicit expectations of building performance with respect to loss of life, damage, and operability, providing a wider range of design options than prescriptive code-based procedures. PBD promises to bring greatly improved economy and functionality for designs to resist windstorms. NWIRP will support development of PBD to resist windstorm hazards, including for tornadoes **[Priority Research Needs 4 and 5]**.
>
> From a structural point of view, PBD has been facilitated by the advent of sophisticated computational capabilities **[Priority Research Needs 7 and 8]** in the practicing engineering community. However, PBD requires more detailed knowledge of how structures **[Priority Research Need 6]** and nonstructural elements perform, including the infiltration of water, as well as a clear understanding of what level of performance **[Priority Research Need 1]** is needed to achieve desired resilience **[Priority Research Need 2]**. Because the step-by step building-code-based procedure is not used, PBD also alters decision-making and liability processes to include more complete and complex analyses, additional consideration of risk levels, and more extensive consideration of cost-risk tradeoffs. This will require more extensive knowledge about social behavior, structural performance needed to support response and recovery **[Priority Research Need 10]**, and investment decision making as described in the following strategic priorities.

This effort will also leverage advances in PBD for seismic design. Earthquake engineering is far ahead of wind and coastal engineering in terms of developing performance-based criteria **[Priority Research Need 9]** for seismic design. The wind and coastal PBD requirements will leverage the methods from the earthquake models for performance objectives applied to the wind and flood resistant structural systems. Different performance objectives are needed for the building envelope **[Priority Research Needs 2 and 3]**.

SP-4 supports Objectives 10, 11, and 12 by guiding the creation of tools **[Priority Research Needs 2, 7, 8, and 9]** to improve the performance of the built environment subject to extreme wind events **[Priority Research Needs 4 and 5]**, supporting the development of windstorm-resilient standards and building codes, and enabling implementation of such methods in professional practice. Initial development of PBD for tornadoes **[Priority Research Need 4]** is a short-term effort, PBD for the broader range of wind hazards is a medium-term effort, and PBD for storm surge-flooding is a long-term effort.

Appendix D. Program Participants: Alphabetical List

Srinivasan Arunachalam, S.M.ASCE	Graduate Student	University of Michigan
Kevin Aswegan, P.E., S.E., M.ASCE	Senior Associate	Magnusson Klemencic Associates
Bianca Augustin, Aff.M.ASCE	Administrator	ASCE/SEI Workshop Coordinator
Michele Barbato, Ph.D., P.E., F.ASCE, F.SEI, F.EMI	Professor	University of California Davis
David Bott, P.E., S.E., AIA, M.ASCE	Principal	Heintges
Melissa Burton, Ph.D., C.Eng., M.ASCE	Principal	Arup
Luca Caracoglia, P.E., M.ASCE	Professor	Northeastern University
Laura Champion, P.E., F.SEI, F.ASCE	Managing Director, SEI, and Global Partnerships	ASCE; *retired June 2023*
Xinzhong Chen, M.ASCE	Professor	Texas Tech University
Do-Eun Choe, Ph.D., P.E., M.ASCE	Professor	New Mexico State University
Greg Deirlein, Ph.D.	Professor	Stanford University
Baichuan Deng, S.M.ASCE	Graduate Student	University at Buffalo
Roy Denoon, Ph.D., M.ASCE	Senior Principal	CPP Wind Engineering Consultants
Jeff Dragovich, Ph.D., P.E., S.E., M.ASCE, F.ACI	Associate	DeSimone Consulting Engineers
Wenbo Duan	Consultant	Arup
Scott Erickson, P.E., M.ASCE	Principal	DCI Engineers
Jason Garber, M.ASCE	Engineer	RWDI
Ramon Gilsanz, P.E., S.E., F.SEI, F.ASCE	Partner	Gilsanz Murray Steficek LLP Engineers and Architects
Jennifer Goupil, P.E., F.SEI, F.ASCE	Managing Director SEI and ASCE Chief Resilience Officer	ASCE/SEI Workshop Program Manager
Larry Griffis, P.E., F.SEI, M.ASCE	Senior Consultant	Walter P. Moore
Hitomitsu Kikitsu		National Institute for Land and Infrastructure Management
John Kilpatrick, Ph.D., P.Eng., M.ASCE	Principal	RWDI
Greg Kopp, Ph.D., P.E., M.ASCE	Professor	Western University
Russell Larsen, P.E., S.E., M.ASCE	Principal	Magnusson Klemencic Associates
Marc Levitan, Ph.D., A.M.ASCE	Lead Research Engineer	NIST

Frank Lombardo, Ph.D., EIT, A.M.ASCE	Assistant Professor	University of Illinois
Marcos J. Martínez, Ph.D., P.E.		DeSimone Consulting Engineers
Mehedy Mashnad, Ph.D., P.E.	Principal	Walter P. Moore
Terri McAllister, Ph.D., P.E., F.SEI., Dist.M.ASCE	Group Leader/ Program Manager	NIST
Ricardo A. Medina, Ph.D., P.E., M.ASCE	Engineering Mechanics & Infrastructure	Simpson Gumpertz & Heger
Angela Mejorin, Ph.D.		Western University-Canada
Viral Patel, P.E., S.E., M.ASCE	Design Director	Walter P. Moore
Juan M. Paulino, P.E., S.E.		Buro Ehring Engineering
Long Phan, Ph.D., P.E., M.ASCE, F.ACI	Group Leader	NIST
Chris Raebel, Ph.D., P.E., S.E., M.ASCE	Vice President Engineering and Research	American Institute of Steel Construction
Ahmad Rahimian, Ph.D., F.ASCE		WSP
Wendy Reyes		HDR Inc.
Dan Rhee, Ph.D.	Research Engineer	NIST
Juliana Rochester, P.E., M.ASCE	Senior Design Engineer	Magnusson Klemencic Associates
Don Scott, P.E., S.E., F.SEI, F.ASCE	President	Don Scott Consulting Workshop Director
Pataya Scott, Ph.D., EIT, Aff.M.ASCE		FEMA
Brian Skourup, P.E., S.E., M.ASCE		EVS, Inc.
Jason Smart, P.E., M.ASCE		American Wood Council
Tom Smith, R.A., F.SEI, M.ASCE	President	TLSmith Consulting, Inc.
Seymour M.J. Spence, Ph.D., Aff.M.ASCE	Associate Professor	University of Michigan
Peter Vickery, Ph.D., P.E., F.SEI, F.ASCE	President	Peter J Vickery Consulting
John Wallace, Ph.D.	Professor	University of California Los Angeles
Workamaw Warsido, Aff.M.ASCE	Senior Project Engineer	CPP Wind Engineering Consultants
Teng Wu, Ph.D., M.ASCE	Associate Professor	University at Buffalo
DongHun Yeo, Ph.D., P.E., M.ASCE	Research Structural Engineer	NIST
Antonio Zaldivar, Ph.D.	Graduate Structural Engineer	Walter P. Moore

Appendix E. Change Log

Corrections made in an errata update do not alter existing or introduce substantive technical information, but rather are intended to remove ambiguity and improve interpretation of the work.

Change	Date change was made	Page number
Corrected author name list	11-14-2023	Cover 1 Cover 2
Corrected name to American Society of Civil Engineers	11-14-2023	Page i