Computational Wind Engineering: Tools and Techniques

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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. 133ND22PNB730391 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 Computational Wind Engineering.* The workshop and subsequent roadmap for the standardization and application of computational wind engineering is to be developed by wind engineering practitioners and researchers for buildings.

Keywords

Computational fluid dynamics; Computational wind engineering; Design; Resilience; System Reliability; Validation and verification; 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 *Advancements in Computational Wind Engineering* and *Advancement in Performance-Based Wind Design*. This report documents the results of the workshop on *Advancements in Computational Wind Engineering*. Wind engineering practitioners and researchers for buildings developed the workshop and subsequent roadmap to standardize and apply computational wind engineering (CWE)

The impetus for the project was the extensive casualties and property losses that have occurred over the last several decades because of 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 the development of standards that will lead to more resilient communities across the nation.

The workshop process included a review of the literature that identified current issues in the areas of Computational Fluid Dynamics Design Tools, Verification and Validation Benchmark Testing, System Reliability and Risk, Storm Type and Generation, and Structural Engineering Applications. This was followed by an extensive workshop preparation process, a two-day workshop to obtain input from the top 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 CWE in practice with the goal of reducing the impacts of these severe wind events. This report includes discussion and specific recommendations on the following nine topics:

1. Development of guidelines/minimum requirements for the application of CWE, including quality assurance/quality control protocols;
2. Development of consensus-based validation case studies using reliable wind tunnel data;
3. Full-scale observation and instrumentation with CWE integration;
4. Enhancing existing and developing new databases appropriate for verification and validation (V&V) of CWE;
5. Community vulnerability through physical testing for component fragility (residential scale);
6. Verification and Validation (V&V) virtual wind tunnel (with potential interactive design tools);
7. Integration of mesoscale simulations with urban scale models;
8. Sensitivity analysis and uncertainty quantification in Computational Fluid Dynamics (CFD); and
9. Leverage CWE to improve understanding between wind characteristics and effects.

SEI is indebted to the leadership of Don Scott, who served as the Workshop Director; Bianca Augustin, who served as the Workshop Coordinator; and Amber Davis who served as the Conference Center Manager; to Workshop Steering Committee members Melissa Burton, Catherine Gorle, Ahsan Kareem, Ted Stathopoulos, and Bradley Young for their contributions to putting the workshop together and developing this report; and to Workshop Steering Committee

scribes Rubina Ramponi, Mattia Ciarlatani, Fei Ding, Theodore Potsis, and Austin Devin 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, and DongHun Yeo from NIST for their input and guidance in developing the workshop and preparing the report.

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Executive Summary

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 Standard No. 7, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures.* To continue with the efforts toward windstorm impact reduction one of NIST's strategies is to further develop the use of computational wind engineering (CWE) with the goal of bringing this tool into design practice for improved estimations of wind loads and effects on buildings. This workshop and resulting report will highlight the research and development efforts needed over the next decade to provide standardization and application of CWE techniques in design practice.

1. Introduction

1.1. Workshop Scope and Purpose

The purpose of the workshop is to assess the current state of the art in CWE 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 included the following two broad subject areas, with associated subtopics:

- Subject Area 1: Computational Wind Engineering (CWE) Methodologies
    - Sub-Topic 1.1: Review of existing tools and methodologies: Capabilities and Limitations.
    - Sub-Topic 1.2: Identification of research needs and prioritization for application of CWE in structural design for wind.
- Subject Area 2: Verification and Validation (V&V) of CWE Methodologies
    - Sub-Topic 2.1: Review of existing methods, data types and services, and experimental methods for V&V of CWE.
    - Sub-Topic 2.2: Identification of research needs and prioritization for V&V of CWE

1.2. Workshop Development Process

The development of this workshop began with the selection of the Workshop Steering Committee (WSC), consisting of leading experts in the CWE field who have been involved in previous research, development, and utilization of CWE in academia and practice. Those selected to serve on the WSC were Dr. Melissa Burton, a Principal with Arup; Dr. Catherine Gorle of Stanford University; Dr. Ahsan Kareem of the University of Notre Dame; Dr. Ted Stathopoulos of Concordia University; and Bradley Young, an Associate Principal with Skidmore, Owings & Merrill. Each WSC member also invited a young professional to participate in the workshop and report development process: Rubina Ramponi at Arup, Mattia Ciarlatani at Stanford University, Fei Ding at the SimCenter at the University of California Berkeley, Theodore Potsis from Concordia University, and Austin Devin from Skidmore, Owings & Merrill.

The WSC started meeting in November of 2022 to start developing the content of the workshop and to select the leaders in this field to be invited 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:

- Computational Fluid Dynamics Design Tools.
- Verification and Validation Benchmark Testing.
- System Reliability and Risk.
- Storm Type and Generation, and
- Structural Engineering Applications.

To help understand the current state of the art, the WSC developed a reading list of relevant documents to share with workshop participants (Appendix B.4 provides this reading list). These documents were used to formulate the workshop sessions.

The two-day workshop was convened on May 18–19, 2023, to identify the highest-priority needs, which form the basis of this report. This workshop was attended by the WSC, the industry's leading experts, academics, and key government agencies, and it was open to members of the public. The workshop was held at the headquarters of the American Society of Civil Engineers (ASCE) in Reston, Virginia; see Figure 1-1.

Fig. 1-1. Participants in the NIST/SEI CWE workshop on May 18, 2023.

The design of the NIST/SEI CWE workshop enabled all 56 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 previously noted workshop topics selected by the WSC. In these breakout groups the participants were given four tasks: to define the current state of the art of CWE in their topic area, to define the future vision for the use of CWE, 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 identified research and development needs.

Members of each breakout group then reported back to all the workshop participants in a general session and described the group's prioritized research and development needs. Following these presentations and subsequent discussions, all the workshop participants identified and prioritized the top research needs from the needs identified in the breakout groups. Section 5 summarizes these prioritized overall research needs, and Appendix A also contains a further discussion of the prioritized research needs.

1.3. Workshop Framework

The framework adopted for the workshop to advance CWE into practice consisted of in-depth consideration of five key areas essential to the overall analysis and design process and verification. These areas include the work in computational fluid dynamics (CFD) design tools, verification and validation (V&V) benchmark testing, system reliability and risk, storm type and generation, and structural engineering applications. The following briefly describes these areas.

Computational Fluid Dynamics Design Tools: The session on CFD design tools was aimed at overviewing the CFD-based tools currently used in research and practice. This session included a discussion of various numerical approaches, turbulence modeling and particle-based simulations, digital twining, and machine learning–based accelerators. The outcome of this session prioritized research needs related to the development of tools with the infusion of innovative technologies to expedite simulations for practical applications and research.

Verification and Validation Benchmark Testing: Verification and Validation (V&V) are often confused. Estimation of deviations between numerical and experimental results belongs to the latter, while the quantification of errors belongs to the former. This session discussed and commented on minimum target uncertainties to be comparable with values derived from experimental results originating from wind tunnel laboratories conducting tests respecting ASCE 49 (2021) standard provisions.

System Reliability and Risk: Computational numerical modeling for design conditions in the built environment has been increasingly used over the last two decades. The application of computational modeling techniques has become an accepted standard for use in assessments of air quality, pollutant entrainment, and pedestrian comfort. For these applications, the length of simulations can be short and often involve mesh simplification. These simulations have reduced reliability when results are required in wake zones, gust speeds are high, or information beyond characterization of mean flows is required. This session discussed the low-cost entry barrier to CWE and the risk of moving too quickly, prior to quality assurance/quality control (QA/QC) protocol development and standardization, to quantify wind loading (static and dynamic) on structures. The session reviewed and discussed when moving too quickly into the use of computational simulations presents too high a risk and when the overall simulation outcomes may have a reduced system-level reliability.

Storm Type and Generation: When calculating wind loading on buildings accurately predicting the turbulent fluctuations of the wind pressures on the structure is important. These pressure fluctuations have two origins: the turbulence in the incoming wind field and the turbulence generated by the presence of the building in the flow. Accurate prediction of fluctuating pressures therefore requires accurate specification of boundary conditions for the wind and sufficient grid resolution and model accuracy to resolve the flow around the building. This session discussed the state of the art and open research questions in specifying realistic turbulent boundary conditions for wind flow, considering both typical neutral surface-layer winds and extreme wind phenomena such as hurricanes, tornadoes, and downbursts. Opportunities and challenges to improve the realism of these inflow conditions were identified.

Structural Engineering Applications: While the use of CWE has become more firmly accepted within the Architecture, Engineering and Construction (AEC) industry for larger-scale flow modeling applications, the unique aspects of bluff body aerodynamics pose challenges in the application of CWE for the development of structural wind loads for the specific purposes of main-wind-force-resisting-system (MWFRS) design and evaluation of wind response such as lateral accelerations. Characteristics of boundary-layer wind turbulence, local/flow separation at the building envelope, and the resulting turbulent wake formation, and computational limitations comprise some of the challenges in this regard. Nevertheless, CWE holds significant potential as a design tool for structural engineers. This session discussed ways to create a collaborative dialogue among leading experts in the CWE field, both from academic and commercial practice backgrounds, to explore the successes and challenges in the use of CWE in developing mean and dynamic structural wind loading and to identify and prioritize areas of needed research to allow CWE to emerge as a more useful and accessible design tool for the engineering industry.

1.4. Workshop Report Organization

Following Section 1. Introduction, the workshop report is organized as follows:

- Section 2 describes the current state of the art of computational wind engineering and the long-term vision for CWE’s use.
- Section 3 describes the current challenges in using CWE as identified during the workshop breakout sessions.
- Section 4 summarizes the research needs identified and prioritized by each breakout group covering the five identified key topics.
- Section 5 describes the priority research needs identified by the overall workshop participants, providing a summary of each research need with anticipated timelines and estimated costs.
- Sections 6 and 7 provide a list of acronyms and abbreviations and references.

The report includes four appendixes with additional details and information about the workshop, presentations given, research needs, recommended reading material, and a list of the workshop participants. Appendix A includes additional discussion about the highest priority research needs identified during the workshop. Appendix B includes the workshop agenda, presentations, breakout session participants, and reading list. Appendix C maps the priority research needs, as identified by the workshop participants as a whole, to the initial research needs identified in the breakout sessions and other NIST programs. Appendix D includes an alphabetical list of the workshop participants.

2. Vision for the Use of Computational Wind Engineering

2.1. Current State of the Art

2.1.1. Computational Fluid Dynamics Design Tools

CWE involves the stochastic generation of wind velocities and loads, the utilization of database-enabled design tools, and the application of CFD to assess wind loading conditions and aid in the configuration design process of structures.

The CFD workflow encompasses setting up boundary conditions, selecting turbulence models, running solvers, and post-processing the results. In CFD, different numerical methods are used to solve the partial differential equations: finite difference method (FDM), finite element method (FEM), and finite volume method (FVM) (Ferziger et al., 2002). CFD software like OpenFOAM and Fluent commonly employ the finite volume method. The lattice Boltzmann method (LBM) (Chen and Doolen, 1998) offers an alternative approach known for its versatility and scalability. As for meshing tools, the immersed boundary (IB) method (Peskin, 2002) facilitates the simulation of fluid flow around complex geometries.

The Reynolds-averaged Navier-Stokes (RANS) approach is widely used in CFD as it requires modest computational resources, but its accuracy is compromised especially in separated flow regimes. Large eddy simulation (LES) provides higher fidelity by solving filtered Navier-Stokes equations but at a higher computational cost. Both low- and high-fidelity models can be utilized in different scenarios, depending on the need for rapid predictions or accurate assessments. Turbulence modeling is an important aspect of CFD, with various models available such as the k-epsilon and k-omega models in RANS. However, understanding the requirements and limitations of each model is important for accurate and reliable simulations.

In addition to these conventional numerical schemes, particle-based methods such as the LBM (Wikipedia, 2023a) and others based on smooth particle hydrodynamics (SPH) (Wikipedia, 2023b) are fast emerging for application to flow-structure interactions (Chang et al., 2022). Generating body-fitted meshes for flows around complex three-dimensional geometries is a time-consuming task. In addition, it requires considerable expertise in the use of mesh generation techniques. To address these shortcomings, immersed boundary methods have been developed for modeling flows around complex geometric shapes where surface geometry is not represented by body-fitted nodal points. This technology can be coupled with recent developments in image-processing techniques and three-dimensional scanning technologies to generate surface representations of complex objects. For example, scanned images of the surface topology of city blocks can be constructed from Google images that are already available in open domain. These images, which are in the form of stereolithography (STL) files, can then be immersed in the computational grid, and employing immersed boundary method, the pressure and velocity boundary conditions can be imposed on the immersed surfaces by employing the immersed boundary method.

Mostly, error bars are not included in the presentation of wind tunnel test results, which are essential to assess the reliability and variability of experimental measurements. Similarly, CFD predictions also lack explicit error bars. Therefore, including error bars both in wind tunnel and in CFD evaluations is essential to account for the uncertainties stemming from different sources.

Integrating machine learning (ML) techniques in CFD for wind applications has tremendous potential to accelerate the field while improving accuracy and computational efficiency. ML algorithms can optimize various aspects of the CFD workflow and optimize computational costs. Furthermore, ML can be applied to turbulence modeling, facilitating the development of data-driven turbulence models that effectively capture complex flow phenomena. This not only enhances the fidelity of CFD simulations but also reduces the computational effort required for accurate predictions. Additionally, the integration of hybrid neural solvers allows for efficient surrogate modeling, enabling the construction of accurate reduced-order models that approximate the behavior of complex simulations. By leveraging ML techniques and incorporating hybrid neural solvers, the field of CFD in wind applications can advance significantly, enabling faster and more accurate analyses.

2.1.2. Verification and Validation Benchmark Testing

Various definitions of verification and validation can be found in the literature; in some cases these are very similar, and in other cases they are contradictory, as also mentioned by Yeo (2020). Oberkampf and Trucano (2002) define the two terms as follows: Model verification is the substantiation that a computerized model represents a conceptual model within specified limits of accuracy, and model validation is the substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model. However, ASME (2006) states that verification is the process of determining that a computational model accurately represents the underlying mathematical model and its solution. Furthermore, in AIAA (1998) validation is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. During the workshop, the participants decided to define verification and validation as one (V&V).

Codes like the National Building Code of Canada (Canadian Commission on Building and Fire Codes, 2020) do not permit the use of CWE for design or give little information regarding the necessary V&V process (for example, ASCE 7, 2022), while waiting for more explicit provisions similar to ASCE 49 (2021), as also mentioned by Yeo (2020). In International Organization for Standardization document ISO 4354 (2020), CWE is referred to as a promising methodology that is evolving at fast pace, but it is still not ready to reproduce the fluctuating (dynamic) flow characteristics and pressure coefficients with confidence, thus it is not recommended for design wind actions. Architectural Institute of Japan document (AIJ, 2015) is the first consistent endeavor to propose a V&V process based on two steps (isolated building and building inside an urban area). A list of benchmark experimental results is available, but the V&V of LES and guidelines for how to implement meaningful numerical analysis have yet to be explicitly defined.

The vital part of the V&V of the CWE process refers to experimental results from wind tunnels. ASCE 49 (2021) was developed to ensure that wind tunnel tests are conducted so as to simulate the physical characteristics of wind. The provisions highlight the permitted assumptions and experimental techniques that can be used. Any wind tunnel test that respects these provisions has been demonstrated to lead to pressure results on building surfaces that structural engineers can trust for design purposes and that can thus be trusted for CFD V&V as well. A common theme in the literature is the inconsistency of experimental results among different wind tunnels and between wind tunnels and full-scale tests, both for local/overall and static/dynamic loads (Li et al., 2021; Chavez et al., 2022; Shelley et al., 2023). Summarizing the aforementioned results, deviations have been observed that range from 15% for total static loads up to 40% for local dynamic loads.

The trend in the last decades is for V&V of CWE to be based on comparisons of mean (static), root mean square (RMS), and peak (dynamic) pressure coefficients from local taps and overall loads. Static wind loads have been captured with RANS modeling in the last decade, while the shift from RANS to LES has led to improvement in determining the static loads and has the potential to capture the dynamic load characteristics. In the last decade, the target level of accuracy has been achieved for dynamic loads with LES for isolated buildings in academic studies, driven by a more accurate expression of the turbulence characteristics in the wind field (Potsis et al., 2023). In general consultancy, achieving matched accuracy in prediction of the dynamic loads is not yet practice-as-usual.

2.1.3. System Reliability and Risk

The use of CWE in the built environment has become more common over the past two decades, both in academia and in industry. The most common approach to performing these CWE numerical simulations in the built environment is to adopt a steady-state RANS approach, where the mean wind flow is resolved, while turbulence is modelled.

Utilizing the RANS approach provides an affordable and reliable solution for problems that are driven by the mean flow component. Examples could be air quality, pollutant entrainment, and pedestrian comfort when the wind environment is not dominated by the wake zone, switching flows, or levels of gustiness in the flow field. However, this approach fails when looking at gust wind speeds, peak pressures, or wake regions, where the description of the mean flow can be inaccurate and sometimes misleading. A relevant example of this involves interrogating wind load effects on buildings and infrastructure, which are largely driven by gust loading.

One of the shortcomings of the rapid development of CWE is the limited availability of guidance on proven parameters to define a reliable CWE simulation. Such guidance could give practitioners and reviewers more confidence that the CWE simulations were performed in a manner that can be expected to yield reliable results. Similar documents have been developed for wind tunnel facilities, providing a standard approach to experimental wind modeling (e.g., ASCE 49, 2021). The different approaches to wind modeling and inconsistency in the reporting standards that should clearly indicate modeling assumptions and related risk and uncertainties reflect the lack of industry-wide consensus.

Further use and industry standard application of CWE in the built environment is not only driven by technical development but equally by the availability and accessibility to computing resources.

2.1.4. Storm Type and Generation

Most CFD modeling efforts have focused on modeling stationary *synoptic winds*, replicating the neutral surface layers generated in atmospheric boundary-layer wind tunnels and defined by empirical relationships in codes and standards. Different approaches to LES modeling of these turbulent boundary layers have been proposed: direct modeling of roughness elements and spires as used in boundary-layer wind tunnels, precursors methods, and synthetic turbulent generators. These methods have different challenges related to computational overhead and to ensuring that the target wind field is correctly reproduced at the building location. Independent of the method used, accurate wind loading predictions can be obtained if the target wind characteristics at the building location are accurately modeled.

To improve the realism of the wind fields used as boundary conditions in CWE simulations, efforts toward coupling or downscaling larger-scale weather forecasting models to building-scale CFD simulations have been explored (Chan and Leach, 2007; Chang and Hanna, 2004; Wiersema et al., 2022). In the context of LES, an important aspect of this coupling or downscaling is the generation of the smaller scales of turbulence that can be resolved in the small-scale simulation but that are modeled at the sub-grid scale in the large-scale simulation. Examples of such methods are eddy injection and eddy recirculation methods (Nagel et al., 2022; Lundquist et al., 2012), but the use of this type of coupling or downscaling for structural wind engineering calculations remains to be explored.

The modeling of extreme wind events, such as hurricanes, tornadoes, or downbursts, is also less frequently explored. For hurricane winds, modified boundary conditions for modeling a hurricane boundary layer have been proposed (Li and Pu, 2020). For tornadoes, most efforts have focused on reproducing the tornado-like flows generated in physical tornado simulators. Large-scale, full-atmosphere models of non-synoptic wind events have been downscaled to near-building resolution (Hendricks et al., 2021; Nolan et al., 2021), but no attempts have been made to use these simulations as input for structural wind engineering simulations.

2.1.5. Structural Engineering Applications

There are two aspects to the current state of the art of structural engineering applications of CWE: the state of the art as it relates to academia and research and the state of practice relating to industry practitioners. The state-of-the-art structural application of CWE is the accurate estimation of localized peak loading. Quantitative wind cladding loads can be estimated based upon CWE methods, as can quantitative snow loading on buildings including temperature dependence and snow drifting. In terms of the state of practice for industry practitioners, mean structural wind loads can be estimated within a reasonable level of accuracy. Qualitative cladding loading studies and snow loading studies can be completed. Wind-driven rain can also be accurately represented by CWE. Wind-driven rain is a significant driver of damage in storm events, and, as wind-driven rain is typically related to mean flow response, it can be accurately modeled using current methodology, in practice.

2.2. Long-Term Vision for Computational Wind Engineering

2.2.1. Computational Fluid Dynamics Design Tools

In the long term, V&V is essential for CFD modeling. The design of a virtual or digital wind tunnel can aid in validation by providing detailed configurations for replicating simulation results. Guidelines for its development can be derived from organizations like the Architectural Institute of Japan (AIJ) and the European Cooperation in Science and Technology (COST), which highlights the need for an ASCE/SEI pre-standard to guide CFD modeling practices. This pre-standard would cover various aspects such as geometry setup, boundary conditions, turbulence modeling, and result interpretation, ensuring reliability in CFD simulations.

The collection of datasets from both experimental and numerical simulations is important in validation of simulation results. Some resources are available, including VORTEX-Winds (accessible at https://vortex-winds.org), Tokyo Polytechnic University (TPU) aerodynamic database (accessible at https://db.wind.arch.t-kougei.ac.jp/), NIST-University of Western Ontario aerodynamic database (accessible at https://www.nist.gov/el/materials-and-structural-systems-division-73100/nist-aerodynamic-database/university-western), and the Johns Hopkins Turbulence Database (accessible at http://turbulence.pha.jhu.edu). Additional data will soon be available at the Natural Hazard Engineering Research Infrastructure (NHERI) SimCenter @ Designsafe (Mackenzie-Helnwein et al., 2020; Cai et al., 2023). These databases could provide resources for validating CFD results and improving simulation accuracy and efficiency.

An end-to-end simulation tool for a digital wind tunnel offers a complete solution for simulating and analyzing aerodynamic flows around structures. It would encompass all stages of the simulation process, from pre-processing by incorporating advanced meshing tools to post-processing, providing a streamlined workflow and advanced features for accurate and efficient virtual wind tunnel simulations.

Additionally, the availability of comprehensive datasets supports the development of machine learning models coupled with CFD. By leveraging these databases, machine learning algorithms can be trained to make fast and accurate predictions of flow quantities, reducing the computational time required for CFD simulations and conducting uncertainty quantification. This integration of machine learning and CFD would allow for efficient and accelerated simulations. In addition, the utilization of graphical processing units (GPUs) promises to speed up the simulation process at multiple orders of magnitude, making it more feasible and affordable to perform numerical simulations for academic and industrial applications.

2.2.2. Verification and Validation Benchmark Testing

CWE for structural design has been evolving rapidly in the last years. At this point, it has reached a stable state, and the structural engineering community needs to decide on specific conditions for its usage. Participants of the breakout session agreed unanimously that establishing benchmark cases for V&V is a way to move toward this goal. Different cases should be established based on the targets of the design, for example, comparisons in local loads in the entire building envelope and not only in specific symmetrical locations. Decisions regarding acceptable deviations of dynamic loads should be based on deviations among various wind tunnel results and not on a single isolated case. Part of the conversation during the session revolved around the possibility of creating recommendations for appropriate usage of CWE to reach consistent deviations from experimental results.

In the long term, breakout group participants agreed that wind tunnel studies should be documented in a consistent way and include comparative results among various facilities. Wind tunnel studies and CWE should continue to evolve together to achieve this vision but also keep in mind full-scale comparisons.

Application of CWE in cases that are problematic to test in wind tunnels was discussed, and V&V of computational procedures is necessary before this can be achieved. For example, experimental results for small-scale building elements, curved surfaces, and high Reynolds numbers are difficult to achieve in wind tunnels, thus CWE may be advantageous for such cases. CWE is considered a more likely tool to be used in non-synoptic (hurricanes, tornadoes, thunderstorms, etc.) because it is extremely difficult to collect wind data in these events. Thus, in the future CWE, when stabilized, will be the most useful tool to obtain the wind pressures.

2.2.3. System Reliability and Risk

The goal for CWE is to be fully integrated in the design process and to contribute to the development of more resilient and carbon-effective solutions for the built environment. In the long term, CWE would be used to complement (as opposed to replace) the capabilities of physical testing and overcome some of the current limitations (where reliability is low and risk is high) with scaled physical modeling.

Wind engineers, software developers, and CFD specialists need to collaborate and provide insights and technical expertise, supported by available computational resources, to resolve complex urban climate processes while integrating large weather systems and the impact of non-synoptic flow fields on the built environment. Such collaboration will create transparency around where the risk of using CWE resides while ensuring that knowledge gained in the physical modeling world over the last seven decades is not lost.

A need exists in CWE for more efficient models (affordable access to cloud computing, GPU solvers, parallelization, etc.) that would enable researchers and practitioners to develop simulation protocols and guidelines that improve CWE reliability in resolving turbulence at a higher resolution and multi-physics problems. Simulations of the built environment at a larger scale could include topographical features and large and complex building structures, which are now prohibited by the scaling ratio of the wind tunnel.

Large-scale CWE simulations would be a useful tool to assess the vulnerability of buildings to extreme wind events at the community level. Most especially when combined with modeling of different storm types (tornadoes, thunderstorm downbursts, and derechos) and multi-physics (wind + rain, ice, snow, urban heat, etc.) behavior. CWE integrated with regional climate modeling would allow simulations of the impact of a changing climate on the urban environment.

To fully unlock the use of CWE as a design tool and to expand the use cases of the application requires developing industry trust in these models. This is imperative to control the risk and enhance the reliability of the outcomes derived from numerical simulations.

2.2.4. Storm Type and Generation

The long-term vision for *typical stationary* wind inflow generation methods in large eddy simulations is the ability to efficiently and reliably model realistic wind fields with a range of exposures and stability conditions to support analysis of wind loads on low- to high-rise buildings. This vision includes modeling the wind flows typically generated in atmospheric boundary-layer wind tunnels, but it is also broader, addressing some of the limitations of wind tunnel modeling, such as the representation of large turbulent scales and non-neutral conditions. In this broader context, the vision is that the generation of inflow conditions will draw more strongly on mesoscale meteorological simulations or field observations to improve the realism of the boundary layer and that validation with field observations will be pursued.

This vision is extended to extreme wind conditions, such as tornadoes, downbursts, and hurricanes. First, computationally efficient methods to reproduce nonstationary flows generated in wind tunnels or tornado simulators should be available to support validation exercises. Second, methods that eliminate scaling challenges in physical experiments should be available, drawing on downscaled meteorological simulations or on field observations. These methods will support realistic simulation of extreme wind events, exploring parameter spaces that cannot be modeled in the lab. The ultimate objective is to calculate wind loads and debris flight and impact and improve understanding of the causes of damage (e.g., what percentage of damage is initiated by wind loading versus debris impact). These simulations could lead to new design guidelines that account for nonstationary effects and for the fact that these storms (in particular tornadoes) are rare events.

The resulting inflow generation methods should come with guidelines that specify their correct use to obtain the desired flow characteristics at the building location of interest. Furthermore, guidelines that specify the required level of accuracy in the wind generation and the level of detail needed in the model to predict specific quantities of interest should be available. Such guidelines would support identifying the right tool for a specific purpose, for example, differentiating between different design stages.

2.2.5. Structural Engineering Applications

The long-term vision for CWE for the use of structural applications is as follows:

Accurate prediction of structural wind loads and responses: The capability to accurately predict structural wind loads and the response of building structures of all heights.

High resolution of cladding pressure results: Utilization of CWE could achieve an increased result resolution for cladding pressures, allowing finer fidelity compared with what is physically and practically feasible with experimental pressure tap testing.

Regulatory acceptance: Regulatory acceptance of CWE is crucial for its implementation and widespread use to estimate structural wind loads on buildings. This could be either in the form of a guidelines document or a standard.

Broader wind engineering knowledge: CWE has great potential to broaden understanding and knowledge in the wind engineering field and to enable investigations of phenomena that are beyond the capabilities of wind tunnel testing. Examples of this would be non-synoptic windstorms, tornadoes, and downbursts.

Global computational wind models: Global computational wind models downscaled to local wind models, such as wind velocity effects, Weather Research and Forecasting (WRF) modeling, mesoscale modeling, and topographical effects.

Comprehensive rapid iterative aerodynamic assessment and design tool: A comprehensive rapid iterative aerodynamic modification assessment and design tool that allows real-time feedback from manipulation of bluff body shapes using parametric geometric modeling would be a powerful tool for designers to create innovative and efficient building structures. Aerodynamic shaping of buildings has the potential to reduce wind loads on buildings.

3. Challenges in the Use of Computational Wind Engineering

3.1. Computational Fluid Dynamics Design Tools

While CFD modeling has made advancements, including mesh-based or meshless approaches, uncertainty quantification (UQ) methods, and data-driven techniques, a gap remains between research and practical applications. In engineering practice, the guidance of CFD experts is crucial to ensure that the modeling process is correct and simulation results are comparable to wind tunnel measurements. Communication and collaboration are lacking among CFD experts, researchers, industry professionals, and even wind tunnel experts to guarantee the appropriate use of CFD techniques. Such collaboration could lead to better understanding and improved guidelines to drive the applications of CFD within civil engineering.

Another significant disadvantage that hinders the widespread use of CFD is the lack of effort in benchmarking CFD models. The absence of comprehensive benchmarking studies poses challenges in assessing and comparing the performance of different CFD models in a consistent and reliable manner, as evidenced by the limited number of published comparative studies that provide detailed modeling information. Information on geometry, boundary conditions, numerical methods, turbulence models, and discretization schemes in CFD should be provided for reproducibility. It is necessary to benchmark and validate the performance of CFD models with well-established reference cases or experimental data.

Furthermore, currently no specific guidelines exist in the United States, like those provided by AIJ (Tominaga et al., 2008) and COST (Franke et al., 2007), to direct the proper utilization of CFD. Considering the urgent need for standardized practices, the development of guidelines for CWE is needed. Such guidelines would provide a unified framework for the successful implementation of CWE, thereby enhancing its reliability and applicability in building industry applications.

In academia, a pressing need exists to develop more robust CFD models that prioritize accuracy and focus on providing standard mesh or meshless tools, refining turbulence models, and developing novel algorithms, etc. Considering computational time demands and scalability is also important to ensure the affordability of CFD simulations. This can be achieved by exploring advanced approaches such as fusion of machine learning and CFD and GPU accelerations. Incorporating uncertainty quantification into CFD modeling is essential to provide a measure of the uncertainty associated with inflow and modeling. This allows for the application of error bars or confidence intervals, which offer detailed information about the reliability and accuracy of the CFD predictions.

The limited knowledge of fluid dynamics and numerical methods among structural engineers prevents the effective application of CFD in real-world applications. Integrating fluid dynamics and introductory CFD courses into the education of structural engineers could effectively address this issue and yield significant benefits. By providing the necessary foundational knowledge, these courses can equip structural engineers with the essential skills and understanding needed to leverage CFD in their work. It would also aid in taking the “fear out of CFD.” Furthermore, additional resources such as tutorials, well-documented case studies, chatrooms, and webinars, including platforms like the NHERI SimCenter, can further support learning and provide valuable guidance in applying CFD effectively.

3.2. Verification and Validation Benchmark Testing

A big challenge at present is the lack of a specific procedure to realize the V&V process. This needs to be addressed at the earliest opportunity to evolve the current application of CFD for design purposes.

Generating recommendations for CWE is a difficult task: because the field is evolving rapidly, the risk exists of creating recommendations that are “born old.” To avoid that, the scientific field should agree on computational procedures that allow future implementations of latest findings. Of course, due to the nature of the field, creating newer editions of the recommendations as soon as new findings are available will be challenging.

One of the biggest challenges to achieve the future goals of CWE is creating numerical procedures that work efficiently for the specific design purposes and that are validated based on other experimental results of different cases. Of course, if experimental results were available, CFD would not be needed, thus the target is to eventually apply it as an independent tool. Reaching this level of confidence and trust in CWE for calculating dynamic loads will take effort and collaboration from scientific laboratories and companies that apply CWE for design.

Defining the threshold of accuracy for each case needs a lot of work and innovative ideas, plus more experimental results. This is due to the unique aerodynamic features that are developed in each specific building in conjunction with the surrounding terrain. Note that this threshold of accuracy should be defined based on the deviations noticed among different wind tunnel results, which introduces another degree of difficulty. Every wind tunnel is unique, and due to the complexity of the Atmospheric Boundary Layer (ABL) flow, results vary from one facility to another. This difficulty was mentioned many times during the session and needs to be tackled to define the threshold of accuracy that the computational procedures should be able to achieve consistently.

Experimental results for high Reynolds numbers (say, more than 10^6) are currently unavailable from physical wind tunnel testing, thus V&V of this type of condition is impossible for CWE. In this sense, expanding the range of available experimental results poses a challenge in the evolution of the CWE field, especially because data seemed to be unreliable in the past, by providing large deviations among similar experiments.

A big challenge is to relate the wind field characteristics with the dynamic loads that are applied on the building envelope. If this were achieved, it would help the profession choose more specific conditions for exposure in urban areas. This also relates to the target to create new applications for real-life buildings, located in various urban areas of interest, and not isolated, idealistic buildings.

Mesh configuration is one of the greatest challenges in any CFD analysis. During the breakout session, participants argued that due to the nature of the flow, the appropriate mesh configuration is different depending on each case and the targeted results of the design. Relating the mesh configuration in validated cases with experimental results and cases in which experimental data are not available but CFD is used as an independent tool will be a significant challenge that the profession will soon face. Standardizing these findings and including them in recommendations will also pose a challenge. Like the mesh configuration, solvers and numerical schemes to include in the recommendations will pose a challenge for the profession. Creating sensitivity studies that can answer these questions is a vital part that relates to the V&V process of CWE.

3.3. System Reliability and Risk

CWE can fully integrate into the design process and contribute to advancing the impact of wind engineering in the built environment. However, the need for benchmarking data from physical testing currently limits the applicability of CWE. CWE suffers from a lack of basic guidelines on parameters that constitute a reliable computational simulation and a lack of QA/QC protocols like those developed for physical testing (e.g., ASCE 49, 2021). Such simulation guidelines and protocols would reduce uncertainties and inconsistencies in the outcomes of numerical simulations across the industry. They would also provide a baseline to educate and inform clients and stakeholders on the risk and reliability associated with CWE for different applications.

The potential for using CWE beyond physical testing not only relates to its technical development but also to the possibility of computing complex models efficiently. Several factors currently affect computing speed and cost. Some are intrinsically related to the numerical codes, including the dependency on structured computer-aided design (CAD) models, the inability of codes such as OpenFOAM to run on faster GPU processors, and the varying efficiency in parallelization. Others depend on the ability to access powerful computing resources, such as High-Performance Computing (HPC) clusters. Unlocking efficiency in CWE is nontrivial and depends on the combined skills of software developers, wind engineers, and computational fluid dynamics experts to cross-examine outcomes and share knowledge that leads to risk reduction and the ability to advance the industry more rapidly and organically.

Most industrial CWE applications focus on the most common (synoptic) winds. However, non-synoptic winds like thunderstorms and tornadoes cause significant wind damage. The development of multi-storm CWE capabilities is limited by the lack of full-scale observational data for V&V and the description of the vertical distribution of the wind profiles in the boundary layer. Wind engineers need to work with CWE specialists to develop suitable computational models for different storm types and integrate regional-scale climatological models with building-scale CWE models. Computational power is a limiting factor for development given the scale, size, and resolution required to accurately represent these flow conditions. Large-scale CWE simulations of storm events offer the potential to assess vulnerability of communities to extreme winds once a workflow is developed to integrate CWE with fragility curves for component and structural systems derived through physical testing.

The ability to run multi-physics simulations (wind + rain, ice, snow, urban heat, etc.) is one of the clear advantages of CWE simulations over physical testing. These models are rather complex, and their use is far from being industry standard. The release of opensource packages and further computational optimization could promote wider adoption and testing and development in the structural engineering community. A strong need also exists to collect full-scale observations for V&V. The inclusion of multi-physics models in the design process and development of specific CWE simulation and interpretation guidelines for practitioners and reviewers is a challenge that goes beyond the CWE community and requires broader multidisciplinary collaboration and industry groups.

Super tall buildings are a challenge for physical testing because of the collapse of stationarity in the boundary layer at height. These buildings often feature smooth or rounded structures that pose Reynolds number issues when modeled at reduced scale. CWE could be a valid alternative to physical testing for modeling wind load effects around super tall buildings and the wind-structure interaction. However, it still lacks capabilities to represent non-synoptic flows and define appropriate boundary-layer conditions for these tests.

3.4. Storm Type and Generation

Challenges in generating synoptic wind fields depend strongly on the method used. Direct modeling of roughness elements and spires as used in boundary-layer wind tunnels (Thordal et al., 2020) and precursor methods (Liu and Pletcher, 2006; Lund et al., 1998; Wu and Squires, 1998) allow for the generation of inflow boundary conditions that are direct solutions of the Navier-Stokes equations. However, they introduce significant computational overhead in CWE simulations, which limits their use for design purposes (Wu, 2017). Synthetic turbulent generators (Aboshosha et al., 2015; Huang et al., 2010; Kim et al., 2013) allow for a reduction in the simulation cost. However, the inflow boundary conditions provided by artificial turbulence generators are not direct solutions of the Navier-Stokes equations, which can introduce artificial pressure fluctuations and result in a streamwise turbulence decay (Wu, 2017).

Artificial pressure fluctuations can be reduced by ensuring that the artificial velocity field is divergence free (Kim et al., 2013), while the streamwise decay can be addressed by using optimization methods that identify the inflow conditions that will produce target wind characteristics at the building location (Lamberti et al., 2018). These methods have been demonstrated on select test cases, but whether they can efficiently and accurately generate surface-layer wind fields for the range of conditions, including the range of different exposures, that are of interest to wind and structural engineers remains to be shown. Furthermore, the simulation of low-rise buildings that are immersed in the roughness sublayer introduces additional challenges in terms of accurately reproducing the turbulent flow characteristics at or below the building height.

Many challenges remain in the generation of extreme wind events in CWE. Modeling efforts in reproducing tornado-like flows generated in physical tornado simulators indicate that the overall vortex structure can be reproduced. However, not all tornado simulators employ roughness elements to introduce the near-surface turbulence scales that are likely present in tornadoes, and most data sets lack detailed turbulence information in the flow field. In general, a lack of near-surface field measurements in non-synoptic wind events limits understanding of full-scale turbulence characteristics in these wind fields. Large-scale, full-atmosphere models of extreme wind events have been downscaled to near-building resolution (Hendricks et al., 2021; Nolan et al., 2021), but validation of the near-surface turbulent flow predictions and the use of these models to calculate the resulting wind loads on structures remains to be explored.

3.5. Structural Engineering Applications

Computational time: Practical application of CWE for structural engineering applications requires the ability to define, set up, analyze, and generate results for interpretation in a reasonable time frame. CWE capabilities can be far-reaching with increased fidelity, but this comes at the cost of expanded computational time requirements. Computational time can vary widely based on hardware resources available, but currently the required computational run time to achieve rigorous results can be on the order of multiple days or even weeks, with significant parallel computing networks and high associated costs. This poses a challenge for practical incorporation of CWE into the design community, where project schedules are fast paced and this extended timeframe cannot be easily accommodated. If CWE is to make inroads into further use in the design profession, the timeframe for results needs to be reduced.

Limited availability of benchmark wind tunnel data sets for validation: While CWE has the potential to ultimately outpace the capabilities of physical wind tunnels, a critical step in the development and wider acceptance of CWE is to compare/validate the CWE results against wind tunnel results that are consensus accepted as reliable benchmarks. While an extensive amount of data from wind tunnel tests for individual buildings over many decades is available, these data are not publicly available and in many instances are considered to be the intellectual property of the wind tunnel laboratories. Therefore, a robust set of available benchmark data against which CWE results can be compared is currently lacking.

Lack of established guidelines: While certain users exhibit strong expertise in the performance of CWE simulations, the democratization of CWE tools available to a wide audience and to the general user means that skill sets and knowledge range widely among general users, resulting in questionable result outcomes in many cases. To properly leverage CWE and establish it as a reliable design tool, developing a set of guidelines or minimum requirements for carrying out a CWE simulation is critically important. Such a guidelines document, like that which currently exists for performing physical wind tunnel testing, can serve as reassurance that computational simulations are carried out with consideration of appropriate assumptions, modeling parameters, etc. This can be a catalyst for acceptance not only within the architecture, engineering, and construction community but also for acceptance by the relevant design codes and standards. Establishing a guidelines document would necessitate a series of steps leading up to the development of such a document, including validation of CWE results against existing benchmarks. This would include evaluation of input and modeling parameters, the analysis process and fidelity, and associated outcomes.

Existing regulatory language: Some codes and standards, within and outside of the United States, currently contain language that prevents the use of CWE for structural engineering applications. ASCE/SEI 7 (2022) allows the use of CWE but maintains that the results from the computational test be verified by a wind tunnel test, along with a requirement for a peer review. As an example of an international standard, the current National Building Code of Canada does not allow the use of CWE for structural applications, while ISO 4354 (“Wind Actions on Structures”) describes limitations in the use of CWE and discourages its application to estimating loading effects.

National Building Code of Canada (Canadian Commission on Building and Fire Codes, 2020), A-4.1.7.1(6): “Computational Fluid Dynamics (CFD). It is not currently possible to verify the reliability and accuracy of CFD and no standards address it; as such, this method is not permitted to be used to determine specified wind loads.”

ISO 4354 (2020): “Pressure and force coefficients can in principle be obtained using suitable computational fluid dynamics (CFD) techniques and this methodology will improve with time and could become a promising tool. Requirements are the same as those outlined in Annex H for wind tunnel measurements, but it should be noted that with the current state of development of CFD techniques, such methods are not able to fully reproduce the fluctuating flow characteristics required to obtain the appropriate fractile of the extreme value distribution of pressure coefficients, or the correct correlations between fluctuating pressure coefficients over the surface to give large area (or global) force or moment coefficients. Until this can be done, the use of such methods for force and pressure coefficient determination is not recommended."

AIJ (2015): The latest version of the AIJ provisions constitutes the first solid endeavor to utilize CWE for structural applications. Although currently only available in Japanese, a procedure is under development that utilizes LES for structural loads estimation. The key elements refer to verification of the numerical set-up, LES modeling with specific conditions (yet to be explicitly defined), two-step V&V (a single isolated building and a building in urban areas), and validation of local and overall results based on experiments (acceptable range: ±20% for mean and peak based on two different experiments).

Lack of cross-disciplinary collaboration: CWE for structural engineering applications represents a unique convergence of knowledge across multiple disciplines, including computational science, wind engineering, and civil/structural engineering. Over the last few decades, a collaboration between wind engineers and civil/structural engineers has developed, in their mutual work on tall, slender buildings; long-span bridges and structures; and other civil engineering projects. The injection of CWE into the civil/structural environment requires that computational fluid dynamics experts are folded into this collaboration, which has not yet happened to a large degree. To make advances in CWE, increased collaboration across these different but convergent fields is necessary.

4. Recommendation of Research Needs

The workshop participants were divided into smaller breakout groups that coincided with their expertise in one of the five workshop topics. These breakout groups then discussed the challenges in their selected topic and what would be required to advance CWE from the current state of the art to the long-term vision. Each group discussed the research needs required to make this transition and then prioritized them in their breakout session (see Table 4-1).

Table 4-1. Breakout Session Research Needs, as Identified by Workshop Participants.

No.	Research Needs
	Computational Fluid Dynamics Design Tools
A	Developing a pre-standard for CWE simulations
B	Verified and validated virtual wind tunnel
C	Consensus on realistic benchmarks
D	Computationally economical tools
E	CPU [central processing unit]/GPU processing
F	Uncertainty quantification in CWE
G	Role of machine learning in accuracy and efficiency
	Verification and Validation Benchmark Testing
A	Enhance existing databases (NIST, TPU, etc.) by including reliable information
B	Develop additional databases providing velocity time series, pressure data, wind tunnel characteristics, and data from more than one scale
C	Establish comparable results from different wind tunnels
D	Develop a reliable CWE technique for high Reynolds number applications
E	Develop CWE simulation workflow for non-synoptic winds (downburst, tornadoes)
F	Identify the source of uncertainties (sensitivity) for CFD verification
G	Develop a set of guidelines for CWE applications: wind loading on buildings
	System Reliability and Risk
A	CWE minimum requirements guidelines, including QA/QC protocols
B	Community-level vulnerability through physical testing for component fragilities and failure
C	Advocacy/messaging/communications about the impacts of storms and losses
D	Fundamentals of the storm systems at higher resolutions
E	Computational resources
	Storm Type and Generation
A	Support robust modeling of a wide range of exposures and atmospheric boundary-layer stabilities and synoptic events to support definition of more realistic boundary conditions
B	Improve fundamental understanding of the relationship between atmospheric boundary-layer characteristics and the resulting wind loads and damage from extreme wind events
C	Identify guidelines and benchmarks for using inflow generation tools

D	Develop new strategies for using larger-scale atmospheric flow simulations of synoptic and non-synoptic wind fields to inform realistic inflow conditions for CWE
E	Leverage field observations during synoptic and non-synoptic storms to support the definition of more realistic boundary conditions and improve CWE simulations
F	Reduce computational costs
G	Improve forecasting accuracy of non-synoptic storms
Structural Engineering Applications	
A	CWE guidelines for structural engineering applications Benchmark verification and validation Wind tunnel testing results Available benchmark data sets from CWE blind study Minimum requirements for undertaking a CWE evaluation for purposes of loading and response predictions for building structures
B	CWE for non-synoptic storms and wind-structure interaction
C	Community-scale CWE investigation of residential buildings
E	Larger geographical-scale CWE studies, e.g., tornado passing through neighborhood
F	Full-scale instrumentation (wind speed, building response, pressure)
G	Interactive design tool

These research needs were then voted on by all the workshop participants to prioritize the top research needs for CWE summarized in Section 5.2.

4.1. Computational Fluid Dynamics Design Tools

The breakout was composed of the following members:

Moderator:	Ahsan Kareem
Scribe:	Fei Ding
Reporter:	Aleksander Jemcov
Participants:	Stefano Capra
	Yunjae Hwang
	Arif Masud
	Huy Pham
	Don Scott
	Richard Szoeke-Schuller
	Jian-Xun Jason Wang, Ph.D.
	Wesam Mohamed

Developing a pre-standard for CWE simulations: Referring to established guidelines such as those from AIJ and COST, the pressing need for an ASCE pre-standard that can serve as a comprehensive guide for CWE modeling practices becomes evident. Developing a pre-standard through collaborations between academia and industry would provide a comprehensive framework and guidelines for appropriate CWE modeling and foster collaboration between researchers and industry professionals. The pre-standard would encompass essential aspects such as geometry set-up, boundary conditions, discretization methods, turbulence modeling, convergence criteria, and results interpretation. Moreover, a pre-standard would provide recommendations for uncertainty quantification using error bars. It would enable engineers to utilize CWE as a robust tool for assessment of wind loads, design optimization, and decision-making processes.

Verified and validated virtual wind tunnel: V&V are essential in the development of CWE models for practical use. The design of a generalized wind tunnel can greatly aid in the validation process by providing detailed modeling configurations for replicating simulation results. Validation involves comparing CWE results with experimental data or well-established reference cases to assess the CWE model's accuracy in predicting wind field or flow around structures. This process helps identify discrepancies and limitations in the numerical model.

Consensus on realistic benchmarks: The benchmarks should encompass different geometries or inflow boundary conditions relevant to the representative CWE applications. The benchmark specifications should be detailed in the numerical methods with the turbulence models and discretization schemes provided, which can serve as a reference for CWE validation.

Computationally economical tools: Considering computational time demands and scalability is important to improve the affordability of CFD simulations in engineering practice.

CPU/GPU processing: Central processing units (CPUs) and GPUs have distinct roles in CFD simulations. GPUs are excellent for use in parallel computations, accelerating the computationally intensive calculations involved in solving Navier-Stokes equations. By utilizing both CPU and GPU resources effectively, CFD simulations can achieve faster processing times and improved performance.

Uncertainty quantification in CWE: In wind tunnel tests, the experimental set-up typically includes measurements of various parameters, allowing for the estimation of uncertainty and the inclusion of error bars. This provides a quantifiable range of possible aerodynamic quantities in the assessment of the reliability of the measurements. Therefore, including error bars is important when evaluating wind loads to account for the variability and reliability of the CWE simulation results. In addition to this need, various sources of (aleatory or epistemic) uncertainty may affect the different quantities of interest for aerodynamic loading characterization, like inflow variability (aleatory) or model form (epistemic)—i.e., adoption of different turbulence modeling schemes. Therefore, both aleatory and epistemic uncertainties need to be appropriately quantified and propagated into the aerodynamic load-response-design cycle.

Role of machine learning in accuracy and efficiency: In recent years, data-driven approaches have received a lot of attention in refining or rapidly predicting CFD solutions. The emergence of machine learning has brought some benefits in accelerating the simulation process and rendering the use of CFD in engineering applications more effective by replacing the originally computationally intensive CFD models. Moreover, there has been a surge of interest in applying machine learning tools fed by high-fidelity computational or experimental data to reduce the model-form error from adopting low-fidelity models, thus enhancing the predictive accuracy of the CFD model without increasing its computational cost.

4.2. Verification and Validation Benchmark Testing

The breakout was composed of the following members:

Moderator:	Ted Stathopoulos
Scribe:	Theodore Potsis
Reporter:	Chao Sun
Participants:	Girma Bitsuamlak
	Tsinuel Geleta
	Hassan Hemida
	Harry Kabodha
	Claudio Mannini
	Joy Pauschke
	Adam Pintar
	R. Panneer Selvam
	Xiaoyun Shao
	Yoshihide Tominaga
	DongHun Yeo

Keeping in mind the trajectory of research and development of CWE applications, the breakout session for V&V discussed the research needs that would support the future evolution of CWE for wind loading. The group established seven research needs and prioritized them by a voting procedure.

The first need is to **enhance existing databases (NIST, TPU, etc.) by including reliable information** that can be used to thoroughly validate computational results. The information that needs to be provided for this purpose differs from that already available in existing databases (TPU, 2013; NIST, 2003; etc.). Mean speed, turbulence intensity profiles, and pressure data might be sufficient to help with design decisions but do not cover the needs of V&V in CWE applications. To enable trust in CWE results regarding dynamic local and overall loads, the breakout participants agreed that the information should include velocity time series of the incident wind profile because this plays a key role in computationally expressing the turbulence field. Wind tunnel characteristics such as roughness elements configuration, clear depiction of the dimensions of the upwind exposure, and the location of the reference pressure should also be included. The experimental uncertainty should be addressed in those reports. The breakout participants proposed that information should be provided for more than one scale from each configuration, in part because Reynolds number effects play a big role in the peak values that will be developed on the building envelope, but also because different wind tunnels use different scales for ABL modeling. In this way more comparable results from various wind tunnels can be created, which refers to the second research need on which the group agreed.

Generating comparable data will expedite the V&V process and provide more confidence in CWE as an independent tool, due to the degree of accuracy that can be calculated from more than one experimental procedure. Therefore it is vital that the CWE community agrees on benchmark tests and conducts experiments for them in many wind tunnel facilities to extract comparable data for the peak values. These benchmark tests should regard the various needs of design, such as urban environment buildings (real cases) and pressure tap locations that cover all elements for design (local loads on the entire envelope and overall loads). The V&V metrics from wind tunnels should also be agreed upon before these decisions are made (peak values estimation at post-processing, higher-order statistics relevance, etc.).

The third need regards the **development of guidelines for CWE applications for wind loading on buildings**. The field is developing rapidly, and thus these recommendations should be flexible to absorb new scientific findings and always keep in mind the compromise between accuracy and computational complexity/cost. Guidelines should focus on inlet boundary conditions and methods to generate turbulence characteristics, mesh configuration, solvers and solution process, V&V metrics for CWE, turbulence models, and numerical schemes. In this way the V&V process for CWE can be established.

The fourth research need also refers to the V&V process for CWE, from the aspect of **identifying the sources of uncertainty in the numerical set-up**. CFD analysis is a hotchpotch of parameters that interact in nonlinear ways; thus, estimating the relevance of each parameter in the peak values target for design is a high priority. **Standard sensitivity studies** constitute the only solution for this issue, allowing the final results of CWE to be expressed as a trusted range of values. The final target for this fourth research need is to evaluate which parameters are more effective in creating computational procedures that can provide accurate results consistently.

Non-synoptic winds such as downbursts and tornadoes were also part of the breakout discussion. **Developing a simulation workflow** to model them is the fifth agreed-upon research need. In particular, more focus should be given to the boundary conditions for computationally evaluating this type of event to be able to get V&V results from wind tunnel measurements.

Enhancing the documentation of existing wind tunnel databases comprises the sixth research need. To this end, a communication channel should be opened with the scientific groups that conducted experiments in wind tunnels to ask for more information to fill the needs of CWE validation, as presented in the first research need.

The seventh and final research need refers to **developing reliable CWE techniques for high Reynolds number applications**. This is important because high Reynolds number flows represent full-scale conditions and are difficult to model in wind tunnels. By improving the current state of the art in modeling these flows, the field will be closer to generating computational procedures that can be part of design decisions.

4.3. System Reliability and Risk

The breakout was composed of the following members:

Moderator:	Melissa Burton
Scribe:	Jennifer Goupil/Rubina Ramponi
Reporter:	Jason Garber
Participants:	Bianca Augustin
	David Banks
	Lakshmana Doddipatla
	Hiroto Kataoka
	Milad Roohi

The breakout participants brainstormed research ideas that would help to address the current challenges around understanding the reliability of CWE assessments. The research ideas noted in Table 4-1 were identified during the breakout session, they were written on sticky notes and grouped together to identify the main research needs. The breakout participants were asked to vote on research priorities to identify the top five research needs, discussed in the sections below.

CWE minimum requirements guidelines, including QA/QC protocols: Currently, CWE approaches lack outcome-based, industry-standard minimum requirements guidelines and QA/QC protocols like those for physical model wind tunnel testing (e.g., ASCE 49, 2021). This may be the greatest constraint on broader inclusion of the use of CWE in the design of the built environment. Investing in the development of such protocols would improve the reliability of CWE simulations and would reduce the dependency on V&V of the results against full-scale behavior and physical testing.

CWE is a rapidly evolving field, and the industry has adopted various tools and approaches for running urban wind simulations. The CWE minimum requirements guidelines, including QA/QC protocols, should avoid the standardization of these approaches and rather focus on the development of a method for checking and balancing the results. This “outcome-based” thinking would upskill the industry in recognizing the key elements of urban wind simulations and allowing innovation and creativity in the process. A crucial aspect of the methodology should be to demonstrate the ability to match key parameters that affect the outcome being assessed (e.g., velocity, turbulence, length scales, statistical stationarity, length of record, etc., for wind load effects).

The CWE minimum requirements guidelines, including QA/QC protocols, could also provide a framework for reporting the results of CWE simulations and the checks carried out by practitioners to demonstrate alignment with the protocols. The potential for the inclusion of peer review processes should also be made.

A multidisciplinary funded task group should be established to develop the guidelines, including CWE experts, wind engineers, meteorologists, software developers, and potentially data scientists. The groups may include others and would be dependent on the application for CWE.

Community-level vulnerability through physical testing for component fragilities and failure: Every year, windstorms account for a greater percentage of damage losses than any other natural hazard, exposing the vulnerability of entire communities to extreme wind events. Understanding and predicting vulnerability at the community level requires the combination of models at different scales. Physical testing is used to describe fragility and failure of building components and is the method of choice for deriving component fragility curves. Coupling this local understanding of component fragility to the overarching vulnerability of communities requires the ability to process vast amounts of data while simulating the complex wind environment. CWE provides the capability to run large-scale simulations that would otherwise be constrained by the modeling scale of physical testing and has the potential to simulate different storm types. Once component-level fragilities have been derived in large-scale physical testing, which includes wind loading protocols, these fragilities can be incorporated at building scale into community models. CWE could then be used to subject a virtual community to a storm of some size (or return period) to review the vulnerability of the community to that particular storm type or size.

Several research tasks are required to define a streamlined workflow for this community-level vulnerability assessment. First, faster, cheaper, and more reliable large-scale simulations that cover entire communities and their physical surroundings including topographic features are needed. Second, a need exists to develop fragility curves for building components using physical testing based upon wind loading protocols. Third, wind and structural engineers, together with CWE and risk specialists, need to develop a workflow to integrate the fragility and hazard curves with the outcomes of the numerical simulations.

Advocacy/messaging/communications about the impacts of storms and losses: CWE has the potential to support resilience-based design at the community level and enable the assessment of current and future climate risks. This technical advancement could lead to a whole new domain to address the risks associated with wind hazards. However, a need exists to increase advocacy and communication around the links among hazards, risks, design, and losses, and ultimately to attract more funding for further development in this space. Educating professionals and the public requires an engagement and educational campaign that identifies the best communication channels to reach different individuals, stakeholders, and/or communities.

The creation of technical education materials, delivered through presentations or white papers, could upskill designers and professionals in the building industry. A broader engagement with engineering and architectural schools can help increase awareness around extreme wind events and adaptation and promote advocacy. Considerations around design for enhanced resilience can become part of existing design courses with the support of wind and other climate-risk specialists.

Fundamentals of the storm systems at tighter resolutions: Most CWE studies are conducted for typical (synoptic or hurricane) winds that are represented by the ABL structure. Resilience-based design, however, requires modeling the impact of both synoptic and non-synoptic wind events on the built environment, including thunderstorms and tornadoes. Climate and storm systems are commonly modeled at large scale using Numerical Weather Prediction (NWP) models that provide insights into the spatial and temporal variation of these systems at resolutions of the order of 30 km × 30 km. These models often get downscaled to tighter grid resolutions (~5 km × 5 km; Copernicus, 2017). However, in most cases these tighter resolutions do not get down to the building scale, nor do they provide information on the lower part of the boundary layer.

Research is needed to streamline the downscaling of NWP models and integration with CWE models. While NWP models provide storm data at a relatively coarse resolution, CWE models simulate the wind flow at high resolution and predict the impact of the flows on the built environment. The identification of a solid workflow for the integration of these models requires synergy among meteorologists, CWE specialists, and wind engineers. Testing and optimization of the computational resources needed for this assessment is also required for these models to be integrated in industry practice.

Computational resources: The potential to use CWE for complex modeling ranging from multi-physics urban processes to large-scale community simulations is intrinsically linked to the availability and costs of the required computational resources. Computational investment is often perceived as one of the main barriers to the adoption of more onerous models such as LES. LES is often a required modeling approach for answering the question at hand, as it provides a more comprehensive and time-dependent description of the flow.

Several factors contribute to increasing the computational costs of CWE simulations. Four notable ones are related to translation of architectural models into a computational mesh, complexity of the city environment, parallelization of analysis on CPU or GPU cores, and hardware. Finding opportunities for efficiency in the process is not trivial and needs a multidisciplinary team that includes CFD specialists, wind engineers, and software developers. Funding the development of opensource tools that run on more efficient resources such as GPU and subsidizing/providing access to high powered computing (HPC) clusters is also a way to broaden the use of more complex models.

4.4. Storm Type and Generation

The breakout was composed of the following members:

Moderator:	Catherine Gorle
Scribe:	Mattia Ciarlatani
Reporter:	Abiy Melaku
Participants:	Bilal Alhawamdeh
	Yanlin Guo
	Fred Haan
	Faiaz Khaled
	Marc Levitan
	Lance Manual
	David S. Nolan
	Gonçalo Pedro, Ph.D.
	Dan Rhee
	Delong Zuo

The storm type and generation breakout session discussed research needs in the areas of synoptic and non-synoptic wind generation in LES. The session participants recognized that accurate simulation of the turbulent wind field is fundamental to obtaining accurate wind loading predictions on structures. Furthermore, participants agreed that the current state of the art in wind field generation only supports modeling a subset of the wind conditions of interest and that future research should center around significantly increasing modeling capabilities for a range of exposures and non-synoptic storm events. The breakout participants defined eight corresponding research needs.

Support robust modeling of a wide range of exposures and atmospheric boundary-layer stabilities and synoptic events to support definition of more realistic boundary conditions: This research need requires improving understanding of the coupling among inflow, numeric, wall functions, and sub-grid models to develop computationally efficient approaches to represent upstream roughness elements. The latter is envisioned to be particularly useful for low-rise building simulations.

Improve fundamental understanding of the relationship between the atmospheric boundary-layer characteristics and the resulting wind loads and damage from extreme wind events: This research needs to be explored using a combination of wind tunnel measurements, CWE, and field observations, leveraging tools from uncertainty quantification, data assimilation, and/or ML. The resulting knowledge should be leveraged to identify the relation between specific model choices for the CWE simulations and the resulting accuracy of the wind loading predictions.

Identify guidelines and benchmarks for using inflow generation tools: These guidelines and benchmarks should support CWE modelers in using established wind generation methods to obtain representative wind characteristics at the building location of interest, considering both synoptic and non-synoptic wind fields.

Develop new strategies for using larger-scale atmospheric flow simulations of synoptic and non-synoptic wind fields to inform realistic inflow conditions for CWE: This research will support advancement beyond modeling wind tunnel boundary layers. To support the development of methods for coupling and/or integrating mesoscale and building-scale calculations, this research need includes (1) speed-up of mesoscale simulations, (2) development of methods to accurately compute pressures on buildings within mesoscale simulations, and (3) extraction of realistic boundary conditions from mesoscale simulations.

Leverage field observations during synoptic and non-synoptic storms to support the definition of more realistic boundary conditions and improve CWE simulations: These field observations should emphasize near-ground measurements and measurements within the urban environment. New methods, based on techniques such as data assimilation and machine learning, are needed to leverage the field observations to improve CWE models and to use CWE to complement field observations. In this context, recognizing that field observations are often nonstationary is important. Hence, new methods to analyze and compare nonstationary quantities among field, CWE, and wind tunnel measurements will be needed.

Reduce computational costs: The computational costs of the simulations remains a limiting factor in addressing many of the research needs and achieving the future vision. As such, there is a clear research need for reducing the cost of the simulations through more efficient codes, numerical schemes, sub-grid models, and machine learning.

Improve forecasting accuracy of non-synoptic storms: This research need is important for obtaining field measurements of non-synoptic storms such as hurricanes and tornadoes. To support such field measurements, accurate predictions of the storm path are required.

4.5. Structural Engineering Applications

The breakout was composed of the following members:

Moderator:	Bradley Young
Scribe:	Austin Devin
Reporter:	Jan Dale
Participants:	Matiyas Bezabeh
	Roy Denoon
	Rakesh K. Kapania
	Emily Kim
	Long Phan
	David Phillips

Sumanth Reddy
Rob Rowsell
Ting Shi
Seymour M.J. Spence
Teng Wu

CWE guidelines for structural engineering applications: A fundamentally critical step in broad acceptance of CWE for structural engineering applications is the development of a guidelines or minimum requirements document that defines input and modeling parameters with which computational analysis shall comply. This guidelines document would be akin to ASCE 67, *Wind Tunnel Studies of Buildings and Structures* (1999) or the subsequent ASCE 49, *Wind Tunnel Testing for Buildings and Other Structures* (2021). Several required steps would lead up to the development of such a document and would include verification of CFD results against benchmark cases:

1. Establish benchmark wind tunnel testing cases and results,
2. Make these benchmark cases available,
3. Perform a series of blind CWE studies to validate results, and
4. Define CWE modeling and analysis parameters that can successfully capture the performance and match results.

The guidelines document would also include protocols for QA/QC of CWE simulation to facilitate interpretation by practitioners and reviewers.

CWE for non-synoptic storms and wind-structure interaction: A long recognized limitation of current physical wind tunnel testing is that it exclusively addresses synoptic wind events and is not readily modifiable for generating flow characteristics associated with downbursts, thunderstorms, tornadoes, or other non-synoptic wind events. Also well known is that non-synoptic wind events such as thunderstorms are a significant component of the wind climate for large geographic regions in the United States. Computational wind tunnels could be more readily modifiable to generate the flow characteristics of these types of events, unlocking the potential to study the influence of these types of storms on building structures.

Community-scale CWE investigation of residential buildings: Low-rise buildings and residential structures represent the vast majority of the overall building stock within the built environment. Windstorm damage represents a large proportion of total property damage/loss across all natural hazards. It stands to reason that low-rise and residential buildings dominate the economic losses in such wind events. Yet these structures are rarely designed or evaluated based on wind tunnel tests due to their scale. CWE may provide a cost-effective means to evaluate these building structures at a community or “neighborhood” scale to better understand the local wind environment imposed upon these structures during wind events. On this basis, improved structural performance may be possible through enhanced design and/or construction considerations, potentially reducing overall property damage/financial loss in strong wind events at the smaller scale.

Larger geographical-scale CWE studies, e.g., tornado passing through neighborhood: CWE offers a powerful potential for evaluating larger “neighborhood-scale” storm characteristics and the performance of residential buildings in these larger-scale wind environments. Current physical wind tunnels are scale limited, and current code-based wind load approximations are unlikely to capture complex wind conditions around residential building clusters well . Considering that most of the building stock consists of low-rise residential buildings, CWE provides a potential means to focus on these “neighborhood-scale” wind environments in a way that previously was not possible.

Full-scale instrumentation (wind speed, building response, pressure): Much of the discussion about the advancement of CWE has included the comparison of CWE results with results from wind tunnel tests. Fundamentally though, the industry sorely lacks a robust amount of in situ measurement data from built structures. With a more robust collection of in situ measurements, direct comparisons between the in situ measurements and the results from CWE simulations could be made.

Interactive design tool: A potentially powerful aspect of CWE is the capability to perform a large number of rapid, iterative simulations of various building forms to evaluate wind performance. The architectural form of a tall building is the single-most influential factor in its wind performance. If tall building forms can be rapidly evaluated and connected to a feedback loop of form adjustments, this could become a valuable tool as part of the design process and could lead to the use of less material to mitigate wind-induced motion.

5. Prioritization and Benefits of Recommended Research Needs

5.1. Prioritization of Research Needs by Workshop Participants

Following the breakout sessions, the workshop participants reconvened into a single group and reviewed the recommended research needs from each session. Table 4-1 summarizes the research needs.

5.2. Overview of Recommended Research Needs, Activity Costs, and Time Requirements

Based upon the workshop participants and combination of similar research needs by the Workshop Steering Committee, the research priorities were selected, and the most urgent needs were identified (Table 5-1). The table shows the order of priority, the Priority Research Need, and its estimated cost and time. Section 5.3, 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 5.4, 5.5, and 5.6 describe the comprehensive budget and schedule, interrelationships among research activities, and their 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 5-1. Workshop Research Priorities, as Voted on by the Workshop Participants.

No.	Priority Research Needs	Estimated Cost	Estimated Time
1	Development of guidelines/minimum requirements for the application of CWE, including QA/QC protocols	Moderate	Moderate/ Long
2	Development of consensus-based validation case studies using reliable wind tunnel data	Moderate	Moderate
3	Full-scale observation and instrumentation with CWE integration	Moderate	Long
4	Enhancing existing and developing new databases appropriate for V&V of CWE	Moderate	Moderate
5	Community vulnerability through physical testing for component fragility (residential scale)	High	Long
6	V&V virtual wind tunnel (with potential interactive design tools)	Moderate	Long
7	Integration of mesoscale simulations with urban scale models	Moderate	Long

8	Sensitivity analysis and uncertainty quantification in CWE	Moderate	Moderate
9	Leverage CWE to improve understanding between wind characteristics and effects	Moderate	Long

Some of the research needs identified in the individual breakout sessions were similar in scope. For that reason, the WSC combined similar research needs into those listed in Table 5-1. These research needs were then prioritized based upon the combined votes received from the workshop participants. The following summarizes how these research needs were combined.

1. **Development of guidelines/minimum requirements for the application of CWE, including QA/QC protocols:** This research need was the top research need identified in the Computational Fluid Dynamics Design Tools (A), the System Reliability and Risk (A), and the Structural Engineering Applications (A) breakout sessions, and a research need identified by the Verification and Validation Benchmark Testing (G) and the Storm Type and Generation (F) breakout sessions. These research needs were combined into this one topic for prioritization by the overall workshop participants. The WSC recognized this research need as the essential item required to move CWE forward into practice, and the workshop participants selected it as their highest priority.
2. **Development of consensus-based validation case studies using reliable wind tunnel data.** This research need was the top research need identified in the Verification and Validation Benchmark Testing (A) breakout session and the second highest research need identified in the Computational Fluid Dynamics Design Tools (B) breakout session and combined into this single research topic. The workshop participants selected it as their second highest priority.
3. **Full-scale observation and instrumentation with CWE integration.** This research need combines needs identified in the Structural Engineering Applications (F) and in the Storm Type and Generation (A) breakout sessions.
4. **Enhancing existing and developing new databases appropriate for V&V of CWE.** This research need was identified as the top need for the Verification and Validation Benchmark Testing breakout session.
5. **Community vulnerability through physical testing for component fragility (residential scale).** The WSC combined research needs from the Storm Type and Generation (B) and the Structural Engineering Applications (C) breakout sessions into this research need.
6. **V&V virtual wind tunnel (with potential interactive design tools).** This research need was identified as the second highest research need by the Computational Fluid Dynamics Design Tools (B) breakout session.
7. **Integration of mesoscale simulations with urban scale models.** The WSC combined research needs identified by the System Reliability and Risk (D) and the Storm Type and Generation (C, D, E) breakout sessions.
8. **Sensitivity analysis and uncertainty quantification in CWE.** This research need was identified in the Verification and Validation Benchmark Testing (F) breakout session.

9. **Leverage CWE to improve understanding between wind characteristics and effects.** This research need was identified as the second highest research need by the Storm Type and Generation (B) breakout session.

5.3. Summaries of Research Priority Needs

The Workshop Steering Committee developed the following in-depth summaries of the Priority Research Needs identified in Section 5.2, which includes 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 Guidelines/Minimum Requirements for the Application of CWE, Including QA/QC Protocols

Description: The overriding consensus among the workshop participants within the wind and structural engineering industries is that CWE needs guidelines to bring a certain level of rigor to its application. Such a document could help propel CWE to wider acceptance, wider application, and more successful use within the wind and structural engineering industries.

The *guidelines document* should follow a performance-based approach like ASCE 49 (2021) does for physical wind tunnel testing but should include minimum performance criteria for CWE simulations. An overly prescriptive approach to the document would limit innovation and continual development of CWE. A *benchmarking document* should be created alongside the guidelines to guide CWE practitioners in properly simulating atmospheric and urban flows and replicating wind action and structural response. The benchmarking document should be connected to an *opensource database* of quality-controlled wind tunnel testing data for the built environment. The database should provide structured data and key parameters for validation of CWE tools and approaches.

The following steps are necessary to establish guidelines, benchmarking documents, and opensource databases. Some activities would naturally occur sequentially, and some could run in parallel.

1. Establish performance criteria for the guidelines/minimum requirements document.
2. Establish a set of benchmark cases for which physical testing data are available to verify the feasibility of the performance criteria and margin of errors.
3. Perform initial “blind” CWE testing, given detailed and accurate information on the turbulent wind field in the experiment.
4. Perform follow-up testing to evaluate and define key CWE parameters to achieve consistent results.
5. Document the CWE process.
6. Draft CWE guidelines document. Included with this shall be the minimum requirements for proper CWE simulation and a definition of QA/QC protocols to substantiate the simulation and facilitate the interpretation of the parameters and results by practitioners and reviewers.

Estimated Cost: $1,000,000–$3,000,000

Estimated Time: 5–10 years

Measurement Science Challenges and Potential Solutions

Challenges	Potential Solutions
Defining benchmark wind tunnel results.	Create diverse groups to arrive at “consensus” results together.
Communicating the key input parameters while maintaining “blind” CWE testing.	Prior discussions to outline parameters to be shared initially or held prior to initial results.
Achieving sufficient agreement between the turbulent wind field generated in the wind tunnel and the	Outline a process to achieve and demonstrate a satisfactory level of agreement in the statistics of the

corresponding wind field generated in the CWE simulation.	three turbulent velocity components and the pressure in the incoming wind field.
Achieving agreement on a satisfactory level of consistency between wind pressure and force predictions from CWE and physical testing.	Prior discussions to outline and define satisfactory correlation, and use of methods to account for uncertainties in physical testing and CWE simulations.
Sharing intellectual property with various stakeholders with differing commercial goals.	Draft formal nondisclosure agreement and commitment statement.
Drafting guidelines document with input from various stakeholders with differing commercial goals.	Draft nondisclosure agreement and commitment statement.

Stakeholders and Roles

Stakeholder	**Role**
Universities/Research Organizations	University laboratories perform CWE simulations and physical wind tunnel testing and share input parameters and results.
Industry	Commercial wind tunnels: Perform CWE simulations and physical wind tunnel testing. Share input parameters and results. Practicing structural engineers: Participate in process. Review results and facilitate communication among the various stakeholders. Commercial CWE Consultants: Perform CWE simulation testing. Share input parameters and results.
Standards Organizations	Participate in the entire process. Help to facilitate communication and information sharing. Review progress results.

Impacts on Standardization and Application in Practice

- A CWE guidelines document would facilitate the wider use of virtual wind tunnel testing by defining a standard of care and in turn making virtual wind tunnel testing more broadly accepted than ever before.
- QA/QC protocols for CWE would limit the need to validate the outcomes of numerical models with physical testing, broadening the range of applicability of CWE in the built environment.

Priority Research Need 2: Development of Consensus-Based Validation Case Studies Using Reliable Wind Tunnel Data

Description: The development of consensus-based validation case studies using reliable wind tunnel data is a critical part of a well-funded future for CWE applications. A list of case studies needs to be selected and organized based on various design targets, and the V&V process should be explicitly defined for practical use of CWE. Experimental results from the case studies are to be extracted from various wind tunnel facilities and be comparable. Low-, mid-, and high-rise buildings should be the main categories of the case studies, and the target is to generate local, overall, static, and dynamic loads for various building configurations and for idealistic and realistic exposure conditions. If these are achieved, the evolution of CWE in practical applications can be based on the V&V of a series of cases of interest on empty domains (to check the turbulence statistics of the three velocity components in the turbulent wind field), isolated buildings (to V&V the conditions of simpler experiments), and non-isolated buildings (to V&V the capacity of the modeling to capture real-life exposures). The series of cases should depend on the final design targets. As a final step, the same wind flow conditions expressed in the numerical set-up should be used for modeling pressures on building configurations where experimental data do not exist, with confidence that the computational results will be within the margin of error.

Estimated Cost: $1,000,000–$3,000,000

Estimated Time: 2–5 years

Measurement Science Challenges and Potential Solutions

Challenges	Potential Solutions
V&V process in terms of accuracy of wind field and pressures	Standardized techniques
Definition of list of all case studies	Agreement of a committee of experts
Comparability of data from wind tunnel and computational studies	Communication channel between experimentalists and computational experts to build consensus

Stakeholders and Roles

Stakeholder	Role
Universities/Research Organizations:	Research and propose standardized V&V technique.
Industry:	Assist with the range of design needs, feedback.
Standards Organizations:	Follow the evolution of the research and include it in the new standards and protocols.

Impacts on Standardization and Application in Practice

- Consensus-based validation case studies are the most reliable path to create a design tool with CWE for structural applications and clearly define the level of performance of numerical results. Outcomes from this research need will be a big part of the guidelines and QA/QC protocols.

Priority Research Need 3. Full-Scale Observation and Instrumentation with CWE Integration

Description: Buildings are designed and constructed based on best estimates of the loading that is imparted upon the structure, and the response of the structure to these environmental loads is estimated through the use of computer simulations/analysis software. Rarely are the input assumptions or the in situ behavior of buildings verified via full-scale monitoring.

As CWE emerges as a more viable tool in civil engineering/architecture, leveraging a combination of field observations and numerical simulations to improve the wind-resistant design of buildings can yield significant benefits. CWE offers the potential for modeling wind effects that are outside of the capabilities of most physical wind tunnels. Limiting the verification and validation of CWE to the processes that can be modeled in physical wind tunnels would hinder the ultimate potential of CWE as a tool.

The approach turbulent wind characteristics have an important effect on the wind loads, highlighting the need to address the lack of full-scale data on near-surface wind characteristics during extreme wind events such as hurricanes, downbursts, and tornadoes. Measurements made for meteorological purposes tend to focus on larger scales and higher heights, while damage to buildings is driven by the local turbulent wind characteristics near the ground. Improving the understanding of near-surface wind conditions in extreme wind events is crucial to improving wind-resistant design.

Estimated Cost: $1,000,000–$3,000,000

Estimated Time: 5–10 years

Measurement Science Challenges and Potential Solutions

Challenges	Potential Solutions
Organizing a generally standardized protocol for instrumentation.	Assemble steering group with requisite experience to form outline of instrumentation protocol.
Identifying candidate buildings and “selling” the concept of instrumentation to the building owners.	Assemble candidate building list and identify contacts related to those buildings, i.e., structural engineers with communication with those target building owners.
Instrumentation “roll-out” logistics.	Budget time and expenses for deployment.
Data acquisition and processing. Maintenance of instruments over time.	Properly budget for longer-term (5 year?) data acquisition and some maintenance.
Technical challenges of installing instrumentation for certain target measurements, for example, spatial wind speeds or pressure measurements.	Establish steering committee to define proven technologies and gaps.
Post-processing of nonstationary data.	Identify working group tasked for post-processing with requisite experience.
Integration of observational data with CWE simulations.	Application of novel methods from data assimilation, uncertainty quantification, and machine learning.

Stakeholders and Roles

Stakeholder	Role
Universities/Research Organizations	Assist in defining the standard monitoring/instrumentation protocol.

	Execute measurement campaigns, process data, and perform accompanying CWE simulations, including integration with measurement data.
Industry	Assist in establishing contacts and agreements with target buildings. Collaborate with universities on measurement and simulation efforts.
Standards Organizations	Steering, organization of the various required working groups (instrumentation, building liaison, roll-out, acquisition, and post-processing).

Impacts on Standardization and Application in Practice

- Enhance the limited pool of verification of in situ testing against in situ testing for improved impact of CWE within the industry.

Priority Research Need 4: Enhancing Existing and Developing New Databases Appropriate for V&V of CWE

Description: An indispensable part of the V&V process is the availability of good wind tunnel data that computational wind engineers can rely on. The structure of the data necessary for this process exceeds the current state of information found in databases. Computational wind engineers need to take control of this information to achieve the needs of CWE.

In this respect, this research needs to refer to enhancing the existing databases and developing new ones that will include the proper range of information. Emphasis should be placed on detailed characterization of the turbulent approach wind and the resulting turbulent wind field at the test specimen location. Detailed wind tunnel configurations, velocity time series of the three velocity components of the entire incident flow profile, and pressure time series on the entire building envelope for various building geometries are the main needs for V&V of CWE.

Uncertainty quantification of the experimental results should be conducted based on uncertainty (e.g., spanwise variability) in the approach wind field, experimental error, and post processing techniques. The new databases should include experimental results for more than one geometrical scaling factor—possibly full scale—and for different exposure conditions that represent code-defined and realistic urban surroundings. Non-synoptic wind conditions should also be included in the future database collection. The target of this research is to extract comparable results from various wind tunnels to support the V&V process of CWE in a standardized form.

Estimated Cost: $1,000,000–$3,000,000

Estimated Time: 2–5 years

Measurement Science Challenges and Potential Solutions

Challenges	Potential Solutions
Agreement on list of experiments and information in the database	Create a committee of specialists from universities and the profession
Every wind tunnel is different; comparability of results	Identify specifically the experimental conditions that should be applied
Enhancing existing databases	Establish communication channel with the experimentalists of those facilities
Uncertainty of experimental results	Multiple experimental runs in various scaling factors to establish the uncertainty and experimental error
Need for experimental results from various facilities	Collaboration of multiple research and industry wind tunnels to gather all necessary experimental data

Stakeholders and Roles

Stakeholder	Role
Universities/Research Organizations	Conduct experiments, approve, and improve the V&V procedure
Industry	Conduct experiments and give feedback regarding the design needs and adequacy of the developed database to cover them
Standards Organizations:	Follow the evolution of the research and include it in the new standards and protocols

Impacts on Standardization and Application in Practice

- The outcome of this research will create the foundation of the appropriate V&V of CWE. The developed database will be included in standards that practitioners can use to apply CWE reliably and eventually establish it as a design tool.

Priority Research Need 5: Community Vulnerability through Physical Testing for Component Fragility (Residential Scale)

Description: Vulnerability analyses to extreme wind events are typically carried out for isolated assets (buildings or infrastructures) and provide a measure of losses (e.g., repair costs or downtime) due to wind hazards based on the asset exposure and the fragility of its components. Fragilities are developed in laboratory environments under testing protocols. Most historic testing of component fragilities has been conducted under seismic loading protocols.

Due to the duration of windstorms, components in wind have the potential for both failure and fatigue. Developing fragilities for key components under a wind loading protocol would benefit building scale/individual asset level vulnerability assessments.

Conducting a vulnerability assessment at a community scale would allow the mapping of areas of the community at greater risk and prioritizing interventions. CWE has the potential to support community-scale wind analyses, due to its capabilities to run large-scale simulations and potential to reproduce different storm types. The outcomes of CWE models would need to be integrated with the fragility curves obtained through physical testing to provide an in-depth vulnerability analysis of the entire building stock to current and future wind conditions.

A workflow that combines the component-level fragility curves with the results of large-scale CWE simulations is not yet defined and should be developed by a multidisciplinary team, including wind and structural engineers and computational fluid dynamics, risk, and climate specialists. One of the challenges that this group would have to face is the significant computational resources that are required for such large simulations. Finding ways to optimize computational resources in collaboration with software engineers and HPC specialists will be required to make this type of study accessible to the broader industry.

Estimated Cost: More than $3,000,000

Estimated Time: 5–10 years

Measurement Science Challenges and Potential Solutions

Challenges	Potential Solutions
Building a library of fragility curves under wind protocols for the large variety of building components requires significant resources.	Prioritize building elements based on their vulnerability to extreme wind events, focusing on communities with high likelihood of exposure.
Community-wide CWE simulations are computationally intensive.	Leverage the potential of faster computational resources (HPC, GPU) and approaches (ML, artificial intelligence) to reduce computational costs.
A successful integration of the fragility curves in the CWE workflow requires a multidisciplinary team.	Engage with structural engineers and with CWE, risk, and climate specialists and support multidisciplinary interest groups.
Modeling of different storm types in CWE is not yet established in the industry.	Fund research to develop better understanding of multiple climate mechanisms and implementation for CWE.

Stakeholders and Roles

Stakeholder	Role
Universities/Research Organizations	Perform laboratory testing and data collection to support the definition of fragility curves.

	Establish methods for combining component-level fragility curves with community-wise CWE simulations. Provide multidisciplinary expertise.
Industry	Provide multidisciplinary expertise. Develop relationship between cost and damage for different building types. Provide risk assessment expertise.
Standards Organizations	Integrate fragility curves in codes and standards.
Communities at Risk	Advocate for resilience-based wind design.

Impacts on Standardization and Application in Practice

- Increase accuracy in quantitative resilience-based wind design practice in the industry.
- Reduce the impact of extreme wind events in vulnerable communities.

Priority Research Need 6: V&V Virtual Wind Tunnel (with Potential Interactive Design Tools)

Description: The development of a virtual wind tunnel offers a comprehensive computational platform for conducting CWE simulations, bridging the gap between academic and design community applications. By providing such interactive design tools, users can configure structural profiles and flow parameters similar to those of a physical wind tunnel. This enables the evaluation of the aerodynamic performance of structures through CWE simulations. To enhance user experience, the implementation of software tools like Jupyter Notebooks can provide a user-friendly computing environment for performing CWE simulations within the virtual wind tunnel.

One important aspect is the model accuracy of the virtual wind tunnel, which needs V&V using experimental and computational data from different sources. The V&V process encompasses detailed modeling information, including mesh generation and post-processing, and guidelines supported by documented CWE case studies. This process enables the validation of the virtual wind tunnel model and enhances confidence in its predictive capabilities.

Estimated Cost: More than $3,000,000

Estimated Time: 5–10 years

Measurement Science Challenges and Potential Solutions

Challenges	Potential Solutions
Insufficiency of the validation database.	Efforts should be dedicated to gathering data through experiments and simulations. It is highly encouraged for researchers to publish and document the experimental and simulation set-ups for the continual enhancement of the aerodynamic database.
Design of the interface and workflows of virtual wind tunnel.	Start by understanding the fundamental features that users need to perform CFD simulations. Involve potential users in the design process to gather feedback and insights. Use effective visualization techniques to present simulation results.
Consensus on model parameters and accuracy.	Document the parameters and assumptions for CFD simulations in the virtual wind tunnel. Benchmark the CFD model by comparing results with the experimental data or through cross-validation. Provide the acceptance criteria for the error bar. Seek input from domain experts.
Educate users on use of the virtual wind tunnel to achieve accurate results.	The efforts would include comprehensive documentation and interactive tutorials. Users should have access to guidance on how to set up simulations and analyze results. User support channels such as forums can be provided to assist users with questions.

Stakeholders and Roles

Stakeholder	Role
Universities/Research Organizations	Develop and conduct the V&V for the virtual wind tunnel, which involves creating benchmark cases,

	performing simulations, analyzing the results, and documenting the case studies.
Industry	Participate and test the platform to collect the specific needs and requirements for industrial applications.
Standards Organizations	Review the process in establishing guidelines and standards for the virtual wind tunnel.

Impacts on Standardization and Application in Practice

- The virtual wind tunnel would streamline and standardize the process of conducting CWE simulations.
- The virtual wind tunnel would provide a computational platform accessible to both academia and industry, fostering collaboration and knowledge sharing.
- The integration of V&V practices into the virtual wind tunnel is essential to guarantee the accuracy and reliability of CWE simulations.

Priority Research Need 7: Integration of Mesoscale Simulations with Urban Scale Models

Description: The lower 1,600 ft (~500 m) of the atmospheric boundary layer drives the interaction between the atmospheric flows and the built environment and represents the interface between CWE and mesoscale models. NWP models are being run at increasingly higher resolutions, and one-way nested grid approaches have been used to predict wind flow in urban areas. However, these methods have not yet become industry standards due to the complexity of the coupling techniques, their computational costs, and the modeling expertise required.

Unlocking the integration between NWP and CWE models is a key research need for the built environment. It could leverage on the ability of mesoscale models to predict the effects of a changing climate at regional and building scales. It would provide an understanding of urban processes at high resolution and provide a better characterization of the wind flow with height. It could also allow CWE to simulate a wider variety of climate mechanisms and topography-driven flows, currently limited by the capabilities of both CWE and physical modeling.

Research efforts could consider, for example,

- Validation and use of mesoscale models for defining more realistic inflow conditions for CWE, both for conventional boundary-layer flows and other wind events;
- Definition of a computationally efficient workflow and guidelines to enable a larger uptake of these simulations in the industry;
- Identification of the most suitable parametrization techniques for different wind events and urban processes; and
- Use of immersed boundary or fitted mesh approaches, involving methods to handle turbulence generation near nested grid boundaries.

Estimated Cost: $1,000,000–$3,000,000

Estimated Time: 5–8 years

Measurement Science Challenges and Potential Solutions

Challenges	Potential Solutions
Difference between formulation of NWP models and standard CWE models (e.g., use of constant temperature, dry air) can complicate integration.	Collaboration among meteorologists, wind engineers, CWE specialists, and software developers to identify efficient and novel integration methods that draw on methods for data assimilation, machine learning, and uncertainty quantification.
Accuracy of methods to handle turbulence at interfaces between different grid resolutions.	Evaluation of accuracy through V&V and comparison with field observations.
Computational cost of high-resolution NWP models.	Leverage opportunities for acceleration by using next-generation computing platforms (including GPUs) and machine learning methods.

Stakeholders and Roles

Stakeholder	**Role**
Universities/Research Organizations	Establish methods for multi-scale integration through collaboration among meteorologists, wind engineers, and CFD researchers.
Industry	Participate in research efforts and provide guidance on the use of integration methods in engineering practice.
Standards Organizations	Review process for incorporating methods in guidelines and standards.

Impacts on Standardization and Application in Practice

- If adequately standardized and validated, the integration of mesoscale and building-scale simulations provides opportunities for more realistic wind loading predictions.
- The integration of larger meteorological systems like thunderstorms and tornadoes in CWE would support community-based vulnerability assessments and more resilient wind design.

Priority Research Need 8: Sensitivity Analysis and Uncertainty Quantification in CWE

Description: CWE involves solving a poly-parametric mathematical system of equations, with nonlinear interactions between the parameters and the quantities of interest. The complexity of the models highlights the need for CWE to include standardized sensitivity analysis and uncertainty quantification for results that will be used in practical applications, meeting certain criteria to provide confidence in the predicted peak design loads. A central consideration in all research efforts toward this goal should be a generalized procedure that simplifies the interaction among the parameters of grid resolution and quality, numerical schemes, inflow boundary conditions, the sub-grid turbulence model, and post-processing techniques. The final target is to answer the following question: Which parameters should be thoroughly investigated and calibrated, such that realistic error bars can be defined, while maintaining a reasonable balance between accuracy and computational cost/complexity of procedures? The answer to this question is vital for reaching a state where CWE can be used as an independent tool for design against wind loads and is closely related to the pre-standard/guidelines that will be developed in the future.

Estimated Cost: $1,000,000–$3,000,000

Estimated Time: 2–5 years

Measurement Science Challenges and Potential Solutions

Challenges	Potential Solutions
Generalized sensitivity analysis procedure	Quantify and qualify the interaction of each parameter with the design targets
Turbulence decay from inflow to incident flow	Revise the already established procedures and develop ones that are more promising
Mesh resolution	Parametric studies that relate various design targets and mesh formulation
Computational efficiency/complexity	Develop new techniques based on coarser computational domains, improve solution algorithms

Stakeholders and Roles

Stakeholder	Role
Universities/Research Organizations	Conduct research to estimate the sensitivity of each parameter and propose standardized procedures for defining error bars of CWE results.
Industry	Provide feedback regarding applicability of the standardized sensitivity analysis.
Standards Organizations	Unify the various outcomes into one document.

Impacts on Standardization and Application in Practice

- This research will be a fundamental part of the guideline's documentation and will improve the understanding of the complexity of modeling techniques, while at the same time providing procedures that inspire trust in computational results from practitioners via reliable error bars.

Priority Research Need 9: Leverage CWE to Improve Understanding of Wind Characteristics and Effects

Description: Incoming wind characteristics significantly influence the prediction of peak design loads. The mean wind profile primarily affects the mean pressure coefficients, while the three turbulence components defined by their intensities significantly affect the fluctuating pressures. The turbulence length scales (nine total) are also known to affect the flow patterns and resulting pressure distribution around buildings.

The sensitivity of the pressure predictions to the incoming wind field is an important challenge in validation and benchmark studies, and it also raises important questions regarding the actual peak design loads that a building might experience. Actual turbulent wind statistics might deviate from the idealized assumptions typically used and the near-surface characteristics of the turbulent wind field during extreme wind events, which cause most of the damage, are not fully understood. Hence, the wind pressures experienced by structures during extreme wind events have significant uncertainty because of the uncertainty in the turbulent wind characteristics.

This research aims to leverage CWE to improve our understanding of the interaction between the turbulent wind statistics and the resulting wind pressures on the building surface. New methods to systematically investigate and quantify this relationship should be proposed, with a focus on identifying the required level of accuracy in the wind statistics to achieve a specific level of accuracy in the predictions. This level of accuracy is expected to be different for different quantities of interest (e.g., mean base forces and moments vs. peak cladding loads on a panel).

Estimated Cost: $1,000,000–$3,000,000

Estimated Time: 2–8 years

Measurement Science Challenges and Potential Solutions

Challenges	Potential Solutions
Need to differentiate between isolated building and urban area analysis.	Consider a range of isolated buildings and urban area test cases.
Turbulence evolution from inflow to incident flow needs to be carefully accounted for.	Simulation efforts to carefully quantify the flow conditions, ideally using an empty domain simulation that uses an identical set-up as the subsequent simulation with the building(s).
Different analysis required for different extreme wind events.	Consider various extreme wind events and leverage nondimensionalization to support generalization of findings.
High sensitivity of wind pressures to wind conditions, geometrical configurations, and measurement or numerical methods can complicate generalization of conclusions.	Combine CWE, wind tunnel measurements, field observations, and/or large-scale weather models for carefully selected test cases to advance knowledge of the relationship between wind characteristics and effects.

Stakeholders and Roles

Stakeholder	Role
Universities/Research Organizations	Perform studies that leverage CWE simulations, wind tunnel experiments, full-scale observations, and mesoscale models to elucidate the relationship between

	wind characteristics and effects for various quantities of interest (e.g., cladding pressures or base forces and moments).
Industry	Participate in research efforts and provide guidance on practical significance of research questions and findings.
Standards Organizations	Formalize research findings into standards and guidelines for CWE simulations.

Impacts on Standardization and Application in Practice

- A better understanding of the relationship between wind characteristics and effects will support guiding research efforts toward improving the accuracy of wind pressure predictions.

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

Based on the Priority Research Summaries provided in Section 5.3, Table 5-2 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 5-2. Proposed Program Budget and Schedule for the First 10 Years (Amounts 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 guidelines/minimum requirements for the application of CWE, including QA/QC protocols	$600	$600	$600	$600	$600						**$3,000**
2	Development of consensus-based validation case studies using reliable wind tunnel data	$1,500	$1,500									**$3,000**
3	Full-scale observation and instrumentation with CWE integration	$300	$300	$300	$300	$300	$300	$300	$300	$300	$300	**$3,000**
4	Enhancing existing and developing new databases appropriate for V&V of CWE	$1,500	$1,500									**$3,000**
5	Community vulnerability through physical testing for component fragility (residential scale)				$600	$600	$600	$600	$600			**$3,000**
6	V&V virtual wind tunnel (with potential interactive design tools)	$600	$600	$600	$600	$600						**$3,000**
7	Integration of mesoscale simulations with urban scale models				$600	$600	$600	$600	$600			**$3,000**
8	Sensitivity analysis and uncertainty quantification in CWE	$1,500	$1,500									**$3,000**
9	Leverage CWE to improve understanding between wind characteristics and effects	$375	$375	$375	$375	$375	$375	$375	$375			**$3,000**
Total Research Estimated Costs:		$6,375	$6,375	$1,875	$3,075	$3,075	$1,875	$1,875	$1,875	$300	$300	**$27,000**

5.5. Interrelationship of Research Activities

Tables 5-1 and 5-2 list the top nine research needs identified during the workshop. Each of these research needs seeks to improve the built environment through development of standards and techniques that will allow the practicing structural engineer to use CWE tools to determine the wind loading and effects caused by wind events, both typical and extreme, that are required for the structural design of their projects. 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.

Short-/moderate-term needs: Priority Research Need 1 (Development of guidelines/minimum requirements for the application of CWE, including QA/QC protocols) can, and must, proceed immediately with input during completion from Priority Research Need 2 (Development of consensus-based validation case studies using reliable wind tunnel date), which should start concurrently with or slightly prior to Priority Research Need 1. Completion of either of these research activities will need to be connected to the findings of Priority Research Needs 4 (Enhancing existing and developing new databases appropriate for V&V for CWE), 6 (V&V virtual wind tunnel) and followed by Priority Research Need 8 (Sensitivity analysis and uncertainty quantification in CWE), to complete the final guidelines and standards noted in Priority Research Need 1. Each of these research needs will provide valuable input into the development of a guideline that can be used as the basis for developing CWE for practice.

Moderate-/long-term needs: Priority Research Needs 3 (Full-scale observation and instrumentation with CWE integration) and 9 (Leverage CWE to improve understanding between wind characteristics and effects) pertain to understanding wind effects on the built environment to use as a validation of the CWE models. These research needs can be launched independently, but do work together, and need to start immediately as both will take a substantial amount of time to complete.

Priority Research Needs 5 (Community vulnerability through physical testing for component fragility) and 7 (Integration of mesoscale simulations with urban scale models) relate to the expansion of CWE beyond the individual building/structure to understand the wind effects on a community with the overall goal of using CWE as the basis of more resilient communities. These two needs should be initiated soon, but the results of the previously listed research activities will need to be understood before they can be finalized.

5.6. Benefits of Implementing Research Activities for Computational Wind Engineering

The benefits of the recommended research program include the following:

- A CWE guidelines document would facilitate wider use of virtual wind tunnel testing by defining a standard of care and thus making virtual wind tunnel testing more broadly accepted than before.
- QA/QC protocols for CWE would limit the need to validate the outcomes of numerical models with physical testing, broadening the range of applicability of CWE in the built environment.

- Consensus-based validation case studies are the most reliable method to create a design tool with CWE for structural applications and clearly define the level of performance of numerical results. Outcomes from this research would be a big part of the guidelines and QA/QC protocols.
- The outcome of this research would create the foundation for appropriate V&V of CWE. The developed database would be included in standards that practitioners can use to apply CWE reliably and eventually establish it as a design tool.
- Accuracy in quantitative resilience-based wind design practice in the industry would increase.
- The impact of extreme wind events in vulnerable communities would be reduced.
- The virtual wind tunnel would streamline and standardize the process of conducting CWE simulations.
- The virtual wind tunnel would provide a computational platform accessible to both academia and industry, which fosters collaboration and knowledge sharing.
- If adequately standardized and validated, the integration of mesoscale and building-scale simulations would provide opportunities for more realistic wind loading predictions.
- The integration of larger meteorological systems like thunderstorms and tornadoes in CWE would support community-based vulnerability assessments and more resilient wind design.
- A better understanding of the relationship between wind characteristics and effects would support guiding research efforts toward improving the accuracy of wind pressure predictions.

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

- Reduction in the 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.

Upon the development of the guideline document, the use of CWE would allow more designers and projects that typically do not have the design budget or design time to utilize a physical wind tunnel study. Also, CWE would offer the benefit of providing community-level wind effects studies that can identify the areas of highest potential for damage and loss. This will allow for the development of more resilient communities and help prevent loss of life and economic loss in extreme wind events.

6. Acronyms and Abbreviations

ABL	atmospheric boundary layer
AIJ	Architectural Institute of Japan
APC	atmospheric pressure change
ASCE	American Society of Civil Engineers
CFD	computational fluid dynamics
COST	European Cooperation in Science and Technology
CPU	central processing unit
CWE	computational wind engineering
GPU	graphical processing unit
HPC	high-performance computing
ISO	International Organization for Standardization
LES	large eddy simulation
ML	machine learning
NHERI	Natural Hazards Engineering Research Infrastructure
NIST	National Institute of Standards and Technology
NWIRP	National Windstorm Impact Reduction Program
NWP	numerical weather prediction
QA/QC	quality assurance/quality control
RANS	Reynolds-averaged Navier-Stokes
SEI	Structural Engineering Institute
TPU	Tokyo Polytechnic University
V&V	verification and validation
WSC	Workshop Steering Committee

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Appendix A. In-Depth Discussion of Priority Research Needs

A.1. Priority Research Need 1. Development of Guidelines/Minimum Requirements for the Application of CWE, Including QA/QC Protocols

Computational methods for simulating and evaluating wind action around objects have existed in some industries such as automotive and aerospace for quite some time and are firmly established as an accepted approach in considerations of nonturbulent environments. The relatively recent emergence of such computational simulations within the civil engineering/architectural industries, combined with the accessibility of these tools to the general user through opensource platforms, has simultaneously made such tools widely accessible and exposed many challenges in undertaking such simulations.

Some of these challenges are lack of adequate technical knowledge/background in computational methods and wind engineering in the general user, difficulty in properly capturing the unique flow characteristics of turbulent boundary-layer flow around bluff bodies, and limited computational capacity to perform such simulations in a reasonable timeframe. As a result, the application of CWE for the built environment has suffered by developing a reputation for mixed, inconsistent, or inaccurate results for some applications, and the perception that CWE tools allow a “wild west” sort of approach, without formal standards or guidelines for how to perform such simulations or any documented methodology to demonstrate that such simulations were performed in a technically sound manner.

Despite the challenges in the emergence of CWE applications in civil engineering/architecture, the high potential for CWE to reach beyond some of the limitations of physical wind tunnel testing is generally acknowledged.

Over the past few decades, as wind tunnel testing was emerging as a more common means to evaluate wind effects on building structures, members of the wind engineering industry began formalizing and documenting a minimum set of requirements for performing wind tunnel testing. These minimum requirements first appeared as a manual of practice and recently were updated and made into an ASCE/SEI standard (ASCE 49, 2021). The standard uses a performance-based approach in defining the necessary and measurable requirements. While this document requires a certain level of rigor in the performance of wind tunnel testing, in effect it facilitates the wider use of wind tunnel testing by defining a standard of care and making wind tunnel testing more broadly accepted than before.

The overriding consensus among interested individuals in the wind engineering and structural engineering professions is that CWE needs similar guidelines to bring a certain level of rigor to the application of CWE. Such a document could help propel CWE to wider acceptance, wider application, and more successful use in the wind and structural engineering professions. This concept of developing guidelines for CWE was perhaps the strongest common thread throughout the CWE workshop and discussed by all the breakout groups in some form. The guidelines are considered to be an absolute necessity in moving CWE forward in the civil/architectural professions.

The guidelines document should follow a similar performance-based approach as the ASCE 49 (2021) example for physical model wind tunnel testing. A too prescriptive approach would limit innovation and continual development of CWE, which is a rapidly evolving field. The guidelines should identify minimum performance criteria for CWE simulations and provide guidance on reporting to demonstrate alignment with accepted practice and facilitate third-party reviews. The guidelines could address demonstration of the following key components, among others: modeling of the atmospheric flow characteristics, velocity spectra, length scales, stationarity of the boundary layer, length of simulation time, flow structures in the wake, extreme value approach taken to derive loads, and time histories at a series of pre-defined monitoring points.

A differentiator of CWE with respect to physical testing is the low-cost barrier of entry for practitioners, due to technological advancements and availability of opensource tools. Many of these practitioners may lack access to reliable wind tunnel testing data and wind engineering expertise to develop and benchmark their CWE capabilities in the built environment. The variability of skills and therefore the variability of CWE outcomes contributes to the perception of CWE as an unregulated and potentially unreliable approach for wind modeling. A benchmarking document for CWE should be created alongside the guidelines to guide CWE practitioners in properly simulating atmospheric and urban flows and replicating wind action and structural response. The benchmarking document should be connected to an opensource database of quality-controlled wind tunnel testing data for the built environment. The database should provide structured data and key parameters for validation of CWE tools and approaches.

The following is a brief discussion of the steps involved in establishing the guidelines, benchmarking document, and opensource database. These steps are included in the intended research effort for establishing this set of documents.

1. **Establish performance criteria for the guidelines/minimum requirements document:** Develop a minimum set of outcomes-based performance criteria to evaluate CWE results in the built environment. Separate criteria may be defined for different applications (atmospheric flows, environmental concerns, pollutant dispersion, static loading, and dynamic loading).
2. **Establish a set of benchmark cases:** Establish benchmark cases for which physical testing data are available to verify feasibility of the performance criteria and margin of error. Summarize all relevant input, testing, and post-processing parameters. Make these parameters available to incorporate into CWE studies. Store the wind tunnel data in a structured database that could become open source.
3. **Perform initial CWE testing:** Perform “blind” CWE tests based on selected benchmark cases. While the initial tests would be blind to the full set of results from the selected consensus wind tunnel tests, ultimately this process will become iterative to adjust the parameters of the computational simulations if initial results are inconsistent with the selected consensus wind tunnel results.
4. **Perform follow-up CWE testing:** Once acceptable correlation exists between the results from the selected consensus wind tunnel results and the CWE simulations (likely after iterative adjustments to the simulation parameters and assumptions), perform further blind CWE testing on additional selected consensus wind test cases. This is to verify the ability of the CWE simulations to consistently match the results (to within an acceptable degree) from the wind tunnel test cases, without the need for adjusting or iterating the simulation parameters to settle on the known outcomes.

5. **Document the CWE process:** After determining key modeling parameters from the successful CWE simulations, document these key parameters and the ability of CWE to match the wind tunnel results. This document will serve as a reference for the guidelines and provide information for the benchmarking document and opensource database.
6. **Draft CWE guidelines document:** A small group, but one that represents all interested and knowledgeable parties, should be formed to write the guidelines. This document should include the definition of QA/QC protocols to substantiate the simulation and facilitate the interpretation of the parameters and results by practitioners and reviewers. A small peer review panel for periodic review of the draft document may be desired. The goal for such a guidelines document may be an ASCE manual of practice, similar to the early version of the wind tunnel testing guidelines (ASCE Manuals and Reports on Engineering Practice 67, *Wind Tunnel Studies of Buildings and Structures*, 1999).

This will be a multi-year effort that requires the participation of experts in computational science, wind engineering, and structural/civil engineering and requires the use of wind tunnel testing facilities and computational resources. Some of the listed activities naturally occur sequentially and some could run in parallel.

A.2. Priority Research Need 2. Development of Consensus-Based Validation Case Studies Using Reliable Wind Tunnel Data

A high-priority research need identified during the workshop concerns the development of consensus-based validation case studies using reliable wind tunnel data. The case studies that need to be included should be organized based on various design needs, and the V&V process should be explicitly defined for the practical use of CWE. Experimental results from these case studies will be extracted from various wind tunnel facilities to create an acceptable V&V process, as discussed in Section 4.3, and to define the target accuracy to expect from computational results. It is highly desirable that wind tunnel data contain error bars and catalog uncertainties.

Low-, mid-, and high-rise buildings should be the main categories of the case studies, by also considering similar pressure taps distribution. In this way, comparable results can be generated from various wind tunnels that do not include the variability of spatial inaccuracies. Both local and overall dynamic loads on walls and roofs must be targeted to cover all the possible design needs that rise in industrial applications. Building configurations (aspect ratio of the three-dimensional testing models) should vary to represent real, contemporary buildings and so the V&V process reflects current industrial needs. As a next step, case studies for irregular shapes, like L- or T-shaped or with curved surfaces, should also be included. The aforementioned categories could be further classified based on the exposure conditions in the wind tunnels. Open, suburban, and specific urban exposures (non-isolated buildings) should be established that follow the definition of code provisions.

A consensus-based validation also means that error and accuracy quantification should be accomplished in a specified way, so the engineers that apply CWE techniques can prove the adequacy of the numerical set-up, based on a given format of calculations. This procedure should first regard the turbulence field that immediately interacts with the target building, in an empty computational domain, to not affect the flow field from the building presence. Validation metrics need to be identified that consider mean speed, turbulence intensity, and integral length scale profiles in the incident flow to match the physical exposure of the model in the wind tunnel with the computational domain. The spectral content also needs to represent the wind tunnel data, at least for the range of frequencies relevant to the experimental procedure. The next step should be to establish the validation metrics of the pressure coefficients on the entire building envelope, which should consider mean, root mean square, peak values, and spectral content for local and overall loads. As presented in AIJ (2015), the validation metrics are compared with two different experimental results (for an isolated and a non-isolated building) and the target level of accuracy for mean and peak pressure coefficients is 20%.

To base the case studies on reliable experimental data, the experiments should be conducted under the provisions of ASCE 49 (2021), and the documentation should include the necessary information for V&V of CWE, as discussed in Section 4.3 and Appendix A.4. If the aforementioned goals are achieved, the evolution of CWE in practical applications can be based on V&V of a series of cases of interest on empty domains (to check the turbulence statistics), isolated buildings (to V&V the conditions of simpler experiments), and non-isolated buildings (to V&V the capacity of the modeling to capture real-life exposures). As a next step, the same wind flow conditions expressed computationally in the numerical set-up should be used for modeling pressures on building configurations where experimental data do not exist. For example, if the local design pressures for high-rise buildings are targeted, several case studies that refer to this issue should be validated and verified prior to using the numerical set-up as an independent tool. In the list of case studies that need to be validated and verified, it is important not to restrict the validation metrics to specific locations of interest for design (e.g., only on the windward wall) but to ensure that the modeling process captures the essence of the physical pressure field due to wind in the entire building envelope. Integrated pressures over the building surface leading to mode-generalized loads should also be validated and compared with the high-frequency base balance results.

A.3. Priority Research Need 3. Full-Scale Observation and Instrumentation with CWE Integration

Buildings are designed and constructed based on best estimates of the loading that is imparted to the structure, and the response of the structure to these environmental loads is estimated through the use of computer simulations/analysis software. Rarely are the input assumptions or the in situ behavior of buildings verified via full-scale monitoring.

The civil engineering/architecture industry sorely lacks in situ measurements of wind effects on tall buildings. In the past, due primarily to scale and network infrastructure, the hardware needed to suitably instrument a tall building was substantial and therefore challenging, both logistically and financially. Other “logistical” challenges included getting agreement and access from the owner to instrument the structure. Isolated instances of tall building monitoring programs have occurred in the past (Kijewski-Correa et al., 2006), along with a few ad hoc measurements taken and documented during major storm events. These programs, however, are quite rare, and while they are invaluable, there simply are not enough data available for definitive conclusions about the wind loading and overall structural response characteristics for these building types.

Compared with tall buildings, more full-scale experiments and monitoring campaigns have been implemented for low-rise buildings (Richardson and Surry, 1991; Richardson et al., 1997; Levitan and Mehta, 1992a,b; Liu et al., 2009; Subramanian et al., 2005; Subramanian et al., 2009), presumably in part because of fewer practical challenges in instrumenting the buildings. Studies comparing model- and full-scale measurements have consistently found peak pressures to be underestimated at model scale (Richardson and Surry, 1991; Richardson et al., 1997; Okada and Ha, 1992; Cochran and Cermak, 1992; Ho et al., 2003; Liu et al., 2009), and the discrepancies have been attributed to suppression of the smaller turbulent scales at lower Reynolds numbers and to differences in the approach turbulent wind fields (Richardson et al., 1997; Hagos et al., 2014; Okada and Ha, 1992; Tieleman, 2003; Morrison et al., 2011). Definitive conclusions on when scaling is problematic, or on the required accuracy of reproducing the higher-order moments of the turbulent velocity in the incoming wind field, will require more data from dedicated measurement campaigns.

The observation that the approach turbulent wind characteristics have an important effect on the wind loads also highlights the need to address the lack of full-scale data on near-surface wind characteristics, in particular during extreme wind events such as hurricanes, downbursts, and tornadoes. Measurements made for meteorological purposes tend to focus on larger scales and higher heights, while damage to buildings is driven by the local turbulent wind characteristics near the ground. Improving understanding of the near-surface wind conditions in extreme wind events is crucial to improving wind-resistant design.

Recently, instrumentation has become more compact and wireless networks allow much simpler networking infrastructure, presumably simplifying to a large degree the installation, access, and maintenance of these monitoring networks. While gaining access to and agreement from building owners to install and maintain monitoring systems may often still be difficult, technology has progressed in the last couple of decades and the industry should be in a better position now to monitor both low-rise and tall buildings.

As CWE emerges as a more viable tool in civil engineering/architecture, leveraging a combination of field observations and numerical simulations to improve wind-resistant design of buildings can yield significant benefits. CWE has the potential to model wind effects that are outside of the capabilities of most physical wind tunnels. Limiting the validation and verification of CWE to processes that can be modeled in physical wind tunnels would hinder the ultimate potential of CWE as a tool: CWE results would be calibrated with wind tunnel results that themselves have been constrained by the lack of the full-scale, in situ measurements needed to validate and recalibrate the modeling parameters.

Building monitoring programs would ideally consist of the following components:

- Vertically distributed accelerometers,
- Vertically and horizontally distributed pressure measurement sensors at the exterior of the building,
- GPS station at roof level,
- Sonic or mechanical anemometers at/above roof level, and
- Met-towers instrumented with anemometers and LIDAR to measure mean wind and turbulent statistics profiles of the near-surface incoming and surrounding wind field.

Measurement campaigns should either focus on the acquisition of longer-term data to quantify the natural variability in the wind and resulting wind pressures, or on obtaining measurements during extreme wind events. The campaigns should emphasize integration with CWE to maximize their possible impact. Examples of possible integration include, but are not limited to,

- Use of preliminary simulations for the design of the field campaign, informing optimal locations of pressure and velocity sensors;
- Use of field observations for validation of CWE simulations, including the use of uncertainty quantification and data assimilation; and
- Use of CWE simulations to fill in the inevitably sparse data from field observations and support a more complete analysis of the observational and simulation results.

A.4. Priority Research Need 4. Enhancing Existing and Developing New Databases Appropriate for V&V of CWE

Existing wind tunnel aerodynamic databases with wind loads on buildings have played a big part in V&V of CWE in the last decade. The ongoing evolution of the state of the art of CWE for wind loads depends on providing scientific groups and practitioners with appropriate sets of experimental results for various building heights (low rise, mid rise, and high rise) and architectural features (aspect ratio of the building envelope). The adequacy of information regarding the experimental set-up is closely related to the numerical accuracy that will be achieved.

During the CWE workshop a lot of discussion centered around a standardized V&V process that can be used to extract accurate design values from computational software (Appendix A.2). An indispensable part of this process is having reliable wind tunnel data that computational wind engineers can rely on to enable V&V. The structure of the data necessary for this process exceeds the current state of the information found in databases. Computational wind engineers need to take control of this information to achieve the needs of CWE. In this sense, this research refers to enhancing existing databases and developing new ones that will include the proper range of information.

The target information necessary starts with the format of the wind tunnel. Identifying roughness element dimensions and their specific establishment in the wind tunnel is a very important step to ensure with CWE the developing profile of the velocity. Drawings should be included that consider this information in detail. The next need is the velocity time series of the entire incident profile. In computational simulations, generating similar incident flow conditions is crucial for meaningful comparisons of the pressures. Thus, information that exceeds the mean speed profile and the turbulence intensity usually found in databases is needed.

Pressure series are necessary in pressure taps situated on the entire building envelope to ensure that the V&V can be used for all design needs. Including the uncertainty and reliability of the aforementioned data, by establishing the experimental error, is important. This can easily be done by repeating some experiments, so the final design conditions for comparisons of CWE and experiments can be considered in terms of error bars. Similarly, as stated in Appendix A.8, the final error bars for the pressure can include post-processing criteria (influence of extreme value analysis). In addition, including experimental results at different geometric scales will help immensely in generating error bars, which can be used for better comparison with CWE.

These data should be generated from more than one wind tunnel facility and comply with the provisions of ASCE 49 (2021). To establish trust and thus allow meaningful computational comparisons, the experimental conditions must reflect comparable data among various wind tunnels. For this purpose, a set of building configurations and exposure conditions should be identified and experimental results should be obtained from various facilities that provide all the necessary results in detail. In this way a new database can be developed for the purpose of V&V of CWE, based on the collaboration of wind engineers at an international scale. Results for non-synoptic wind flow should be included to expand the V&V of CWE and be in touch with targets of CWE.

Enhancing existing databases with the necessary information for V&V of CWE is a very enticing goal that will save time and effort. This means that a communication channel should be established with the experimentalists of those facilities to request the rest of the data. More experiments might be required if the results are unavailable, so the participation of these experimentalists in covering this research need will be important. Furthermore, gathering participants from different wind tunnel facilities for this endeavor is very important for the development of a new database for V&V of CWE.

A.5. Priority Research Need 5. Community Vulnerability through Physical Testing for Component Fragility (Residential Scale)

Windstorms, and hurricanes in particular, are one of the most disruptive natural hazards in the United States, causing more deaths and financial loss than any other extreme weather events. According to the National Oceanic and Atmospheric Administration (https://coast.noaa.gov/states/fast-facts/hurricane-costs.html#:~:text=Of%20the%20310%20billion%2Ddollar,6%2C697%20between%201980%20and%202021), hurricanes caused more than $1.1 trillion in financial loss between 1980 and 2021, with Hurricane Harvey accounting for about $125 billion and Hurricane Katrina for about $161 billion. Hurricanes were also responsible for the highest death toll from natural disasters over the same period (1980–2021), with 6,697 deaths. These figures would be even higher when including tornadoes, thunderstorms, and other natural hazards that are exacerbated by wind such as wildfires.

The extent of financial and human losses reveals the vulnerability of entire communities to extreme wind events and the need to look at both the building and community scales to identify climate risks and define adaptation plans. Vulnerability studies typically focus on single assets (buildings or infrastructures), where vulnerability is expressed as a measure of losses (e.g., repair costs or downtime) based on hazard intensity (e.g., wind speed). The losses are obtained from the asset exposure and its response to the degree of damage/failure of its individual components, expressed through fragility curves.

Fragilities are developed in laboratory environments under testing protocols that are defined for specific hazards. One of the limitations of the current methodology for a vulnerability assessment of a single asset is that most of the available fragility curves were developed under seismic loading protocols. The behavior of building components during windstorms, however, is different than in a seismic event. The long duration of a storm can cause direct failures and failure through fatigue of building components. Developing a broader database of fragility curves for key components under a wind loading protocol would benefit the building scale/individual asset vulnerability assessments and improve resilient design.

Extending the vulnerability analysis to the entire community would provide a more granular exposure assessment for the individual assets that are part of the building stock. This would account for the effect of the surrounding context and local topography and would allow a refinement of the wind pressure on the building by storm types, building massing, orientation, and surroundings. Ultimately, this would allow a CWE simulation to integrate explicitly an individual building's fragilities into an assessment for community-based vulnerability and risk.

CWE is a promising tool to support community-scale wind analyses due to its capabilities to run large-scale simulations and the potential to reproduce different storm types. The outcomes of CWE models could be integrated with the fragility curves obtained through physical testing to provide an in-depth vulnerability analysis of an entire community to current and future wind conditions.

The development of the workflow for community-level vulnerability assessments remains at preliminary stages and a few challenges need to be addressed to be successful, some of which are discussed in the following.

As noted previously, component-level fragilities need to be determined through large-scale physical testing in laboratories capable of developing and replicating the components themselves coupled with appropriate wind loading protocols. These component-level fragilities should be developed for key components at risk of suffering fatigue in a single or over multiple wind events.

Large-scale CWE simulations sometimes require prohibitive computational resources. Further computational resource development is imperative to enable faster, cheaper, and more reliable simulations. This technological development requires the support of software developers and potentially HPC specialists and may include access to more efficient resources (GPU clusters, HPC), better parallelizing schemes, or more efficient meshing and modeling algorithms.

The biggest potential for using CWE to support resilience-based design lies in the combination of large-scale and multi-storm simulations. The ability to use numerical models to represent multiple storm types is a research need in itself and requires further investigation. Mesoscale numerical weather prediction is used to predict different storm systems and the impact of changing climate conditions on the wind environment. Downscaling NWP models into smaller-scale numerical models can provide wind flow characteristics at high resolution and an estimate of exposure to the winds at building scale. Modeling different storms at high resolution will increase the computational costs, and finding ways to optimize computational resources will be required to make this type of study accessible to the broader industry.

Finally, conducting a community-based vulnerability assessment will require the integration of various data sets and data types through various computational methods. A multidisciplinary group of specialists that includes wind and structural engineers and computational fluid dynamics, risk and climate specialists will need to work together to develop an effective workflow.

A.6. Priority Research Need 6. V&V Virtual Wind Tunnel (with Potential Interactive Design Tools)

The development of a virtual wind tunnel for CWE simulations encompasses various stages, including setting up boundary conditions, selecting turbulence models, running solvers, and post-processing the results. The objective is to create an end-to-end simulation tool capable of accurately simulating and analyzing aerodynamic flows around structures. Central to the development of the virtual wind tunnel is the design of a generalized platform for CWE modeling. This platform should incorporate model fidelity information to determine appropriate mesh sizes and turbulence models. Generating and validating the mesh to ensure the reliability of the CWE model is also important. Additionally, the flow field should be validated using available data sets, and the output should include error bars to indicate the confidence level of the predicted aerodynamic quantities. Also essential is ensuring that the simulation platform is not only accurate but also computationally efficient by employing adaptive meshing techniques or leveraging HPC resources like CPU and GPU computing, making it practical and affordable for widespread use.

Regarding the predictive capabilities of the virtual wind tunnel, CWE simulations tend to provide more accurate predictions for integrated loads such as drag forces, while discrepancies may arise in local peak pressure predictions. Wind field predictions for clusters of buildings generally exhibit greater accuracy compared with isolated building models due to the presence of interference effects.

In the V&V processes, detailed modeling configurations are essential for replicating simulation results. Benchmark test cases from existing databases serve as valuable references for CWE validation. Collaborations among the developers of the virtual wind tunnel and participation from both academic and industrial fields are important and beneficial for the advancement of CWE modeling and its application in practical engineering scenarios.

A.7. Priority Research Need 7. Integration of Mesoscale Simulations with Urban Scale Models

The lower 1,600 ft (~500 m) of the atmospheric boundary layer drives the interaction between the atmospheric wind flows and the built environment. The wind patterns in this region affect the usability of outdoor spaces, the dispersion of pollutants, the movement of snow drifts, and the wind loading on buildings and infrastructure. Large-scale global weather systems are traditionally analyzed using meteorological models, which focus on the upper atmosphere and are not resolved at ground level and through the lower portions of the atmospheric boundary layer. CWE, in contrast, focuses specifically on this lower portion of the boundary layer and resolves the near-surface wind characteristics. CWE, however, neglects the interaction of ground-level flows with atmospheric systems, which drive wind directionality and extreme wind events such as hurricanes, downbursts, and tornadoes. An opportunity exists to leverage larger-scale meteorological simulations to improve understanding of the urban and near-surface wind conditions in both synoptic and non-synoptic weather systems and to define more realistic wind boundary conditions in CWE simulations.

NWP models are being run at increasingly higher resolutions. For environmental engineering applications, one-way nested grid approaches have been used to model wind flow and pollutant dispersion in urban areas under nominal synoptic wind conditions (Nagel et al., 2022; Lundquist et al., 2012; Wiersema et al., 2022). In these simulations, the buildings are generally represented using immersed boundary methods, and the turbulence transition between nested grids is handled using eddy injection or recirculation techniques. These methods have yet to become industry standard due to the complexity of the downscaling and nesting techniques, their computational costs, and the expertise required to perform such modeling.

Unlocking the integration between mesoscale and CWE models is a key research need for the built environment for the following key reasons:

- It could leverage the ability of mesoscale models to predict the effects of a changing climate at regional and building scales. Climatic change has the potential to affect many areas, such as the aviation and renewables industries (through wind directionality shifting or reduced energy yield), or the design of the build environment through increasing wind effects on structures.
- It could allow CWE to simulate a wider variety of climate mechanisms and gain insights into the impact of different storm types (derechos, tornadoes, thunderstorms, etc.) on the built environment.
- It could provide an understanding of urban processes such as urban heat islands at a much higher resolution.
- It could improve the modeling of topography-driven flows, which are currently limited by the capabilities in both CWE and physical modeling. The outcomes could support, among others, the development of more accurate wind codes in mountainous areas with sparse weather stations and limited high-quality data.
- It could also provide a better characterization of the wind flow at height, which is crucial for the design of super tall buildings that are not only affected by the conventional boundary layer but also by veering effects due to the Ekman layer.

This research aims to advance the integration of mesoscale simulations with urban- and building-scale models. Integration is broadly defined as any form of information exchange regarding the incoming turbulent wind characteristics between a mesoscale and an urban- or building-scale simulation. For example, research efforts could consider

- Validation and use of mesoscale models to provide input for defining more realistic boundary conditions in traditional LES models, both for conventional boundary-layer flows and other wind events;
- Definition of a computationally efficient workflow to enable a larger uptake of these simulations in the industry;
- Identification of the most suitable parametrization techniques for different wind events and urban processes;
- Development of guidelines related to the use of different mesoscale models for CWE; and
- Use of immersed boundary or fitted mesh approaches, involving methods to handle turbulence generation near nested grid boundaries.

This research will greatly benefit from collaboration among meteorologists, wind engineers, CWE specialists, and software developers. Furthermore, novel integration methods will draw on methods for data assimilation, machine learning, and uncertainty quantification.

A.8. Priority Research Need 8. Sensitivity Analysis and Uncertainty Quantification in CFD

To improve the current state of the art and achieve the imminent targets of CWE, experimental and computational results for pressure measurements should be considered estimates with confidence intervals instead of exact numbers. Numerical simulations require many modeling choices, including the design of the computational mesh, the selection of discretization and solution methods, the turbulence model, and the definition of boundary conditions. These modeling choices and corresponding parameters interact nonlinearly in the Navier-Stokes equations, and their effect on the predicted pressures should be quantified to define error bars that inspire confidence in the design decisions derived from simulation results. The research necessary to support the required sensitivity analysis and uncertainty quantification is important to generate guidelines for proper CWE usage. The final target is to answer the following question: Which parameters should be thoroughly investigated and calibrated, such that realistic error bars can be defined while maintaining a reasonable balance between accuracy and computational cost/complexity of procedures? The answer to this question is vital for reaching a state where CWE can be used as an independent tool for design against wind loads.

While defining errors bars for simulation results, computational wind engineers should keep in mind the theoretical background of LES modeling. In LES, the grid resolution not only affects the numerical accuracy of the discretized solution to the equations, but it also defines the cut-off frequency between the modeled and resolved scales. As such, the solution accuracy is determined by a complex interaction between the grid resolution and grid quality, the numerical schemes, and the sub-grid turbulence model. Furthermore, the unsteady nature of the simulations requires the specification of a time-dependent boundary condition for the incoming turbulent wind field, which will act in concert with the discretized Navier-Stokes equations to provide a numerical solution. The nonlinear interaction between the modeling choices introduces a significant challenge because conclusions regarding the accuracy or sensitivity of results obtained with a specific computational model do not necessarily generalize to simulations that employ different baseline model choices. For example, conclusions regarding adequate grid resolutions or the impact of the sub-grid model or the inflow boundary conditions can differ between two codes that employ different spatial or temporal discretization schemes. This challenge should be a central consideration in all research efforts toward sensitivity analysis and uncertainty quantification of CWE simulations, particularly when considering analysis of the effect of the computational mesh and the boundary conditions.

The design of the computational mesh, including the topology of the cells, the definition of local refinement regions, and the resolution within each region, significantly influences the accuracy of LES results and is closely related to the computational cost. Mesh sensitivity studies for LES must become standardized and clearly distinguished from mesh independence studies that are typically used for RANS simulations. Because the mesh resolution also determines the cut-off frequency between modeled and resolved scales, LES results are always mesh dependent.

Hence, generalizable methods to establish the appropriate mesh resolution for the required level of accuracy in predicting specific quantities of interest are needed. The generalizability of the methods should be emphasized throughout each research effort; studies that simply aim to identify the adequate grid resolution for predictions with one specific code will have limited impact because the conclusions will depend on the interaction between the chosen grid resolution with the numerical schemes and sub-grid model. Investigations of the impact of numerical and solution schemes and sub-grid models should aim to explore similarly generalizable approaches. This research need is closely related to the development of a pre-standard/guidelines.

The definition of the inflow boundary conditions is another dominant uncertainty in CWE simulations. Generally, Dirichlet inlet conditions are used at the inlet boundary based on velocity time series calculated either from precursor domains, synthetic methods, or physical time series (Potsis and Stathopoulos, 2022). The main scope is to generate the target profiles in the incident flow to match the profiles measured in the wind tunnel measurements for which LES results will be validated and verified. The target profiles should prescribe at a minimum the mean wind speed, the turbulence intensities, and the length scales; the effect of higher-order velocity statistics remains to be investigated. A first challenge in this process is that the imposed inflow conditions tend to evolve between the domain inlet and the location of interest further downstream in a way that is dependent on the mesh, the numerical schemes, and the sub-grid model. To support generalizing findings about the sensitivity of wind pressure predictions to the inflow conditions, the relationship between the inflow conditions and the wind flow at the location of interest should be known. Second, significant uncertainties can exist in the target flows, for example, due to uncertainty or even a lack of data in the wind tunnel measurements.

Novel methods for sensitivity analysis and uncertainty quantification to efficiently represent these uncertainties in the simulations and support meaningful validation are needed. In addition to the inflow boundary conditions, effects of the computational domain size and other boundary conditions, including the outlet, side, and top planes, should be investigated. These other boundary conditions are significant when modeling non-synoptic winds.

Finally, this effort should consider uncertainties introduced during the post-processing of the pressure time series to determine the peak pressures. The assumptions used in this process should be thoroughly examined and accounted for in the reported error bars. Importantly, this uncertainty is not unique to processing computational results, and the knowledge gained from high-quality experimental studies provide an excellent reference to support quantifying the effect of parameters used for extreme value analysis (total duration, number of windows, percentage of non-exceedance, etc.).

In summary, CWE involves solving a poly-parametric mathematical system of equations with nonlinear interactions between the parameters and the quantities of interest. The complexity of the models highlights the need for CWE to include standardized sensitivity analysis and uncertainty quantification for results that will be used in practical applications, meeting certain criteria to provide confidence in the predicted peak design loads. Similar sensitivity reports for the quantification of CWE pressure results with LES modeling will be included soon in similar provisions of AIJ (2015).

A.9. Priority Research Need 9. Leverage CWE to Improve Understanding of Wind Characteristics and Effects

Incoming wind characteristics significantly influence the prediction of peak design loads. The mean wind profile primarily affects the mean pressure coefficients, while the three turbulence intensities significantly affect the fluctuating pressures. The turbulence length scales (nine total) are also known to affect the flow patterns and resulting pressure distribution around buildings.

The sensitivity of the pressure predictions to the incoming wind field is an important challenge in validation and benchmark studies. Differences in the incoming wind field are one of the main reasons for discrepancies among different wind tunnel experiments and for discrepancies between reduced and full-scale measurements (Morrison et al., 2001). Similarly, uncertainty in the wind profiles measured in the wind tunnel has been shown to explain discrepancies between CWE predictions and wind tunnel measurements (Lamberti and Gorlé, 2020). Most of these studies focused on predicting pressures around an isolated structure. The influence of the incoming wind field will likely be reduced if upstream and surrounding buildings are included in the analysis. However, the extent to which the influence is reduced and the upstream distance within which buildings should be represented remain to be determined.

The sensitivity of wind pressures to the incoming wind field also raises important questions regarding the actual peak design loads that a building might experience. Current analysis methods assume the wind field acts as a neutral synoptic surface layer with idealized turbulence characteristics; actual values might deviate from this assumption. Furthermore, the near-surface characteristics of the turbulent wind field during extreme wind events, which cause most of the damage, are not fully understood. Hence, the wind pressures experienced by structures that are exposed to hurricanes, downbursts, and tornadoes have significant uncertainty because of the uncertainty in the turbulent wind characteristics.

This research aims to leverage CWE to improve understanding of turbulent wind statistics and resulting wind pressures on the building surface. New methods to systematically investigate and quantify this relationship should be proposed, with a focus on identifying the level of accuracy in the wind statistics required to achieve a specific level of accuracy in the predictions. This level of accuracy is expected to be different for different quantities of interest (e.g., mean base forces and moments vs. peak cladding loads on a panel).

In this effort, accounting for the fact that the wind characteristics imposed at the inflow of CWE simulations might evolve when moving downstream in the computational domain is essential. Because the evolution depends on the specific boundary conditions, numerical methods, mesh, and sub-grid model used, the relationship to be investigated is the one between the turbulent wind statistics at the building location (as for example obtained from an empty domain simulation) and the resulting pressures on the building. Note that the wind characteristics also evolve in wind tunnel experiments, and careful characterization of the statistics at the building location of interest is equally important in these experiments.

This research will benefit significantly from the combined use of CWE simulations with wind tunnel experiments, field observations, or larger-scale weather prediction models. The ultimate goal is to support matching the level of detail and accuracy in CWE inflow boundary conditions for different extreme wind events to the level of detail and accuracy required in the predictions for the quantities of interest.

Appendix B. May 2023 Reston, Virginia, Workshop

B.1. Workshop Agenda

NIST Computational Wind Engineering Workshop

DATE: May 18–19, 2023

LOCATION: ASCE Bechtel Conference Center;
1801 Alexander Bell Drive, Reston, VA 20191

Workshop Agenda – v6

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

Day 1: Thurs., May 18; 9:00am – 5:00pm Eastern

8:00 am–9:00 am: Continental Breakfast Provided

9:00 am–9:30 am: Welcome

- Purpose, Goals, and Workshop Agenda
  - Opening Remarks from Dr. 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–10:30 am: State-of-the-Art Presentations: Computational Fluid Dynamics Design Tool—Theory and Practice [60 mins]

- **Mathematical approaches** [20 mins = 15 mins + 5 mins Q&A]; Arif Masud, Ph.D., F.EMI, M.ASCE; Professor, University of Illinois, Urbana-Champaign
- **Combine machine learning and CFD** [20 mins = 15 mins + 5 mins Q&A]; Jian-Xun Wang, Ph.D.; Assistant Professor, University of Notre Dame
- **Technical aspects of software** [20 mins = 15 mins + 5 mins Q&A]; Aleksander Jemcov, Ph.D.; Associate Research Professor, University of Notre Dame

10:30 am–10:45 am: Coffee Break and Group Photo (on front steps of building)

10:45 am–11:45 am: State-of-the-Art Presentations: Verification and Validation Case Studies [60 mins]

- **Synoptic and non-synoptic wind** [20 mins = 15 mins + 5 mins Q&A]; Girma Bitsuamlak, Ph.D., A.M.ASCE; Professor, Western University
- **Static** [20 mins = 15 mins + 5 mins Q&A]; Hassan Hemida, Ph.D., Professor, University of Birmingham, UK
- **Dynamic** [20 mins = 15 mins + 5 mins Q&A]; Abiy Melaku, Ph.D., Aff.M.ASCE; University of California, Berkeley

11:45 am–12:30 pm: State-of-the-Art Panel Discussion

- Panel Discussion: Potential Risks [45 mins = 30 mins discussion + 15 mins Q&A]
  - Moderator: Melissa Burton, Ph.D., C.Eng; Principal, Arup
  - Panelists:
    - Gonçalo Pedro, Ph.D.; RWDI
    - Stefano Capra; Ramboll
    - David Banks, Ph.D.; CPP Inc.
    - R. Paneer Selvam, Ph.D., University of Arkansas

12:30 pm–1:00 pm: Working Lunch Provided in Breakout Sessions

BREAKOUT SESSIONS

12:30 pm–4:45 pm: Five concurrent sessions (see the following descriptions)

- Computational Fluid Dynamics Design Tools: Moderator Ahsan Kareem
- Verification and Validation Benchmark Testing: Moderator Ted Stathopoulos
- System Reliability and Risk: Moderator Melissa Burton
- Storm Type and Generation: Moderator Catherine Gorle
- Structural Engineering Applications: Moderator Brad Young

2:30 pm–2:45 pm: Coffee Break

4:45 pm–5:00 pm: Reconvene

- Summary and Adjourn Day 1

Day 2: Friday, May 19; 8:00 am–12:00 pm Eastern

7:30 am–8:00 am: Continental Breakfast Provided

8:00 am–8:15 am: Welcome

- Purpose and Goals of Day 2

8:15 am–10:45 am: Report-Out

- Breakout Session Report-Out: Expert for Presentation [30 mins EACH = 20 mins + 10 mins Q&A]
    - Storm Type and Generation
    - Verification and Validation Benchmark Testing
    - System Reliability and Risk
    - Structural Engineering Applications
    - Computational Fluid Dynamics Design Tool

10:45 am–11:00 am: Coffee Break

11:00 am–11:50 am: Prioritization

- Prioritization of Research Needs [20 mins]
- Moderated Panel Discussion of WSC [30 mins]

11:50 am–12:00 pm: Conclusion

- Summary and Adjourn Day 2

12:30 pm–4:00 pm: Workshop Steering Committee Meeting

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NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

SEI-NIST CWE Workshop Breakout Topics and Participant List

12/10/2022

The following describes the breakout sessions organized for the afternoon, as well as identifying the WSC member moderating the session and the proposed participant lists.

TOPIC: Computational Fluid Dynamics Design Tool

CWE WSC Moderator: Ahsan Kareem

The session on Computational Fluid Dynamics (CFD) Design Tools will aim at overviewing the current CFD-based tools being used in research and practice. That will include a discussion on the various numerical approaches, turbulence modeling and particle-based simulations, digital twining, and machine learning-based accelerators. The expected outcome will include a prioritization of research needs for the development of tools with the infusion of new technologies to expedite simulations for practical applications and research.

TOPIC: Verification and Validation Benchmark Testing

CWE WSC Moderator: Ted Stathopoulos

Verification and Validation (V&V) are often confused but estimation of deviations between numerical and experimental results belongs to the former, while the quantification of errors belongs to the latter. The session will discuss and comment on minimal target uncertainties to be comparable with values derived from experimental results originating from different wind tunnel laboratories carrying out tests respecting the ASCE 49 standard provisions. This session will also include a discussion to prioritize research needs.

TOPIC: System Reliability and Risk

CWE WSC Moderator: Melissa Burton

> The use of computational numerical modelling for design conditions in the built environment has been used more and more prevalently over the last two decades. The use of the tool has become an accepted standard for use in assessments around air quality, pollutant entrainment, and pedestrian comfort. For these applications the length of simulations can be quite short and often involve mesh simplification. The quality of the outcome of these simulations begins to collapse when results are required in wake zones, gust speeds are high, or much beyond a characterization of mean flows is required. In this session we will discuss the low-cost barrier to entry of CWE and the risk of moving too quickly, and prior to QA/QC protocol development and standardization, to quantifying wind loading (static and dynamic) on structures. We will also review and discuss when we believe the opportunity for reliability of results could be low. In summary, this session will include prioritization of identified research needs.

TOPIC: Storm Type and Generation

CWE WSC Moderator: Catherine Gorle

When calculating wind loading on buildings it is important to accurately predict the turbulent fluctuations of the wind pressures on the structure. These pressure fluctuations have two origins: the turbulence in the incoming wind field, and the turbulence generated by the presence of the building in the flow. Accurate prediction of fluctuating pressures therefore requires accurate specification of boundary conditions for the wind, as well as sufficient grid resolution and model accuracy to resolve the flow around the building. In this session we will discuss the state of the art and open research questions in specifying realistic turbulent boundary conditions for wind flow, considering both stationary neutral surface layer winds and more complex nonstationary flows such as tornadoes and downbursts. Opportunities and challenges to improve the realism of these inflow conditions will be identified and a prioritized list of research needs will be identified.

TOPIC: Structural Engineering Applications

CWE WSC Moderator: Brad Young

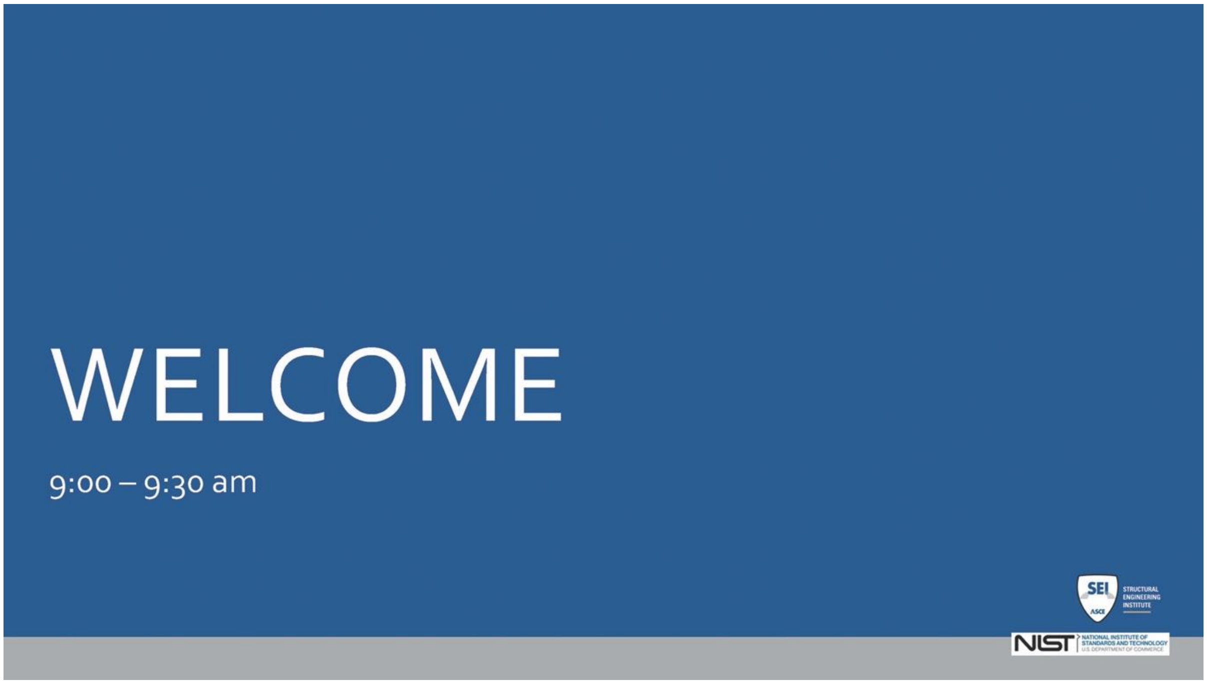
While the use of CFD has become more firmly accepted within the AEC industry for larger scale flow modeling applications, the unique aspects of bluff body aerodynamics pose challenges in the application of CFD/CWE for the development of structural wind loads for the specific purposes of main-wind-force-resisting-system (MWFRS) design, and for evaluation of wind response such as lateral accelerations. Characteristics of boundary layer wind turbulence, local/acute flow separation at the building envelope, and the resulting turbulent wake formation, and computational limitations comprise some of the challenges in this regard. Nevertheless, CFD/CWE holds significant potential to emerge as a valuable design tool for structural engineers. This session aims to create a collaborative dialog between leading experts in the CWE field, both from academic and commercial practice backgrounds, to explore the successes and challenges in the use of CFD/CWE in the development of static and dynamic structural wind loading, and to identify and prioritize areas of needed research to allow CWE to emerge as a more useful and accessible design tool for the engineering industry, in this regard.

B.2. Workshop Presentations

SEI-NIST PERFORMANCE BASED DESIGN WORKSHOP

Feb. 23-24, 2023

American Society of Civil Engineers, Reston, Va.



WELCOME

9:00 – 9:30 am

GENERAL SESSION

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

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

12:00pm-12:30pm – WORKING L

BREAKOUT SESSIONS
12:30pm-4:45pm – F
1. Wind climate
2. System reliab
3. Wind-structur
4. Structural ana
5. Design – Mod

2:30pm-2:45pm – CO

4:45pm-5:00pm – Re
- Summary and

Day 2: Fri., Feb. 24; 8
7:30am-8:00am – CO

GENERAL SESSION
8:00am-8:15am – We
- Purpose an

8:15am-11:45am – R
- Breakout
  1. W
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  4. St
  5. De

10-minute CO

- Moderate
- Prioritizat

11:45am-12:00pm –
- Summary and

12:00-4:00pm – Worl

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

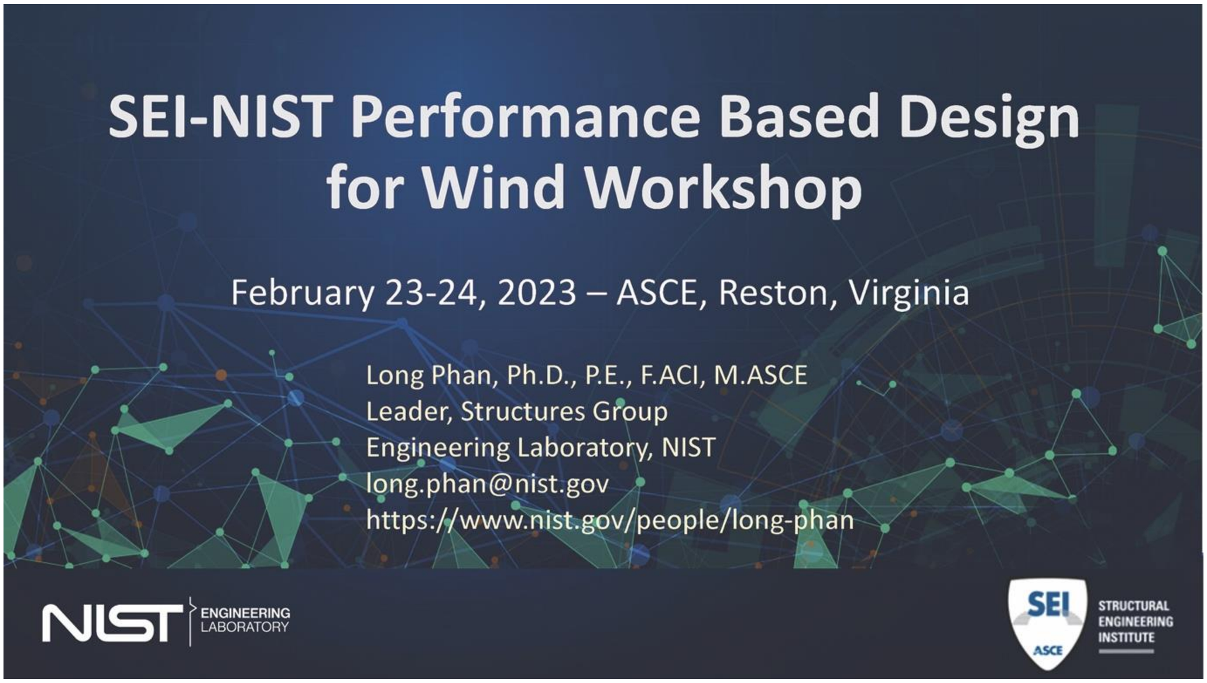
Performance-Based Wind Design Methodologies

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

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.

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

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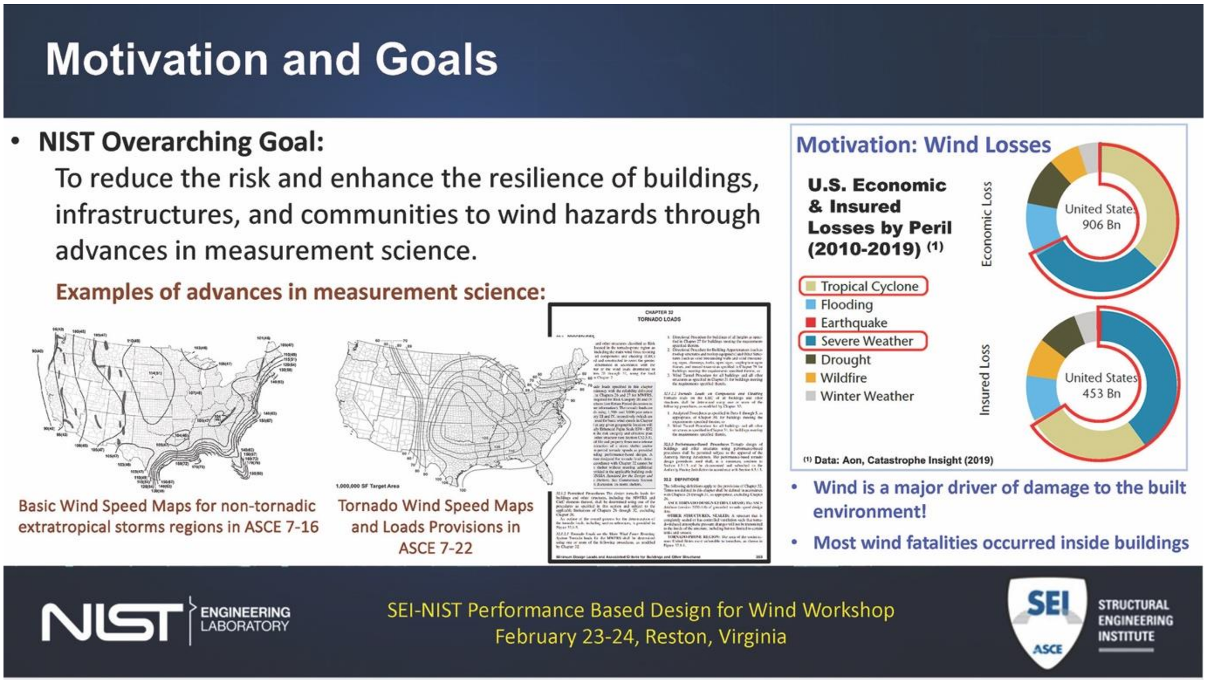

Motivation and Goals

- **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

U.S. Economic & Insured Losses by Peril (2010-2019) (1)

🟨 Tropical Cyclone
🟦 Flooding
🟥 Earthquake
🟦 Severe Weather
⬛ Drought
🟧 Wildfire
⬜ Winter Weather

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

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

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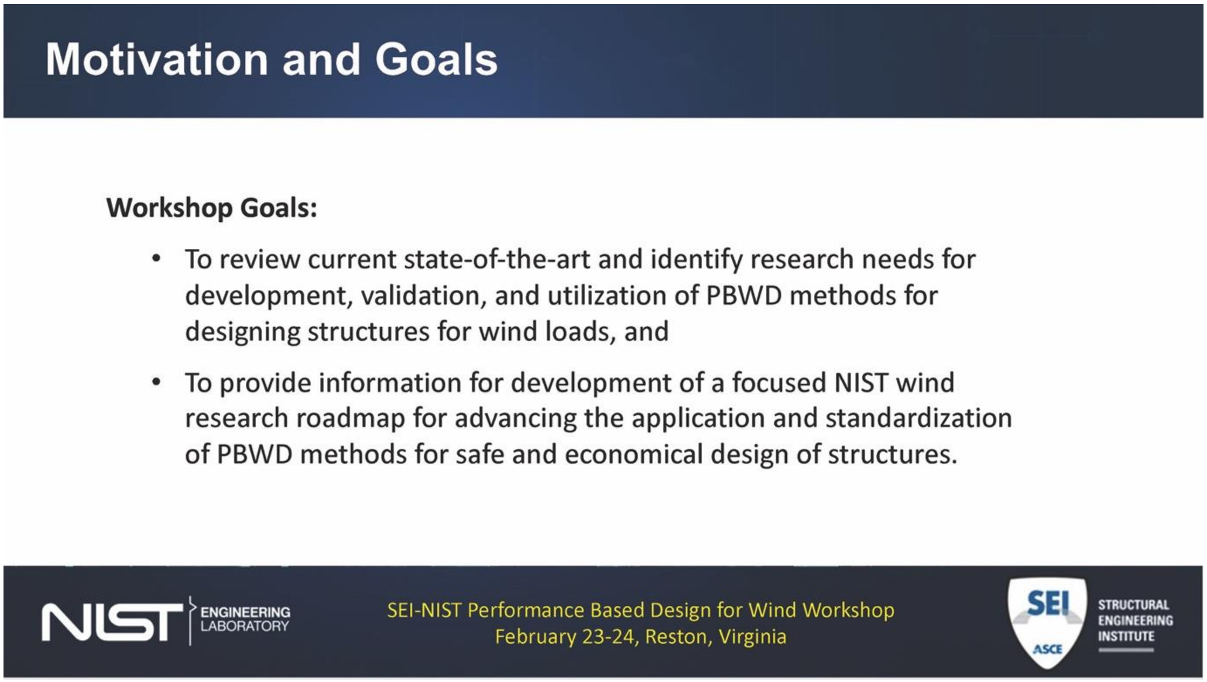

Motivation and Goals

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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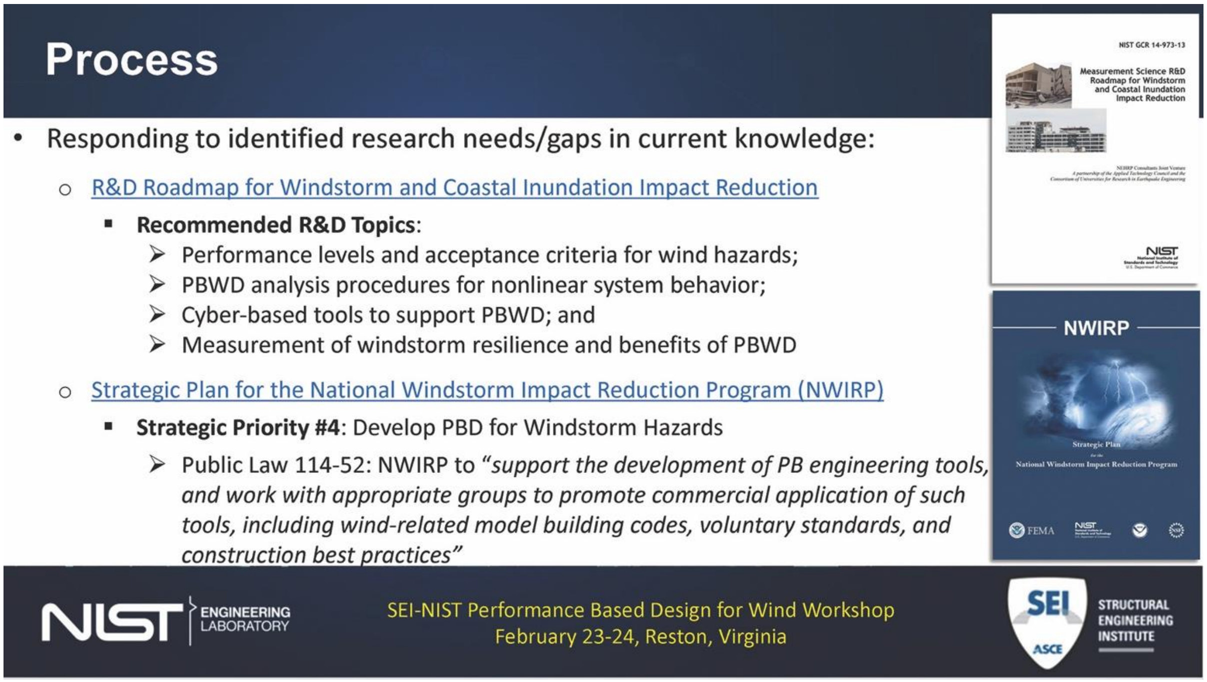

Process

- 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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February 23-24, Reston, Virginia

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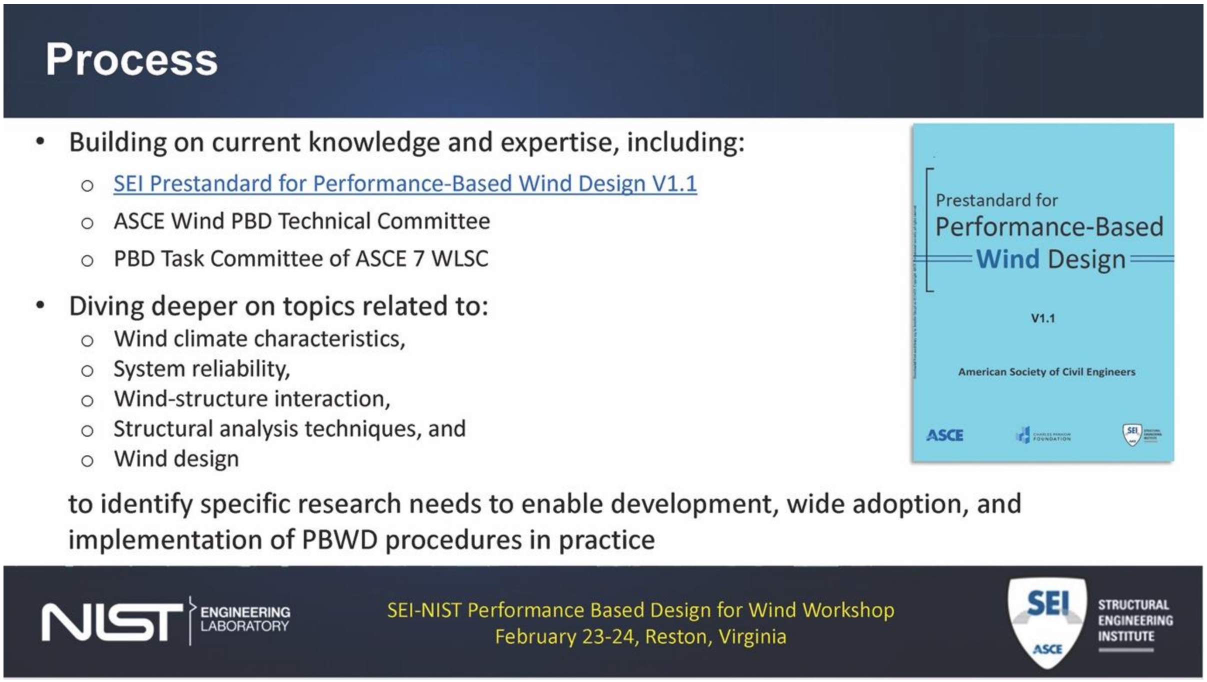

Process

- 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

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

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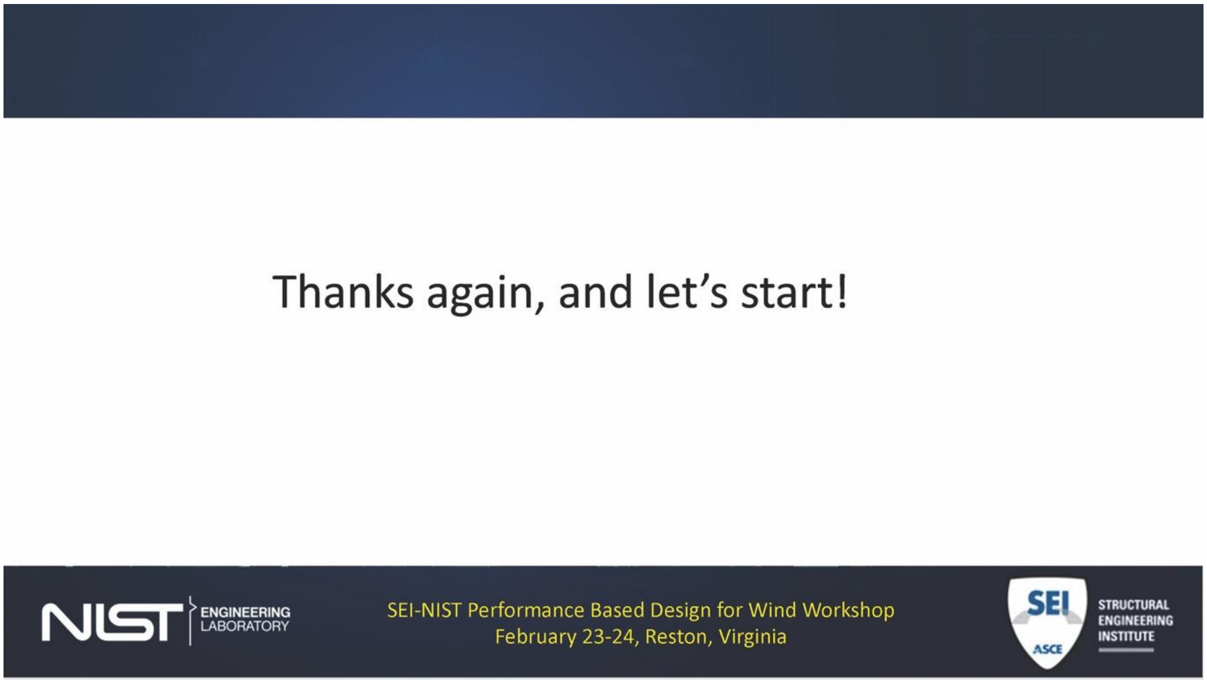

Thanks again, and let’s start!

NIST ENGINEERING LABORATORY

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

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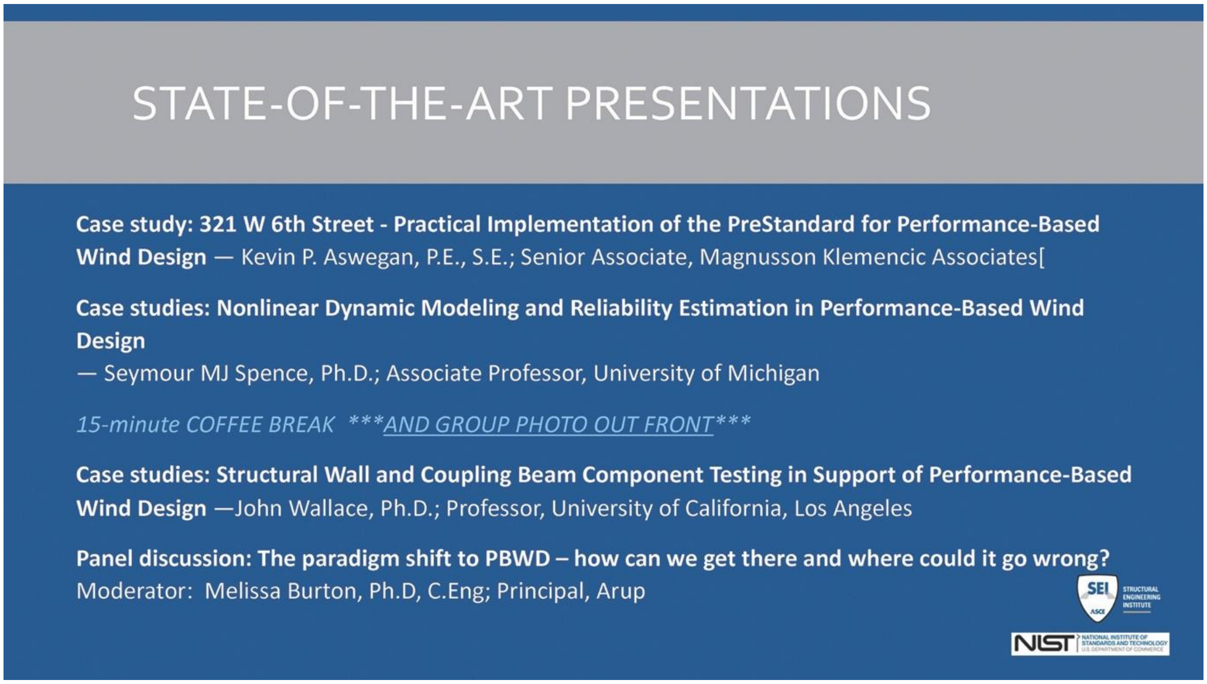
SELF INTRODUCTION

Name, Organization, Interest in PBWD

STATE-OF-THE-ART

9:30 am – 12:00 pm



STATE-OF-THE-ART PRESENTATIONS

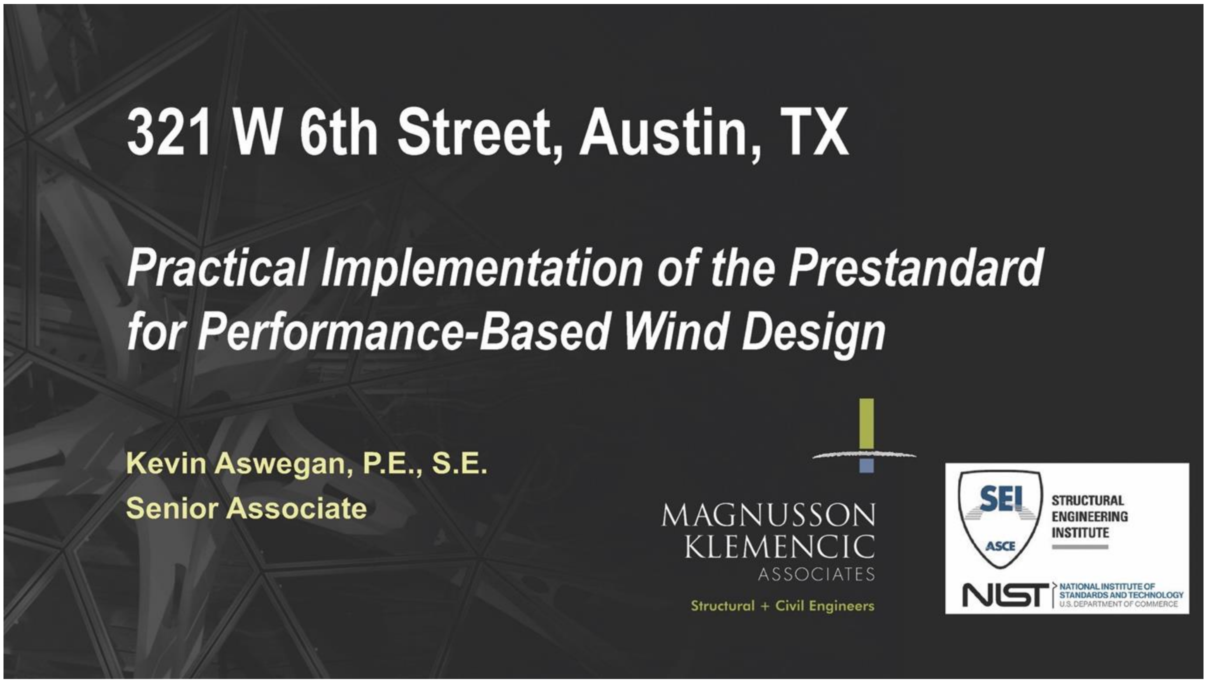
Case study: 321 W 6th Street - Practical Implementation of the PreStandard for Performance-Based Wind Design — Kevin P. Aswegan, P.E., S.E.; Senior Associate, Magnusson Klemencic Associates[

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

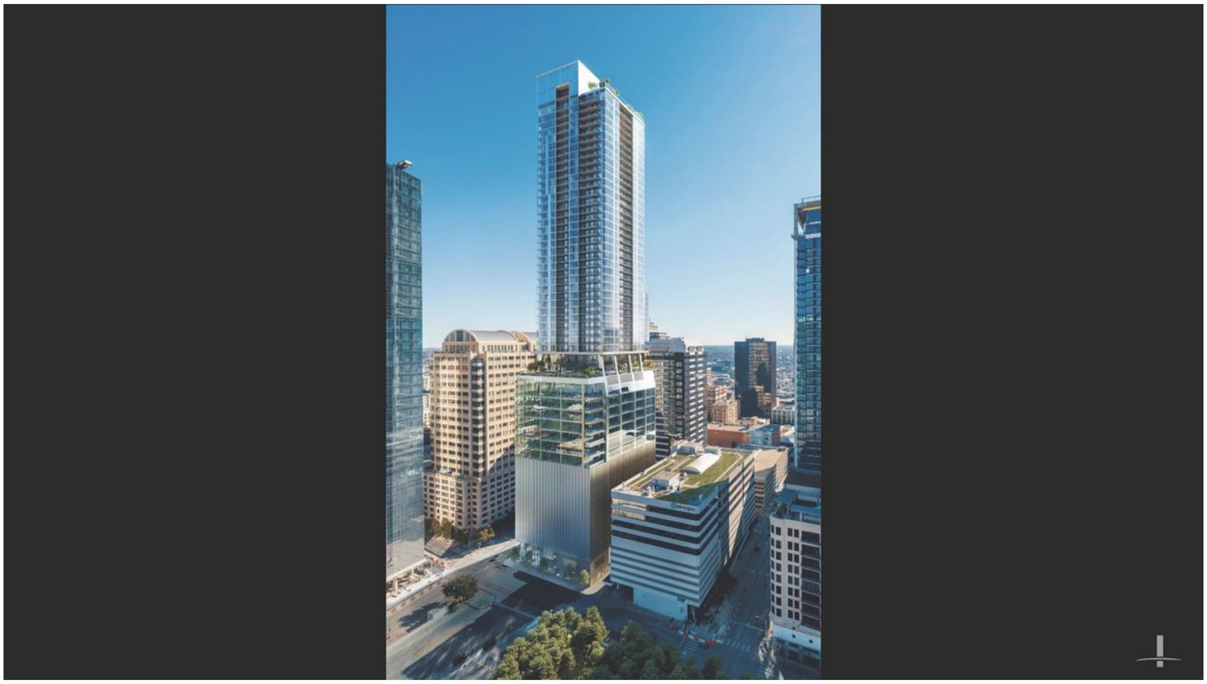


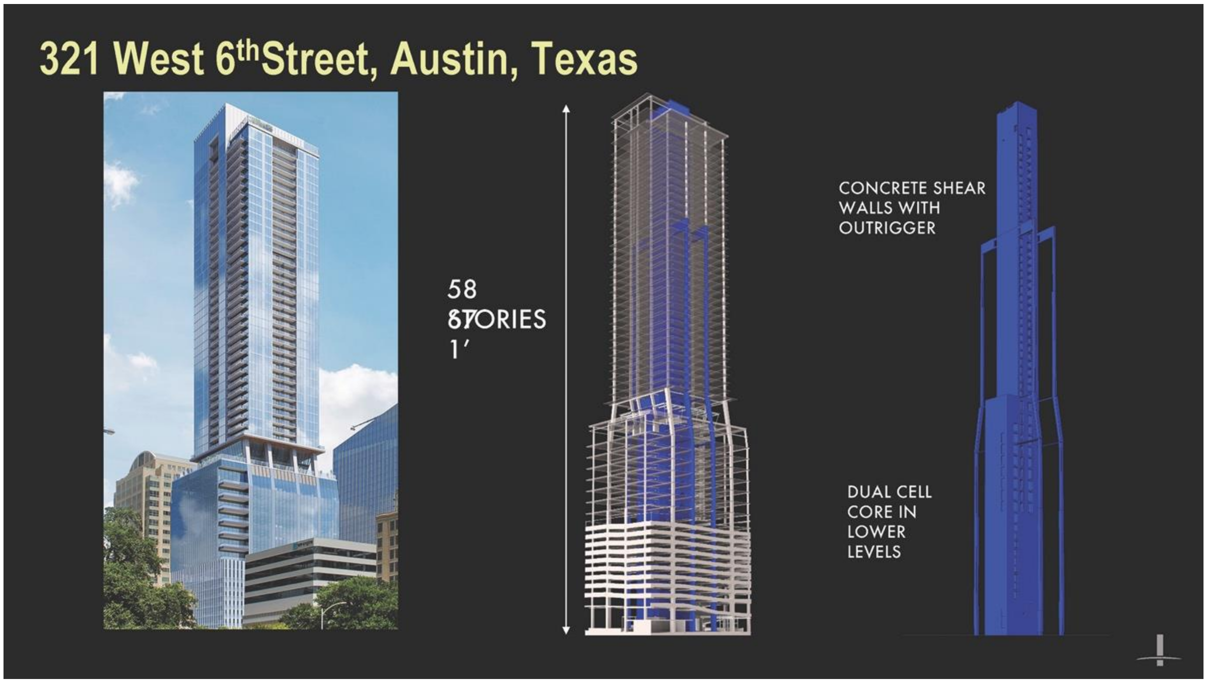
321 W 6th Street, Austin, TX

Practical Implementation of the Prestandard for Performance-Based Wind Design

Kevin Aswegan, P.E., S.E.
Senior Associate

MAGNUSSON KLEMENCIC ASSOCIATES
Structural + Civil Engineers



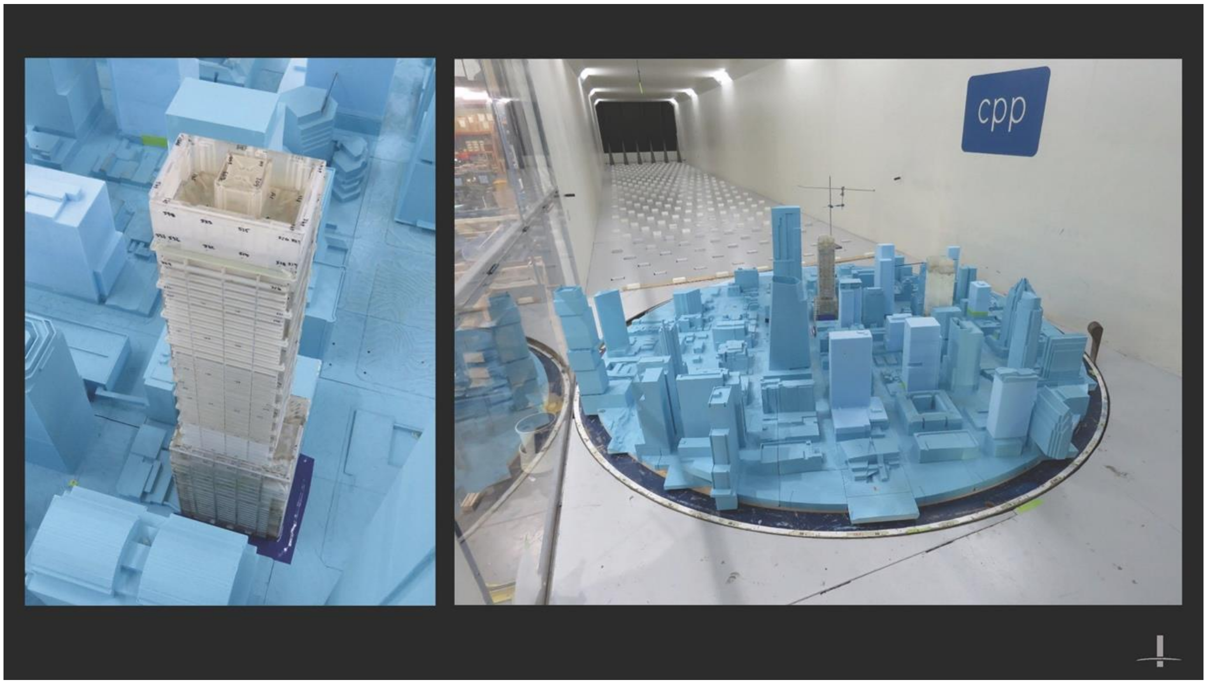


321 West 6th Street, Austin, Texas

58
67STORIES
1′

CONCRETE SHEAR
WALLS WITH
OUTRIGGER

DUAL CELL
CORE IN
LOWER
LEVELS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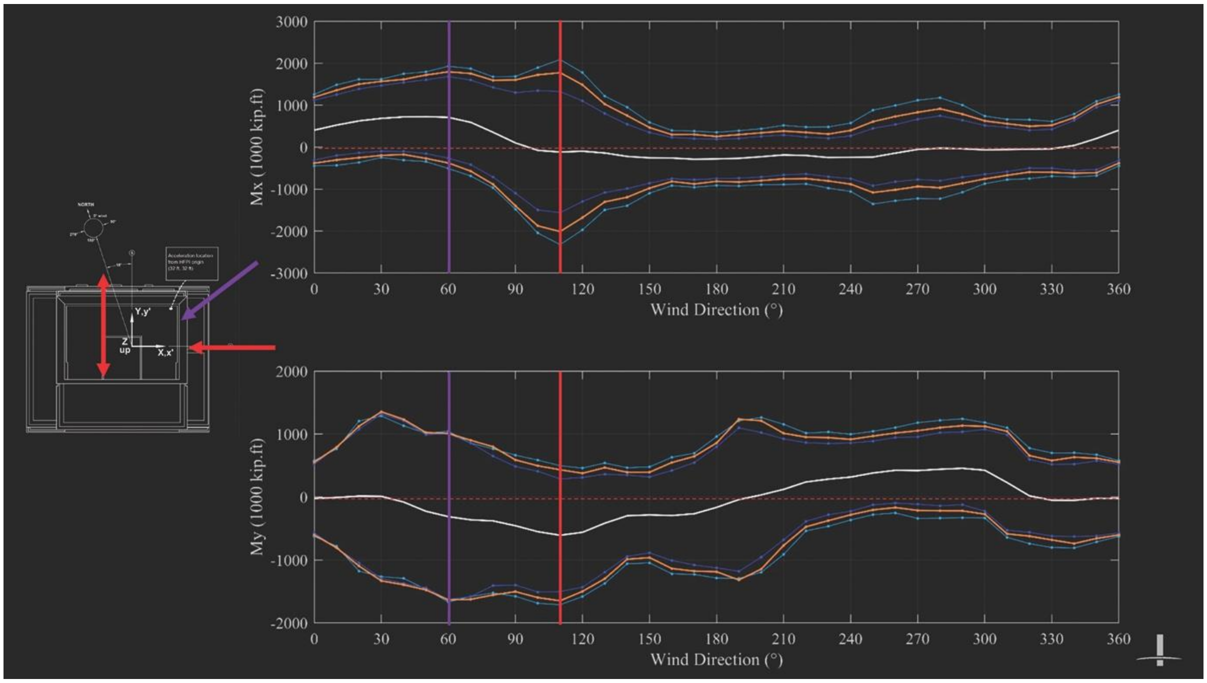
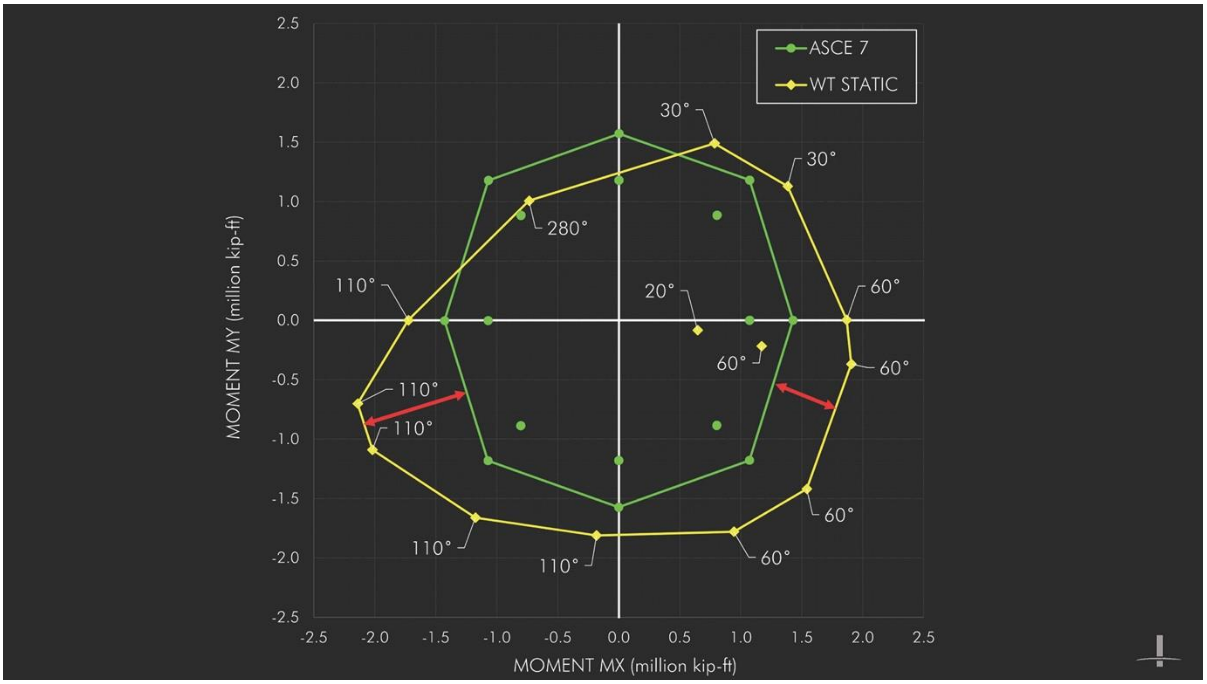
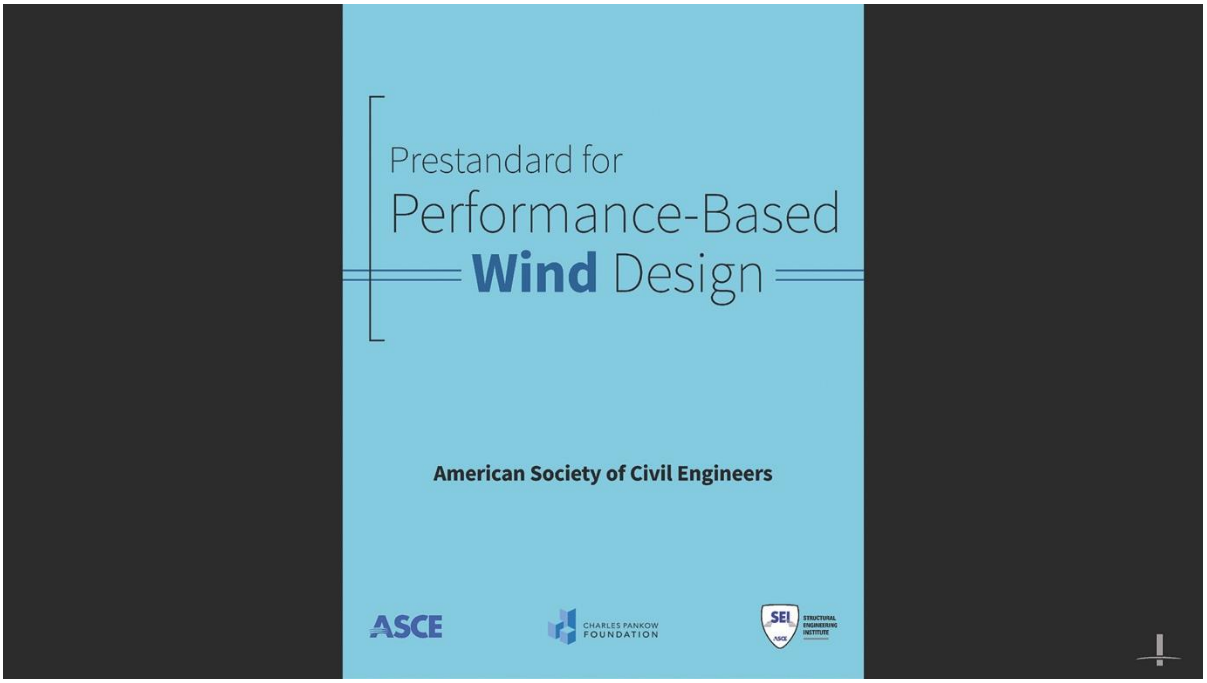

Mx (1000 kip.ft)
3000
2000
1000
0
-1000
-2000
-3000
Wind Direction (°)
0
30
60
90
120
150
180
210
240
270
300
330
360
My (1000 kip.ft)
2000
1000
0
-1000
-2000
NORTH
Y,y'
Z
up
X,x'





Prestandard for
Performance-Based
Wind Design

American Society of Civil Engineers

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?

YES ? NO

EVALUATION SATISFIED

LINEAR ELASTIC ACCEPTANCE CRITERIA SATISFIED?

YES ? NO

EVALUATION SATISFIED

OR

METHOD 1 TIME HISTORY

METHOD 2 OR 3 RELIABILITY ANALYSIS

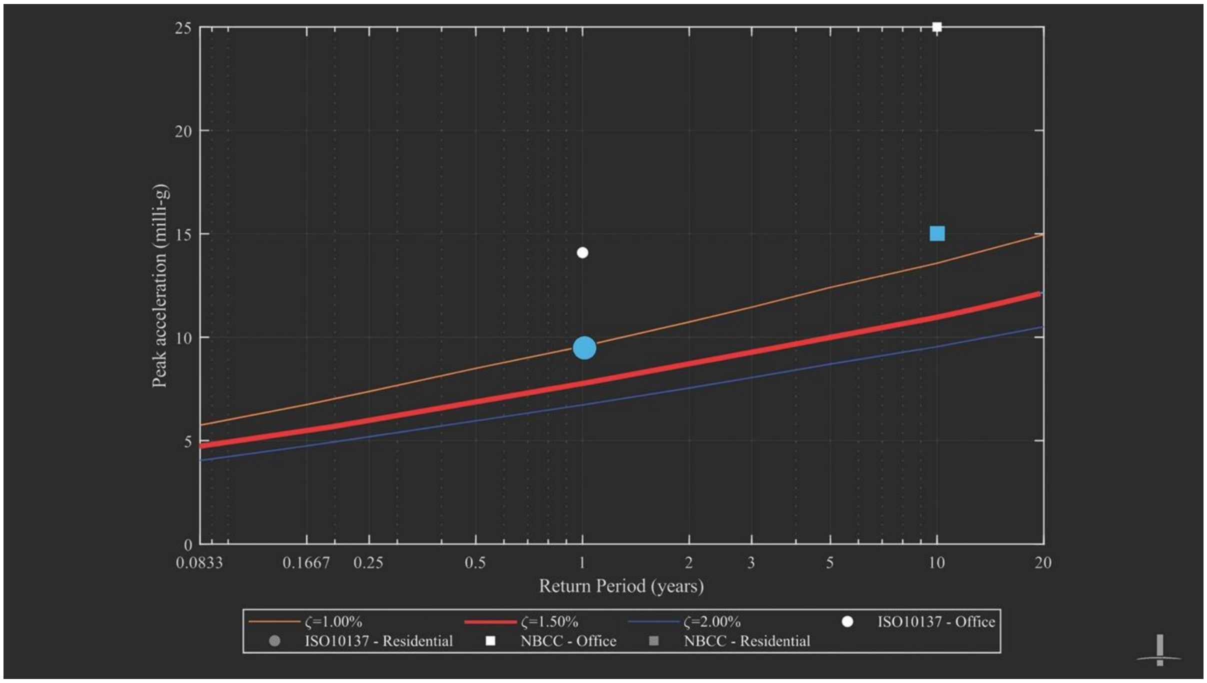
ACCEPTANCE CRITERIA SATISFIED?

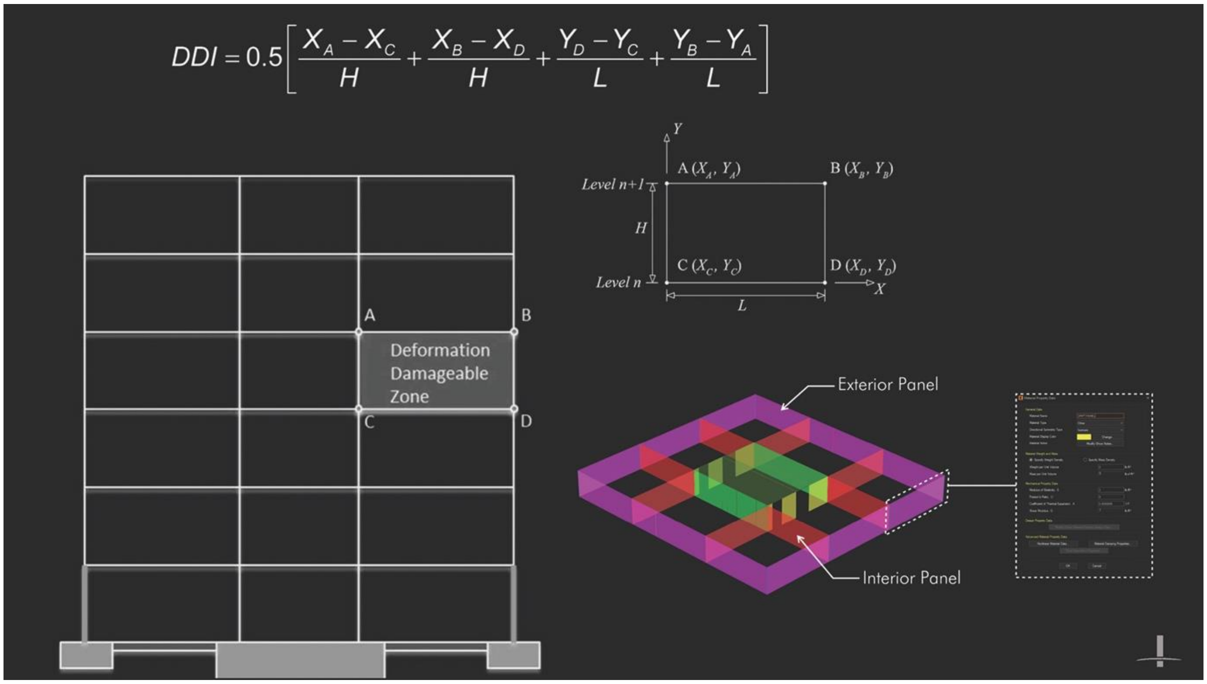
NO ? YES

REVISE DESIGN

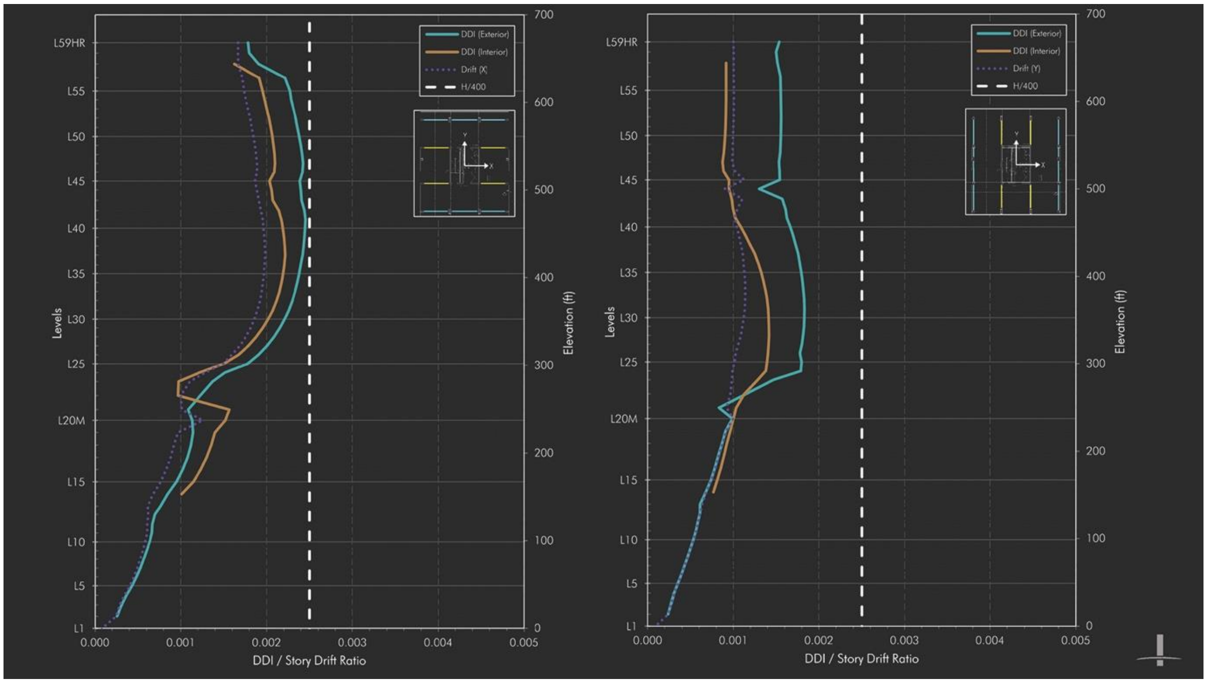
DESIGN ACCEPTABLE WHEN OCCUPANT COMFORT, OPERATIONAL AND CONTINUOUS OCCUPANCY EVALUATIONS ARE SATISFIED

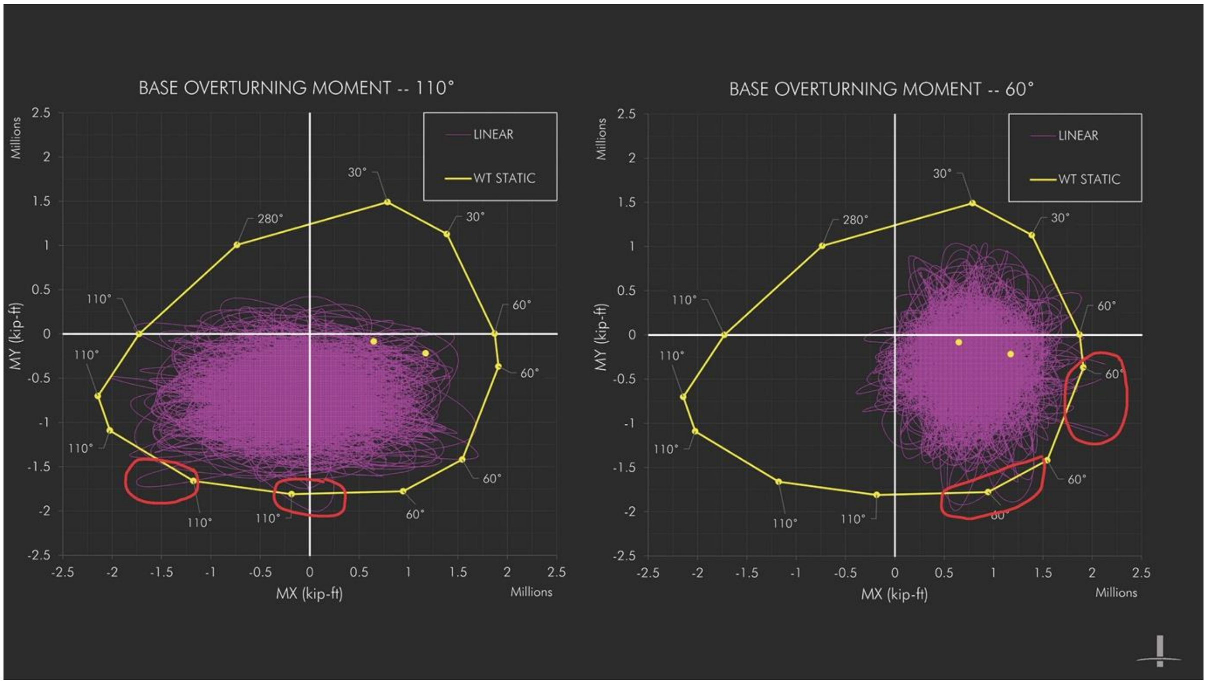
EVALUATION SATISFIED

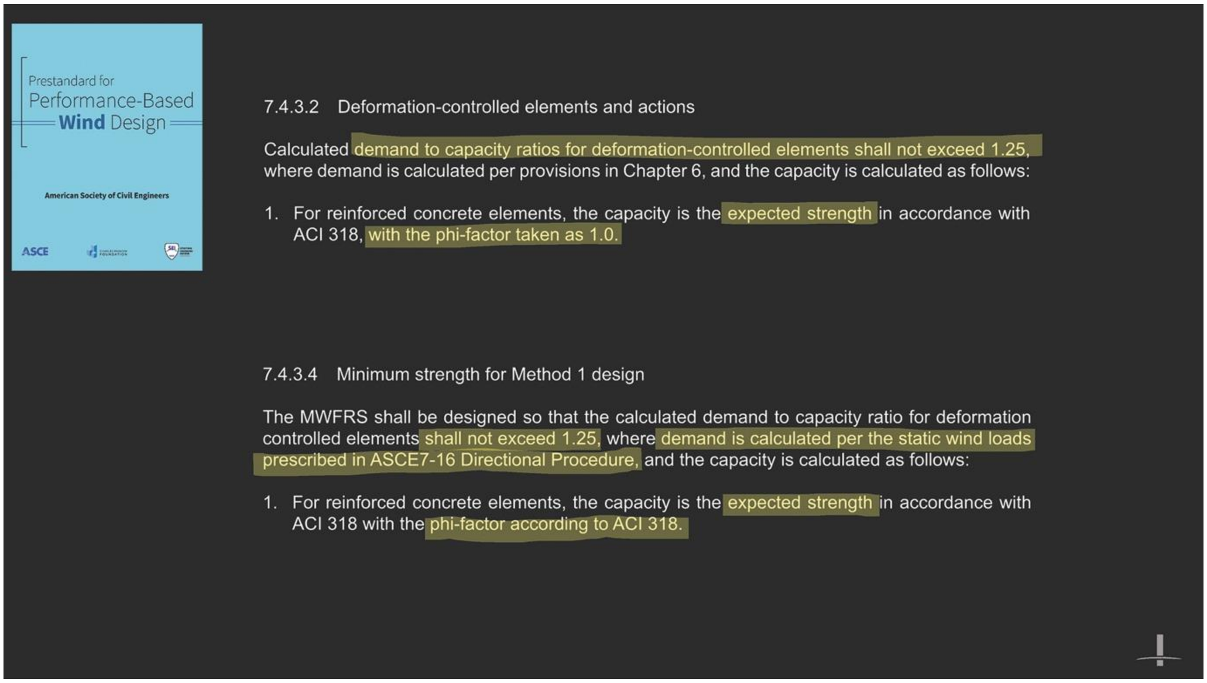




$$DDI = 0.5\left[\frac{X_A - X_C}{H} + \frac{X_B - X_D}{H} + \frac{Y_D - Y_C}{L} + \frac{Y_B - Y_A}{L}\right]$$







7.4.3.2 Deformation-controlled elements and actions

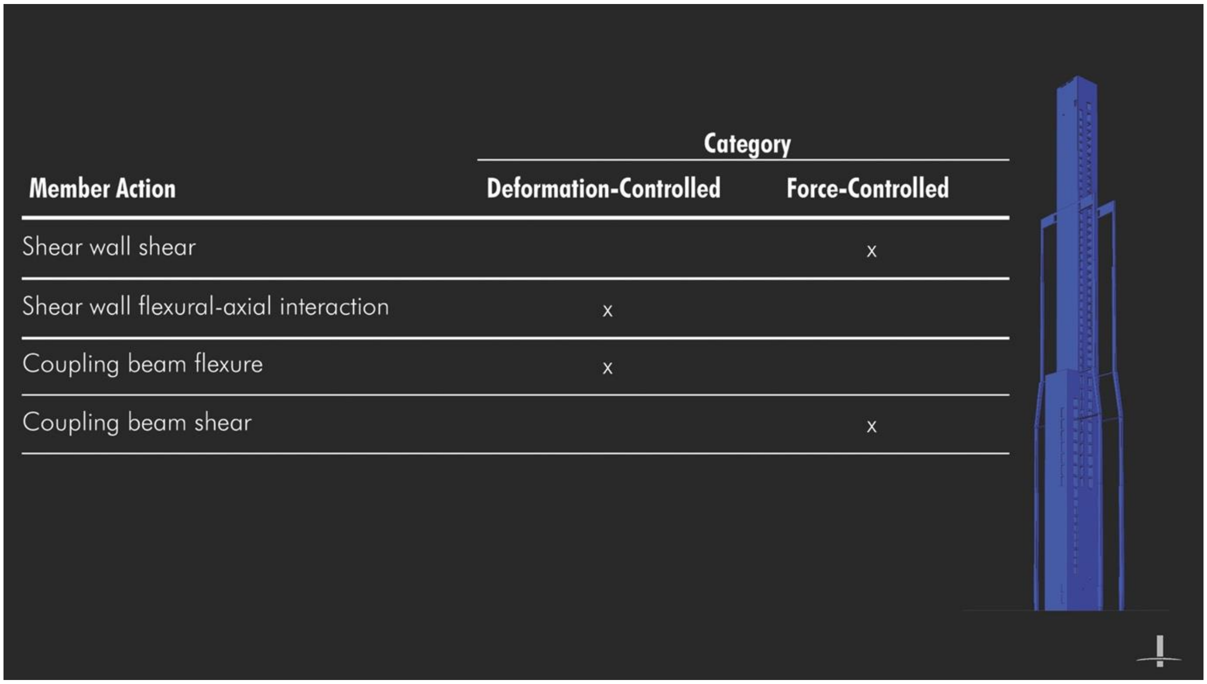
Calculated demand to capacity ratios for deformation-controlled elements shall not exceed 1.25, where demand is calculated per provisions in Chapter 6, and the capacity is calculated as follows:

1. For reinforced concrete elements, the capacity is the expected strength in accordance with ACI 318, with the phi-factor taken as 1.0.

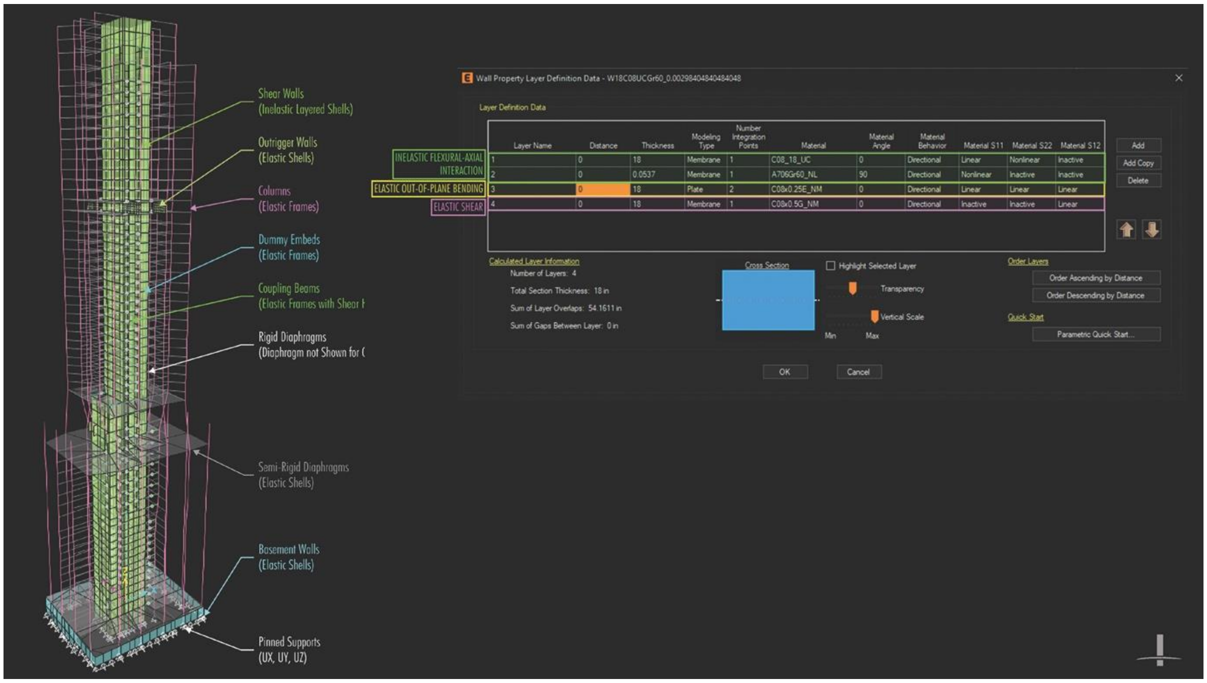
7.4.3.4 Minimum strength for Method 1 design

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



Wall Property Layer Definition Data - W18C08UCGr60_0.00298404840484048

Layer Definition Data

Layer Name	Distance	Thickness	Modeling Type	Number Integration Points	Material	Material Angle	Material Behavior	Material S11	Material S22	Material S12
1	0	18	Membrane	1	C08_18_UC	0	Directional	Linear	Nonlinear	Inactive
2	0	0.0537	Membrane	1	A706Gr60_NL	90	Directional	Nonlinear	Inactive	Inactive
3	0	18	Plate	2	C08x0.25E_NM	0	Directional	Linear	Linear	Linear
4	0	18	Membrane	1	C08x0.5G_NM	0	Directional	Inactive	Inactive	Linear

Calculated Layer Information

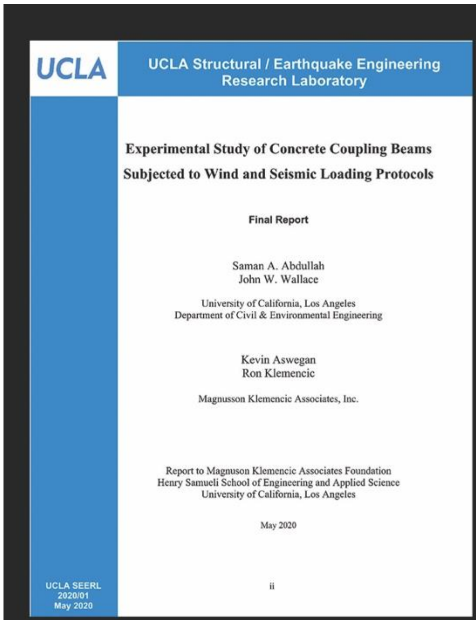
Number of Layers: 4

Total Section Thickness: 18 in

Sum of Layer Overlaps: 54.1611 in

Sum of Gaps Between Layer: 0 in

☐ Highlight Selected Layer



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

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UCLA SEERL
2020/01
May 2020

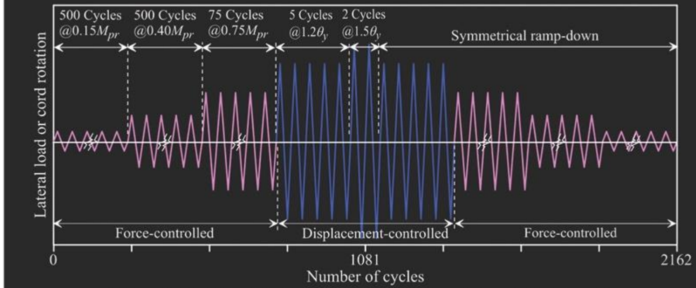
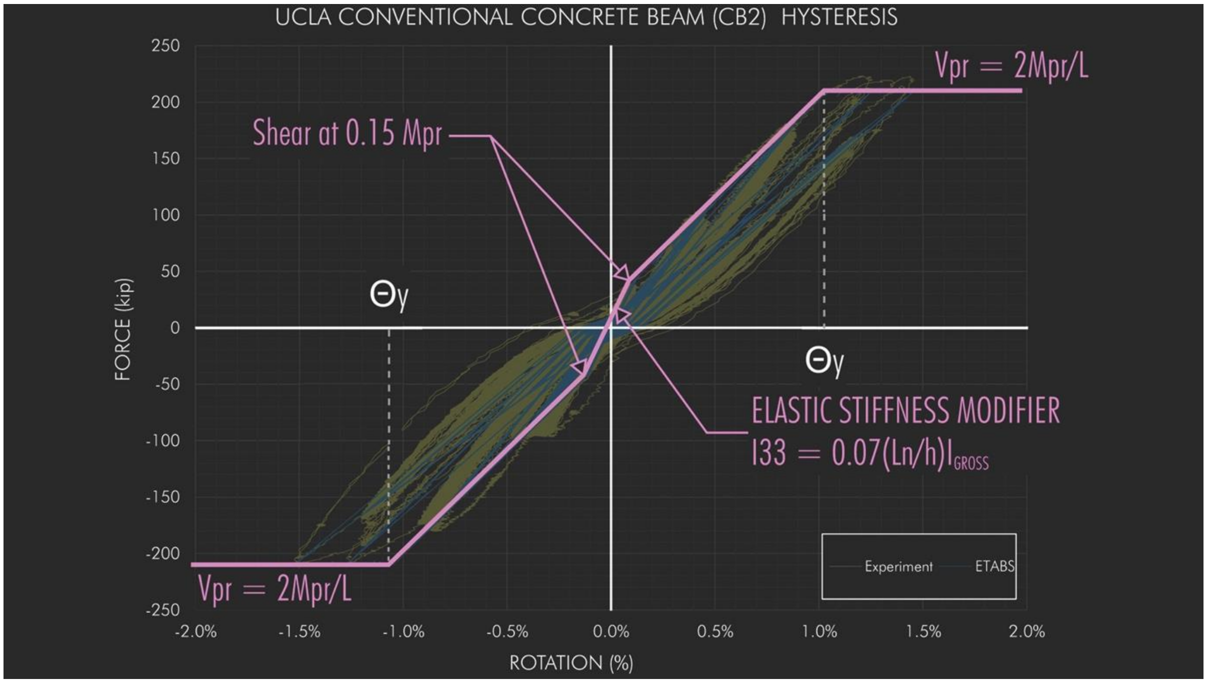
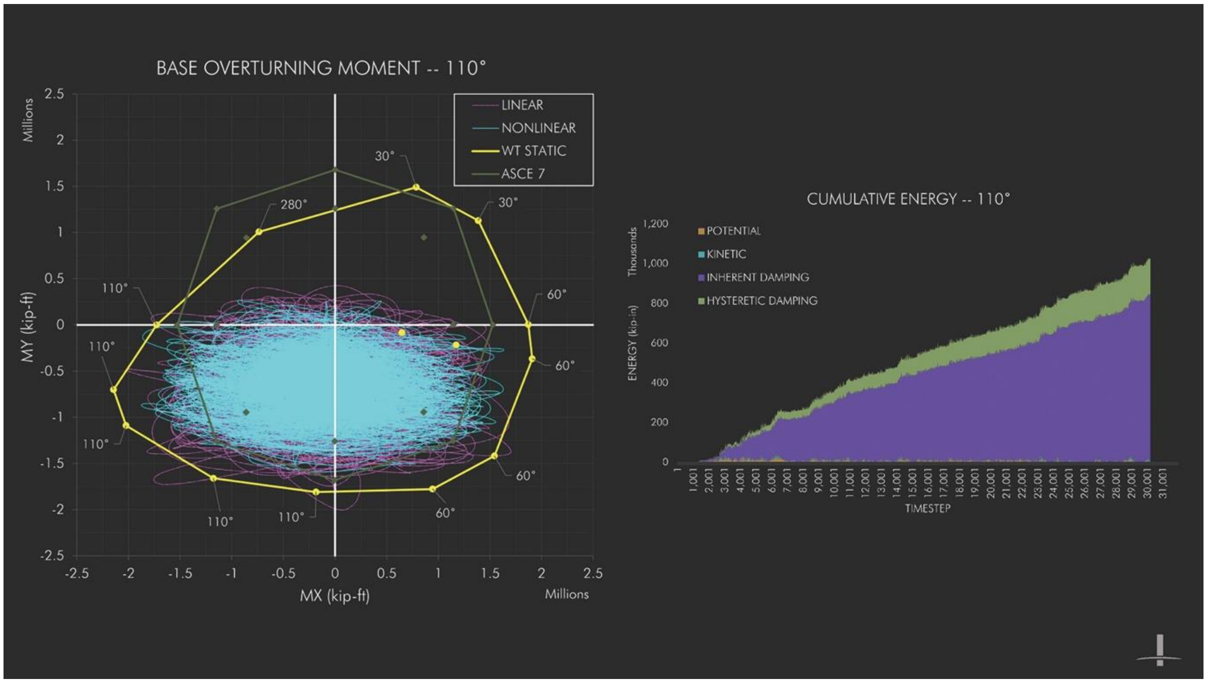


Figure 2-21. Wind loading protocol used to test beams in Phase I.




BASE OVERTURNING MOMENT -- 110°
LINEAR
NONLINEAR
WT STATIC
ASCE 7
Millions
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
MY (kip-ft)
30°
280°
30°
110°
60°
110°
60°
110°
60°
110°
110°
60°
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
MX (kip-ft)
Millions
CUMULATIVE ENERGY -- 110°
POTENTIAL
KINETIC
INHERENT DAMPING
HYSTERETIC DAMPING
Thousands
1,200
1,000
800
600
400
200
0
ENERGY (kip-in)
1
1,001
2,001
3,001
4,001
5,001
6,001
7,001
8,001
9,001
10,001
11,001
12,001
13,001
14,001
15,001
16,001
17,001
18,001
19,001
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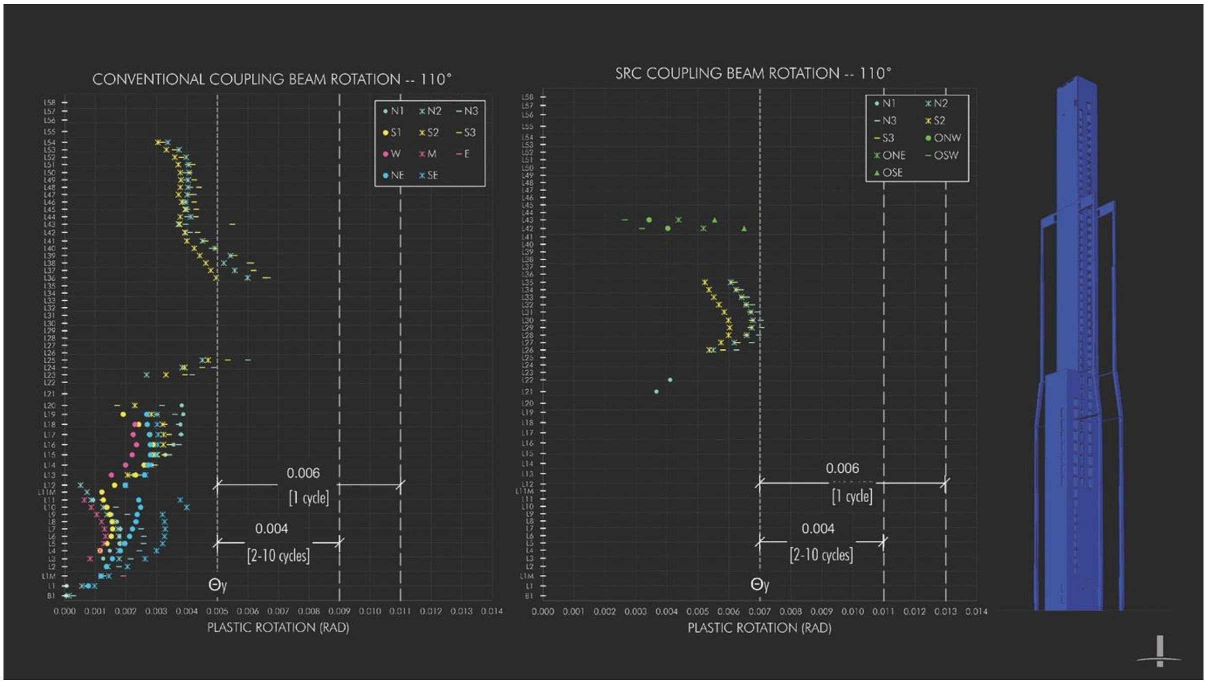
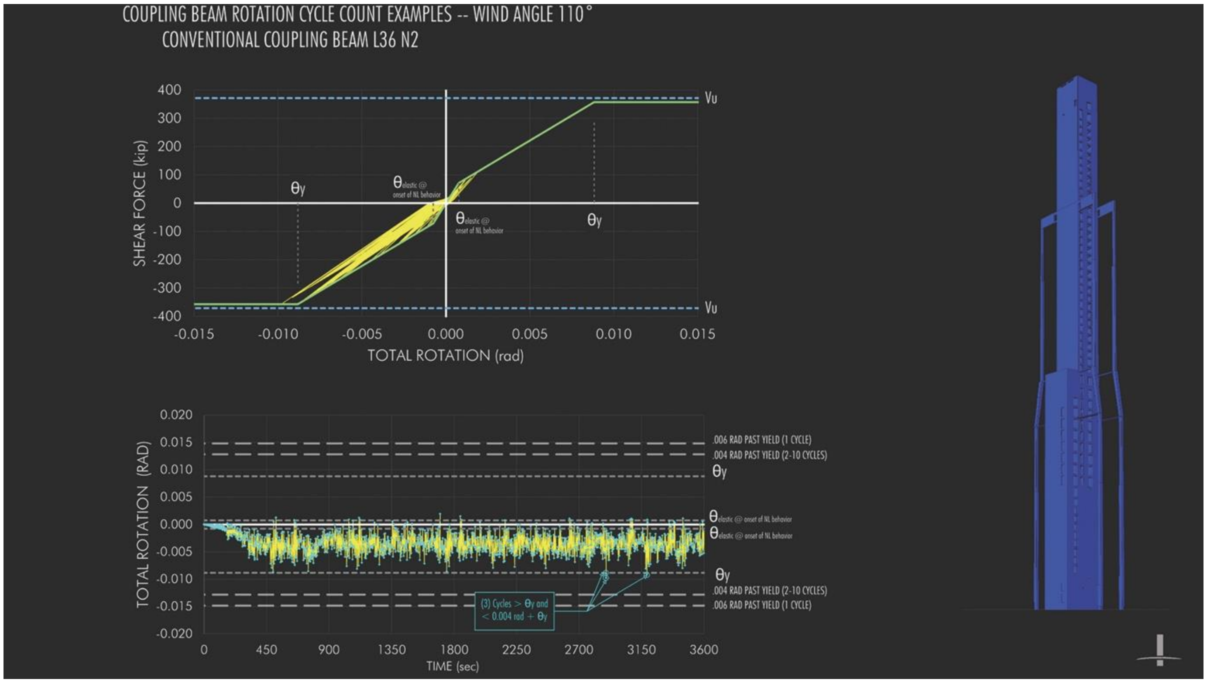
25,001
26,001
27,001
28,001
29,001
30,001
31,001
TIMESTEP

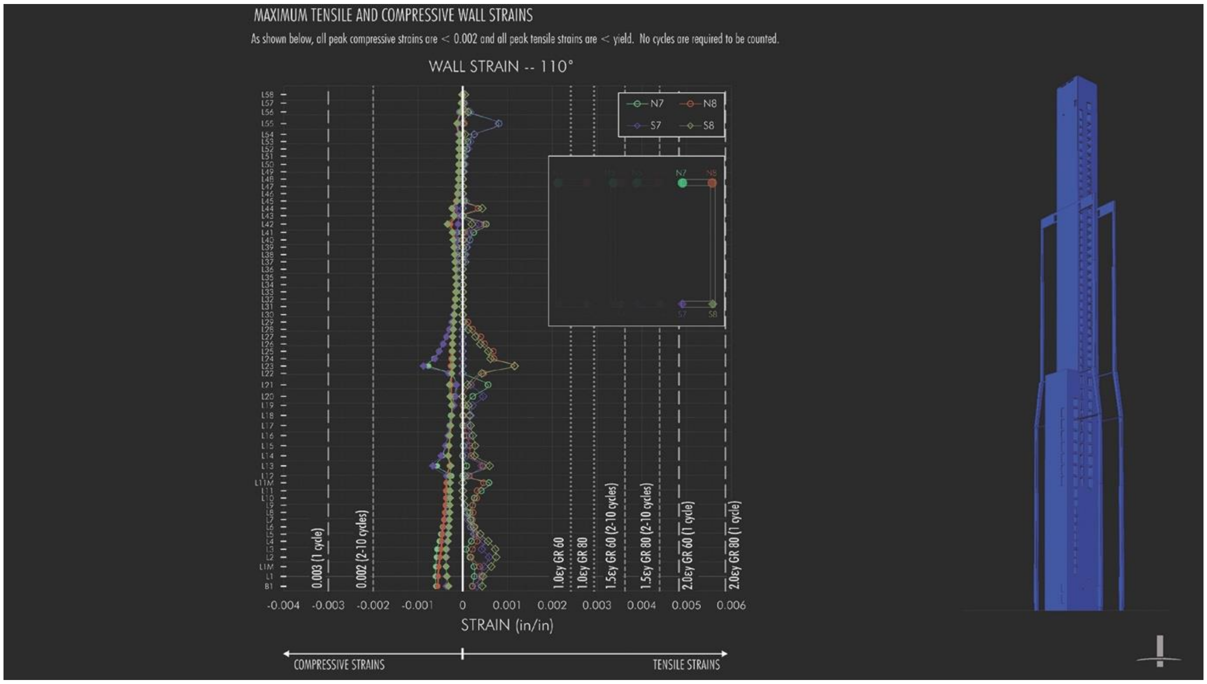


CONVENTIONAL COUPLING BEAM ROTATION -- 110°

SRC COUPLING BEAM ROTATION -- 110°

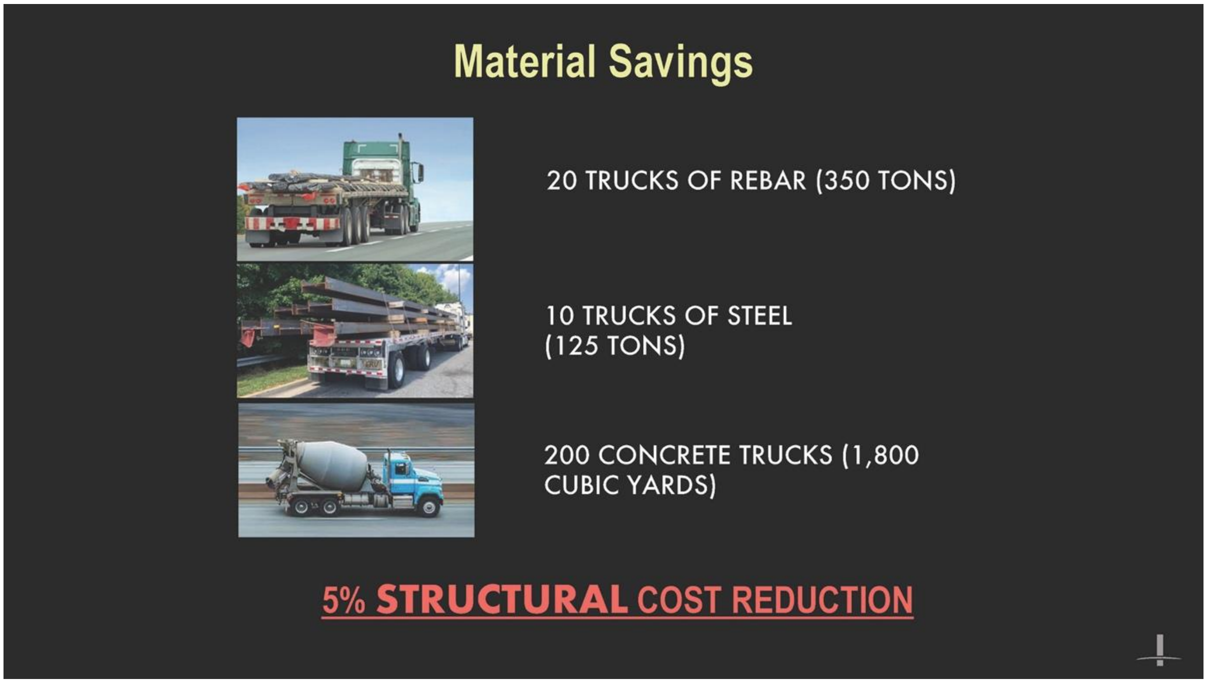


COUPLING BEAM ROTATION CYCLE COUNT EXAMPLES -- WIND ANGLE 110°
CONVENTIONAL COUPLING BEAM L36 N2



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.



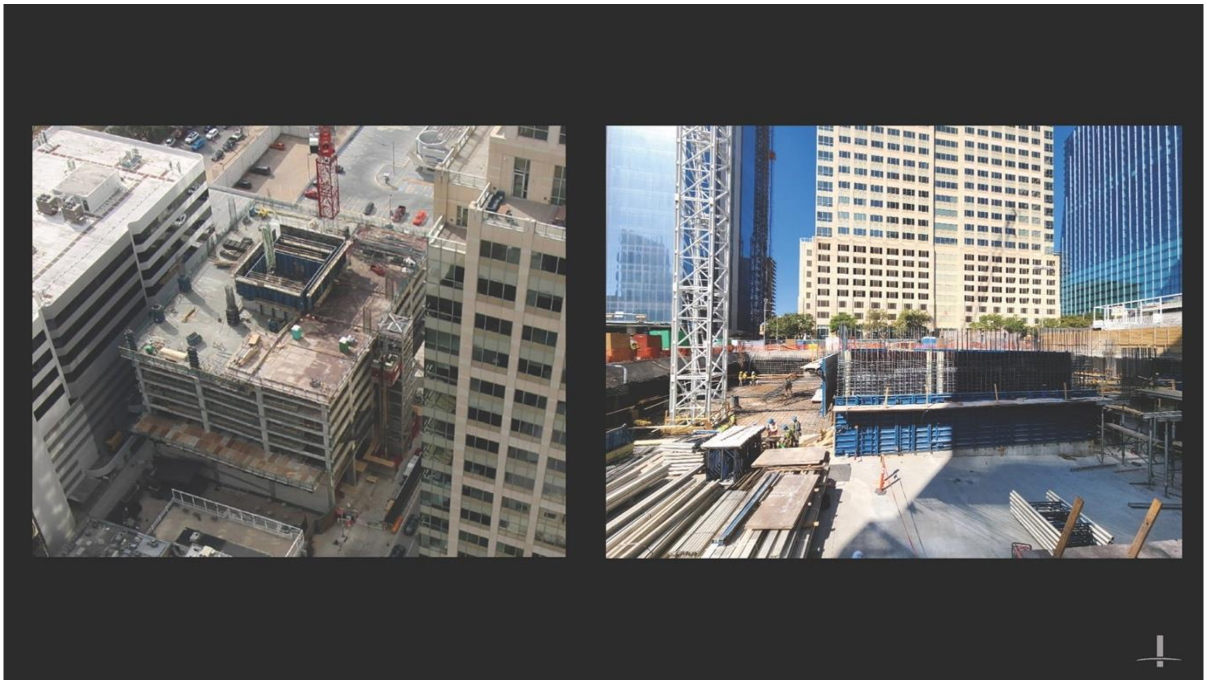
Material Savings

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

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Engineering News-Record

JUNE 27/JULY 4, 2022 • enr.com

INSIDE:
THE TOP
PROFESSIONAL
SERVICES FIRMS
(P. 53)

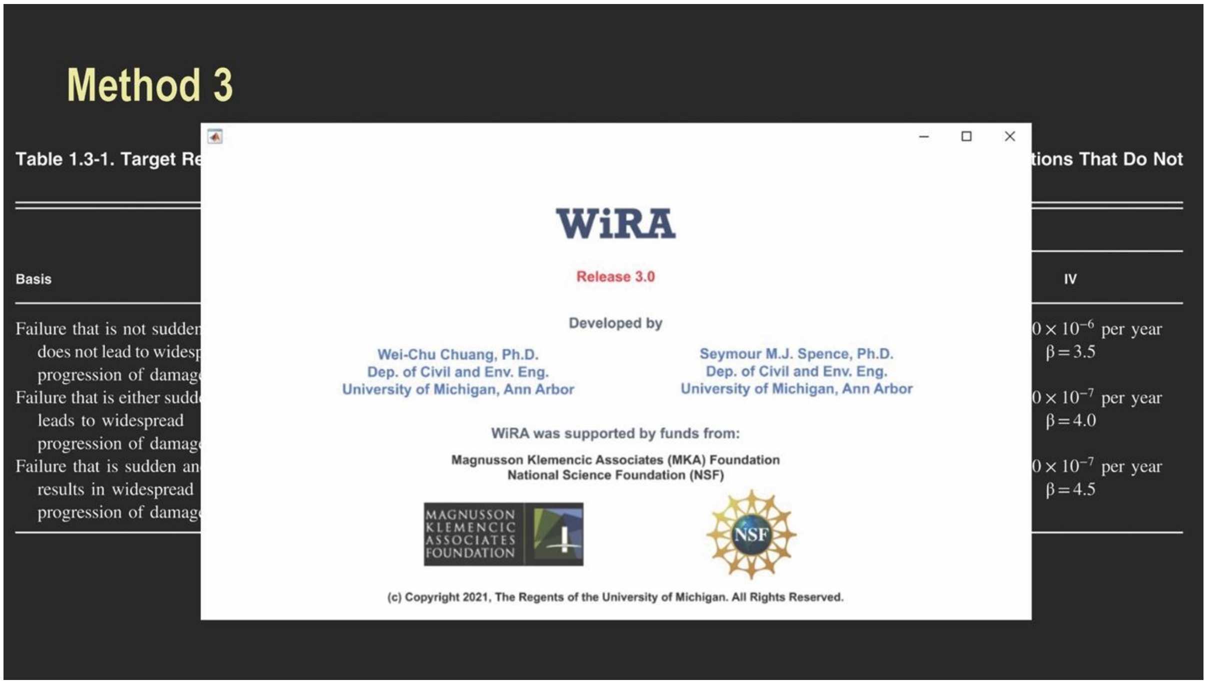
WIND SIMULATION FOR
321 WEST 6TH STREET
AUSTIN

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)

A bnp PUBLICATION



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 damage … 0 × 10⁻⁶ per year $\beta = 3.5$

Failure that is either sudd… leads to widespread progression of damag… 0 × 10⁻⁷ per year $\beta = 4.0$

Failure that is sudden an… results in widespread progression of damag… 0 × 10⁻⁷ per year $\beta = 4.5$

WiRA

Release 3.0

Developed by

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WiRA was supported by funds from:

Magnusson Klemencic Associates (MKA) Foundation
National Science Foundation (NSF)

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RESEARCH

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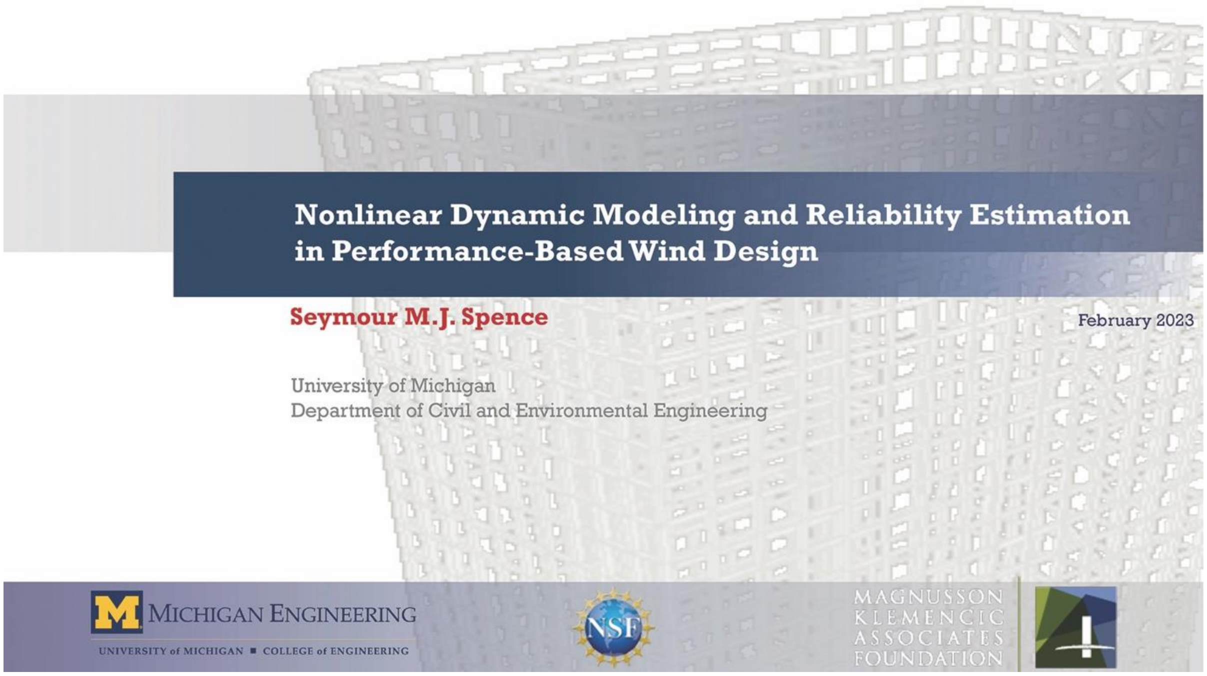
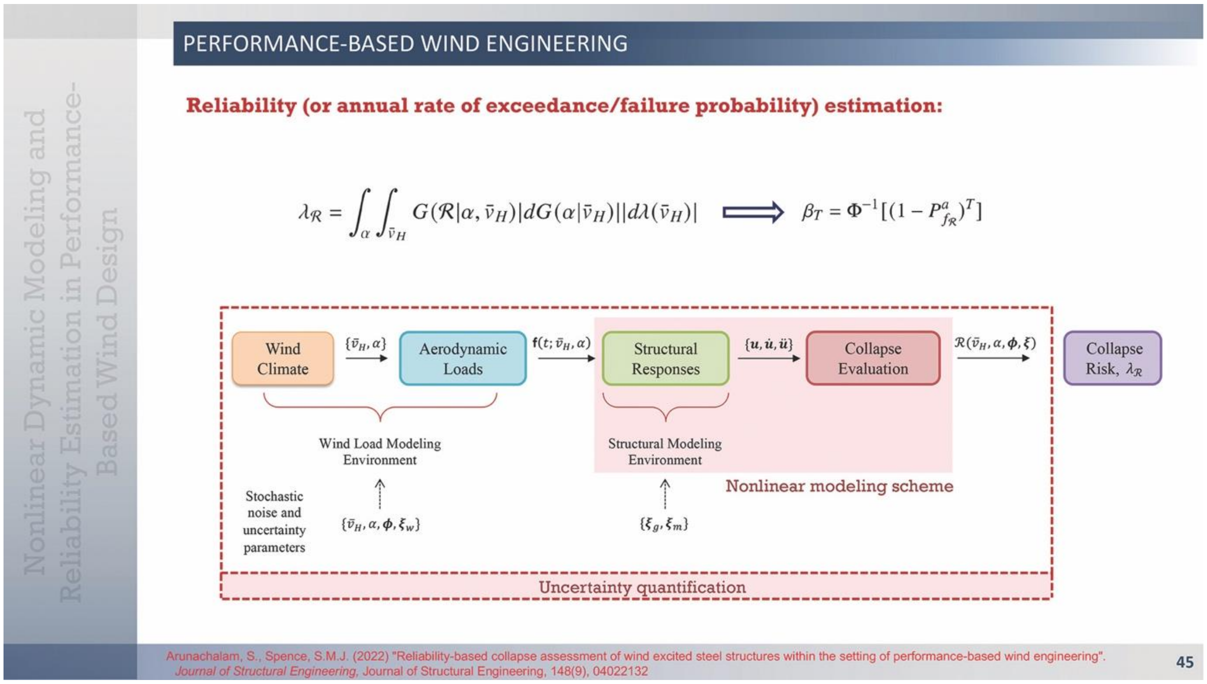


Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design

Seymour M.J. Spence

February 2023

University of Michigan
Department of Civil and Environmental Engineering



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

PERFORMANCE-BASED WIND ENGINEERING

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

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

Wind Climate $\xrightarrow{\{\bar{v}_H, \alpha\}}$ Aerodynamic Loads $\xrightarrow{\mathbf{f}(t; \bar{v}_H, \alpha)}$ Structural Responses $\xrightarrow{\{\boldsymbol{u}, \dot{\boldsymbol{u}}, \ddot{\boldsymbol{u}}\}}$ Collapse Evaluation $\xrightarrow{\mathcal{R}(\bar{v}_H, \alpha, \boldsymbol{\phi}, \boldsymbol{\xi})}$ Collapse Risk, $\lambda_{\mathcal{R}}$

Wind Load Modeling Environment

Structural Modeling Environment

Nonlinear modeling scheme

Stochastic noise and uncertainty parameters

$\{\bar{v}_H, \alpha, \boldsymbol{\phi}, \boldsymbol{\xi}_w\}$

$\{\boldsymbol{\xi}_g, \boldsymbol{\xi}_m\}$

Uncertainty quantification

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

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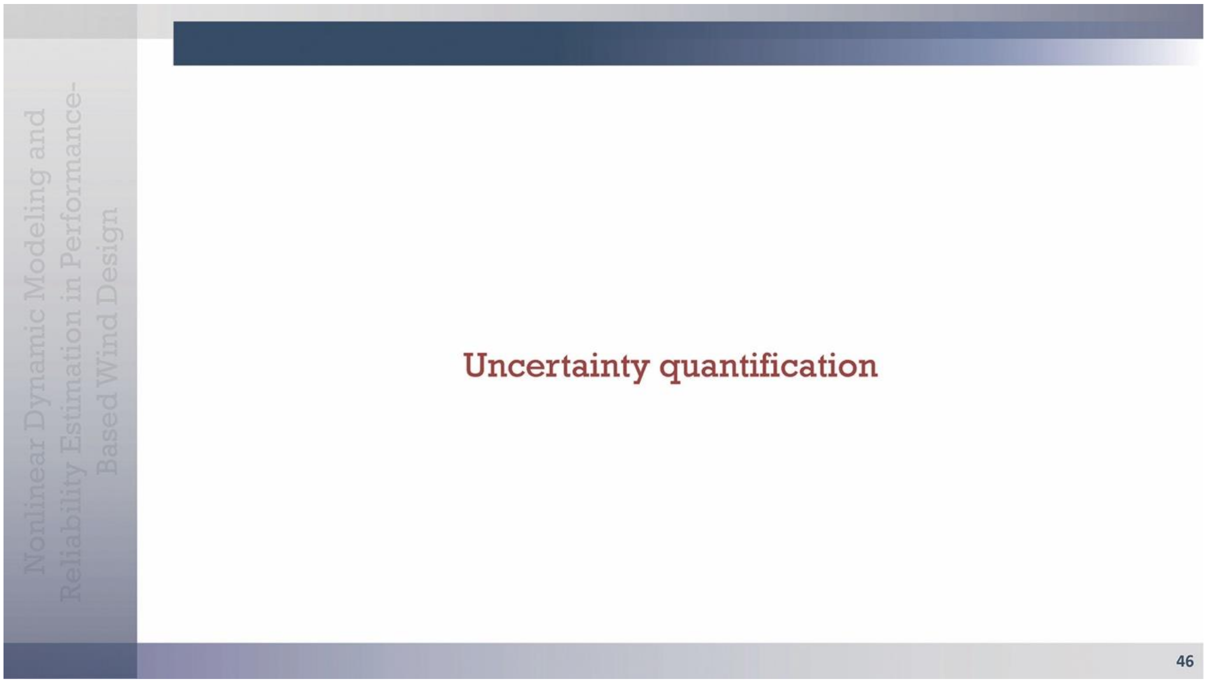

Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design

Uncertainty quantification

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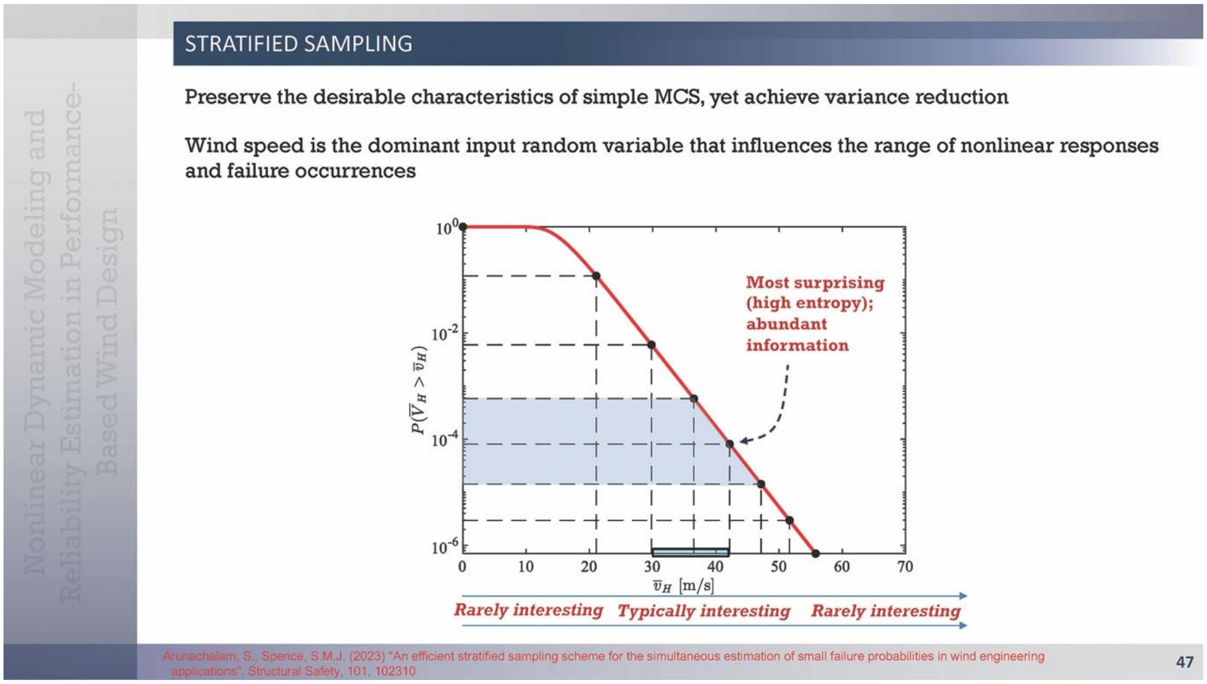


Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design

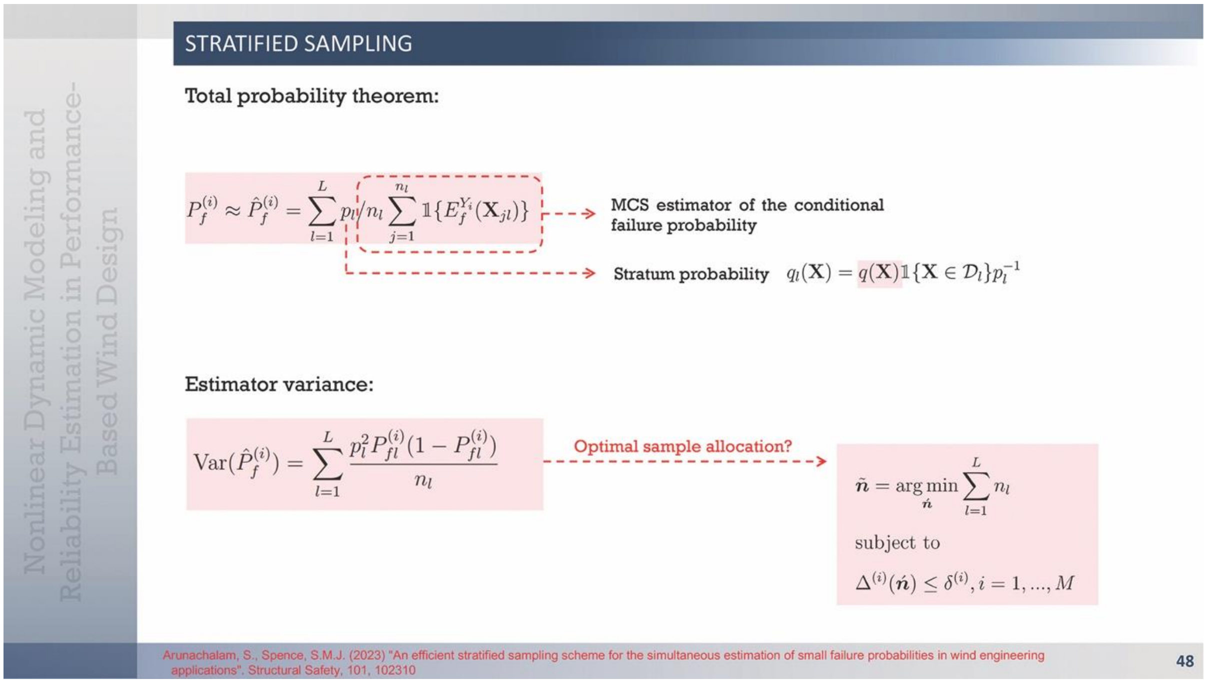
STRATIFIED SAMPLING

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

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



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

STRATIFIED SAMPLING

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

$$\Delta^{(i)}(\acute{\boldsymbol{n}}) \leq \delta^{(i)}, i = 1, ..., M$$

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

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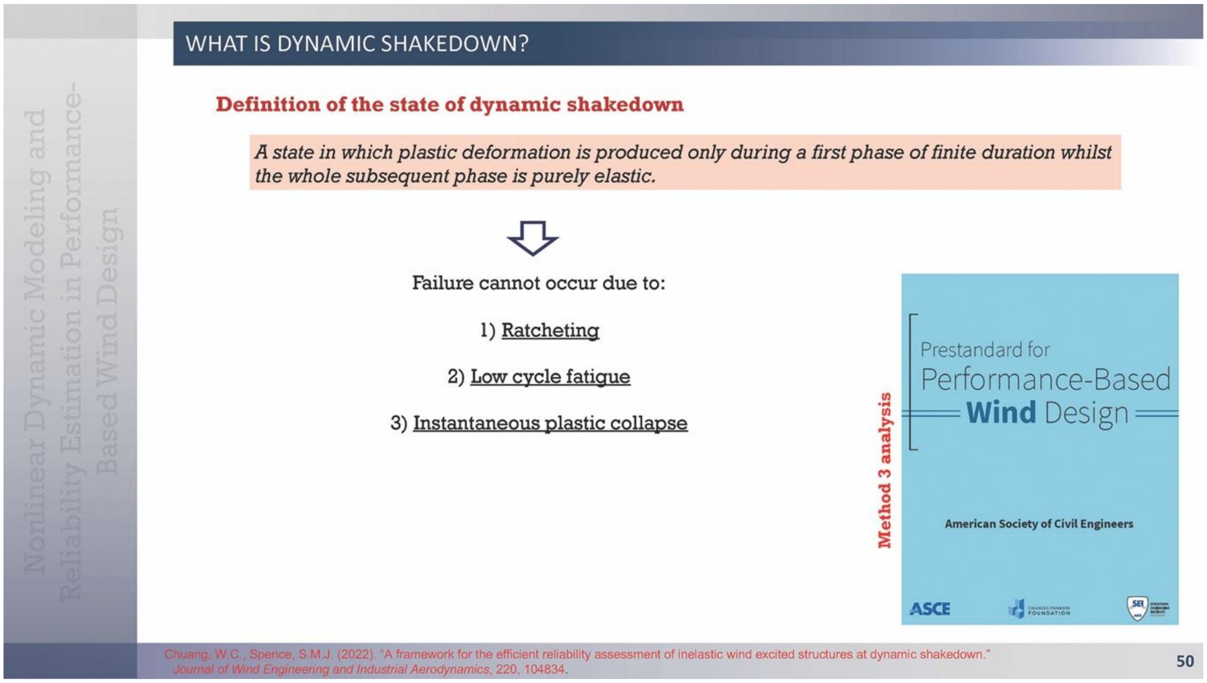
Nonlinear modeling scheme: Dynamic shakedown



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:

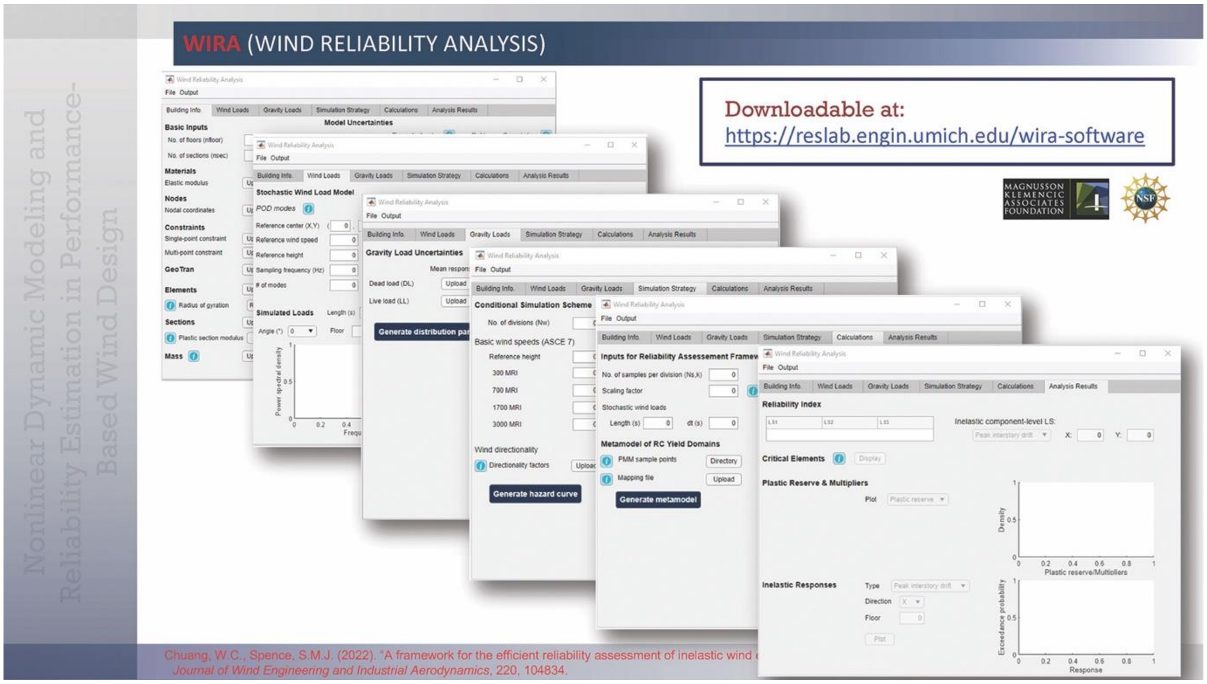
1) Ratcheting

2) Low cycle fatigue

3) Instantaneous plastic collapse

Method 3 analysis

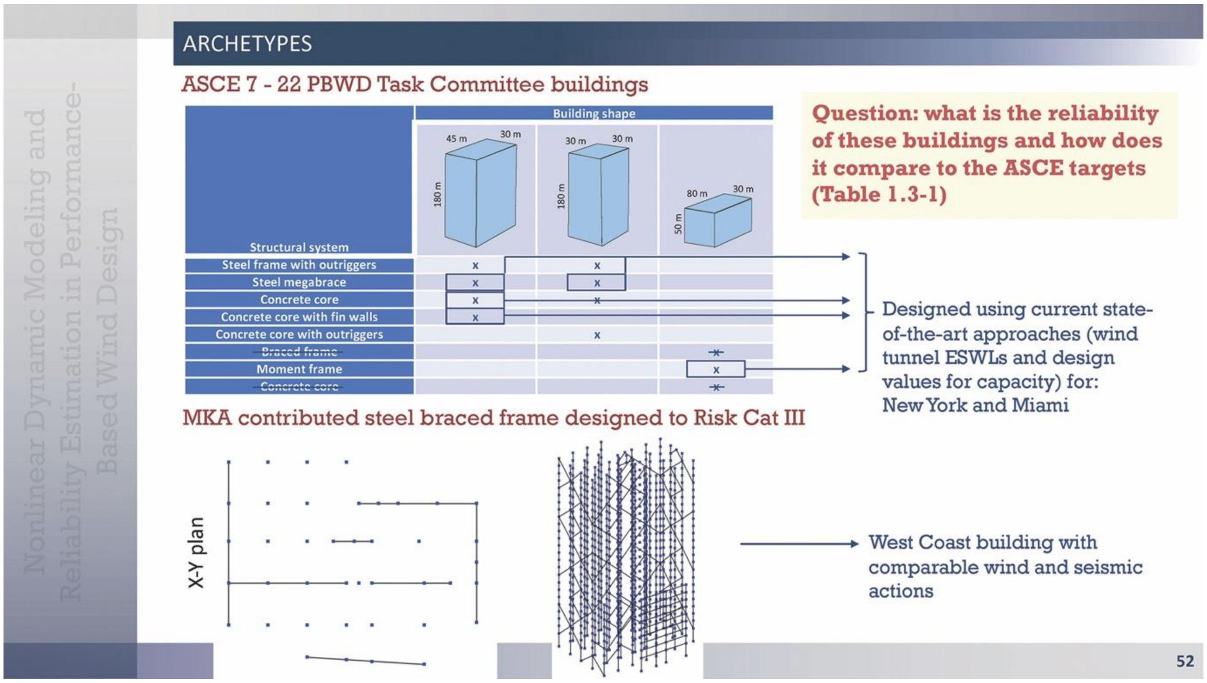
Chuang, W.C., Spence, S.M.J. (2022). "A framework for the efficient reliability assessment of inelastic wind excited structures at dynamic shakedown." *Journal of Wind Engineering and Industrial Aerodynamics*, 220, 104834.



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.



ARCHETYPES

ASCE 7 - 22 PBWD Task Committee buildings

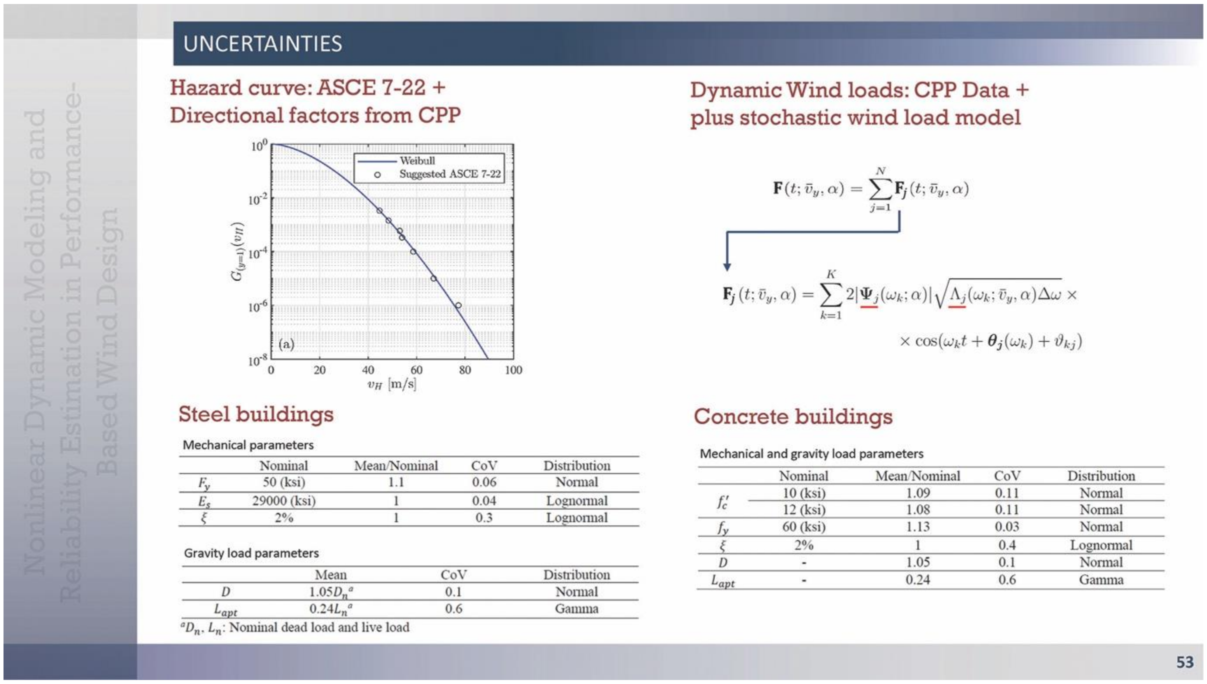
Structural system	Building shape		
	45 m × 30 m × 180 m	30 m × 30 m × 180 m	80 m × 30 m × 50 m
Steel frame with outriggers	x	x	
Steel megabrace	x	x	
Concrete core	x	~~x~~	
Concrete core with fin walls	x		
Concrete core with outriggers		x	
~~Braced frame~~			~~x~~
Moment frame			x
~~Concrete core~~			~~x~~

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

West Coast building with comparable wind and seismic actions



UNCERTAINTIES

Hazard curve: ASCE 7-22 + Directional factors from CPP

Dynamic Wind loads: CPP Data + plus stochastic wind load model

$$\mathbf{F}(t;\bar{v}_y,\alpha)=\sum_{j=1}^{N}\mathbf{F}_j(t;\bar{v}_y,\alpha)$$

$$\mathbf{F}_j(t;\bar{v}_y,\alpha)=\sum_{k=1}^{K}2|\underline{\boldsymbol{\Psi}_j}(\omega_k;\alpha)|\sqrt{\underline{\Lambda_j}(\omega_k;\bar{v}_y,\alpha)\Delta\omega}\times$$
$$\times\cos(\omega_k t+\boldsymbol{\theta_j}(\omega_k)+\vartheta_{kj})$$

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

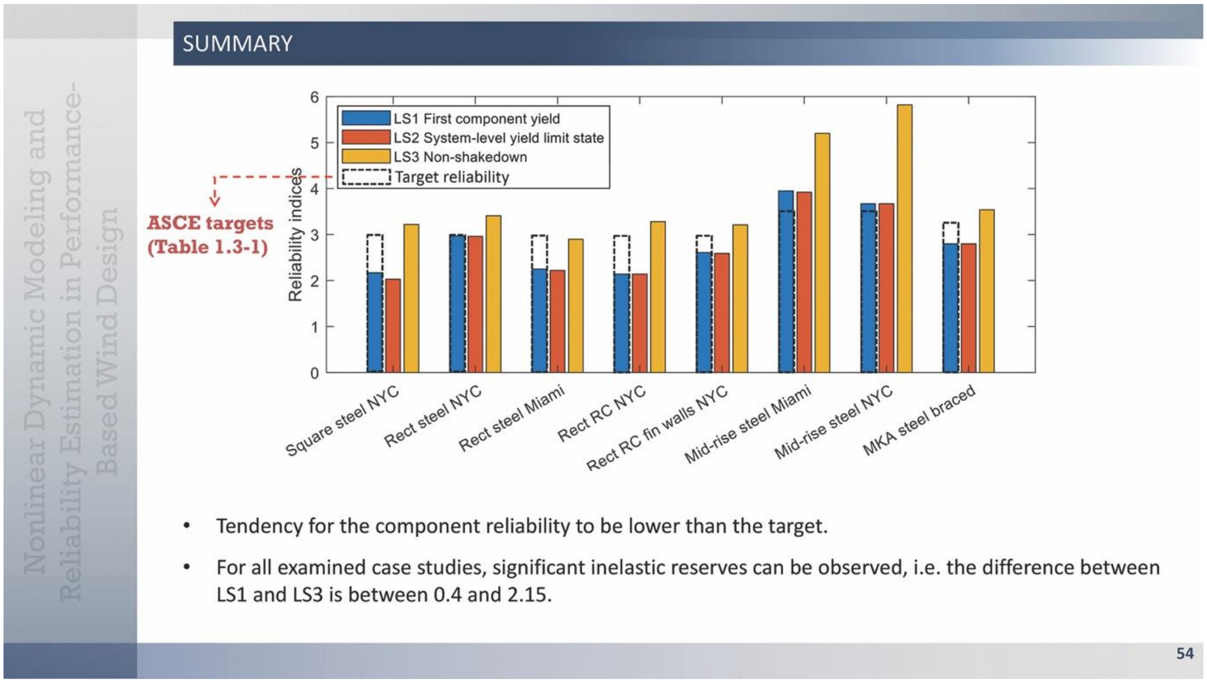
	Mean	CoV	Distribution
D	$1.05D_n{}^a$	0.1	Normal
L_{apt}	$0.24L_n{}^a$	0.6	Gamma

[a] D_n, L_n: Nominal dead load and live load

Concrete buildings

Mechanical and gravity load parameters

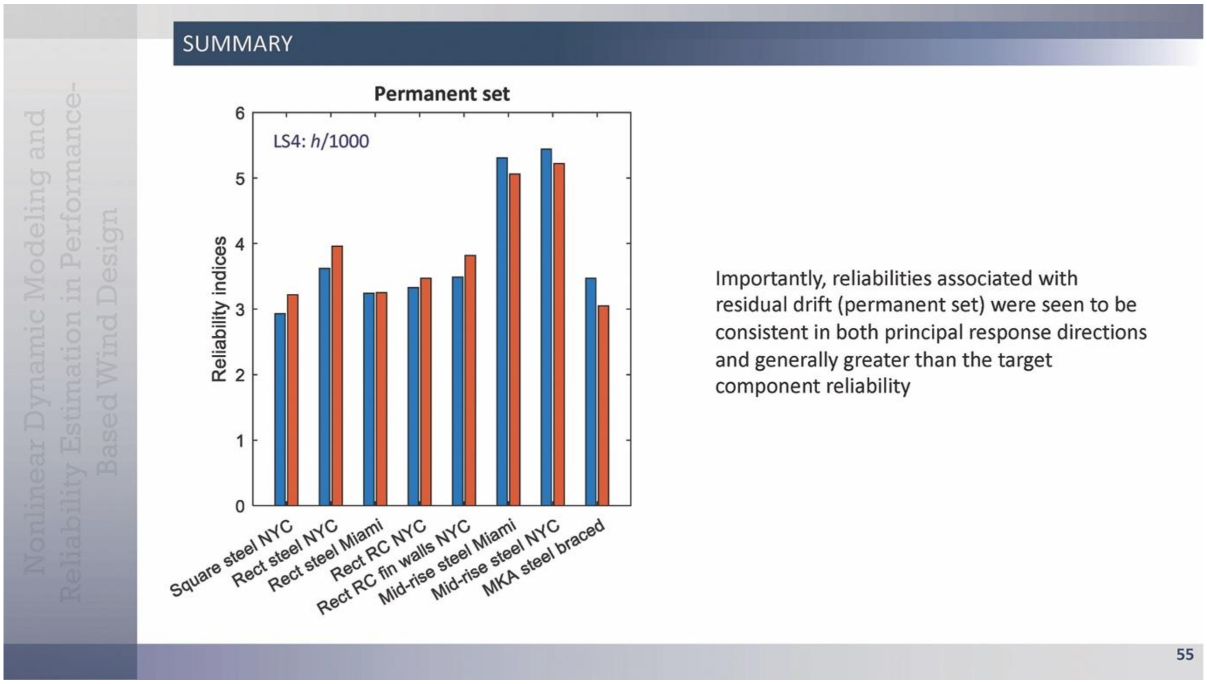
	Nominal	Mean/Nominal	CoV	Distribution
f_c'	10 (ksi)	1.09	0.11	Normal
	12 (ksi)	1.08	0.11	Normal
f_y	60 (ksi)	1.13	0.03	Normal
ξ	2%	1	0.4	Lognormal
D	-	1.05	0.1	Normal
L_{apt}	-	0.24	0.6	Gamma



SUMMARY

ASCE targets (Table 1.3-1)

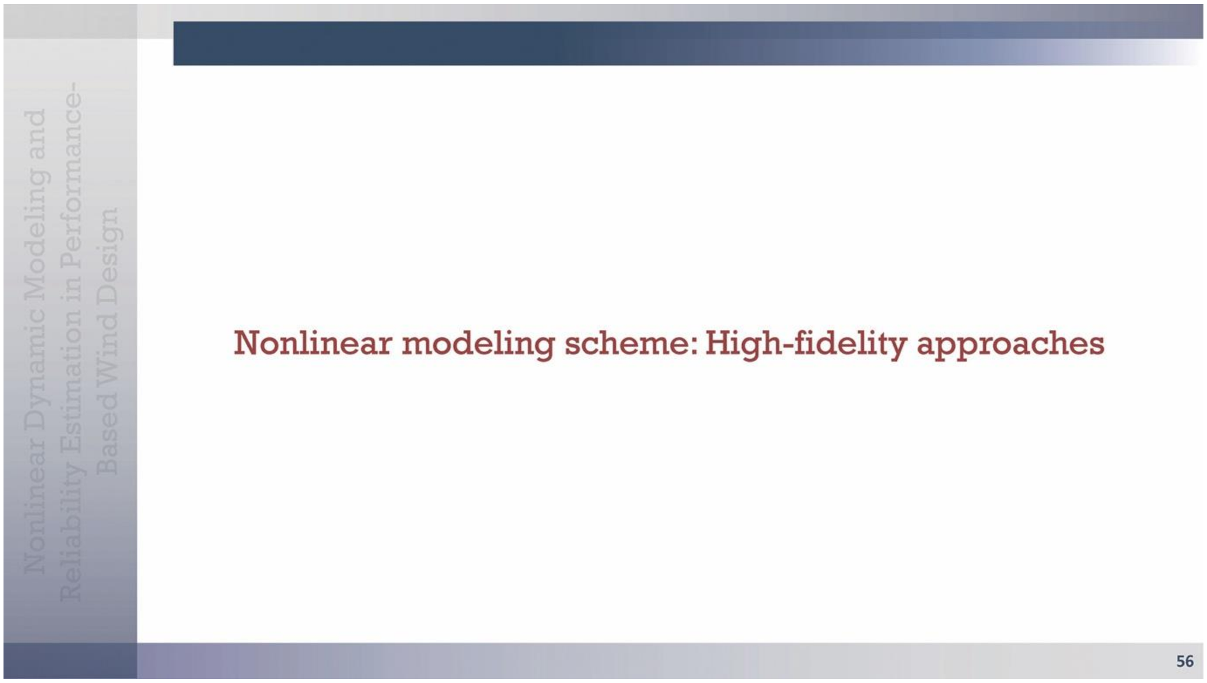
- Tendency for the component reliability to be lower than the target.
- For all examined case studies, significant inelastic reserves can be observed, i.e. the difference between LS1 and LS3 is between 0.4 and 2.15.



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

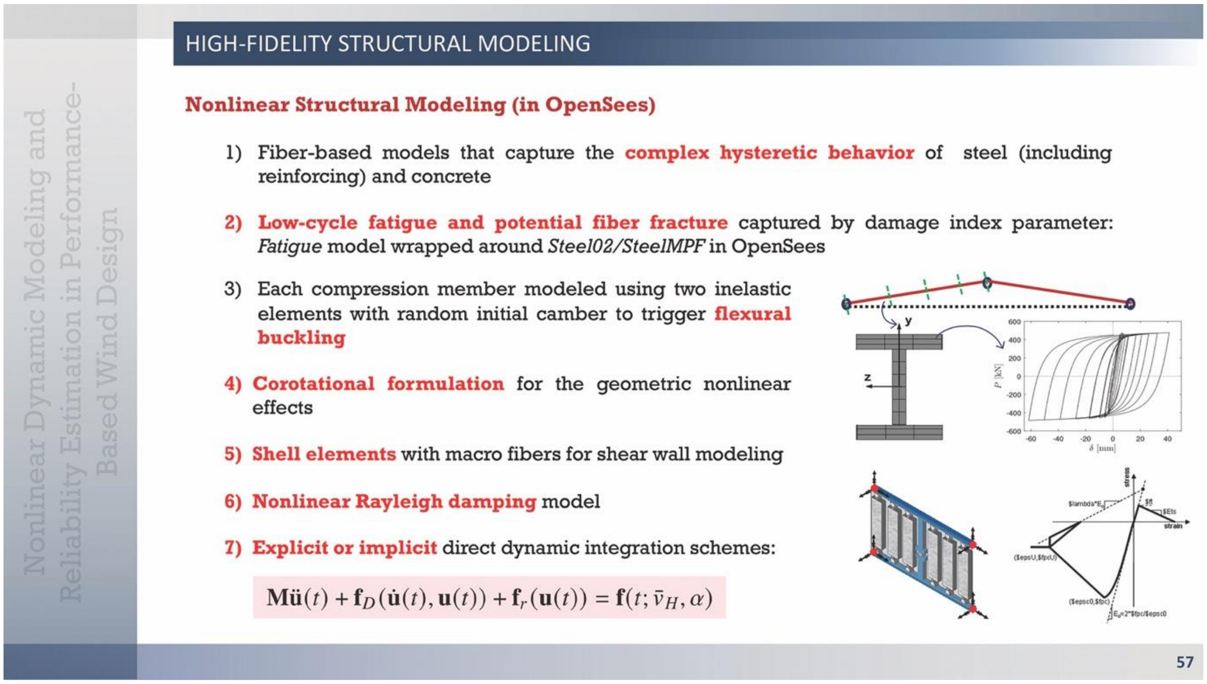
SUMMARY

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



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

Nonlinear modeling scheme: High-fidelity approaches

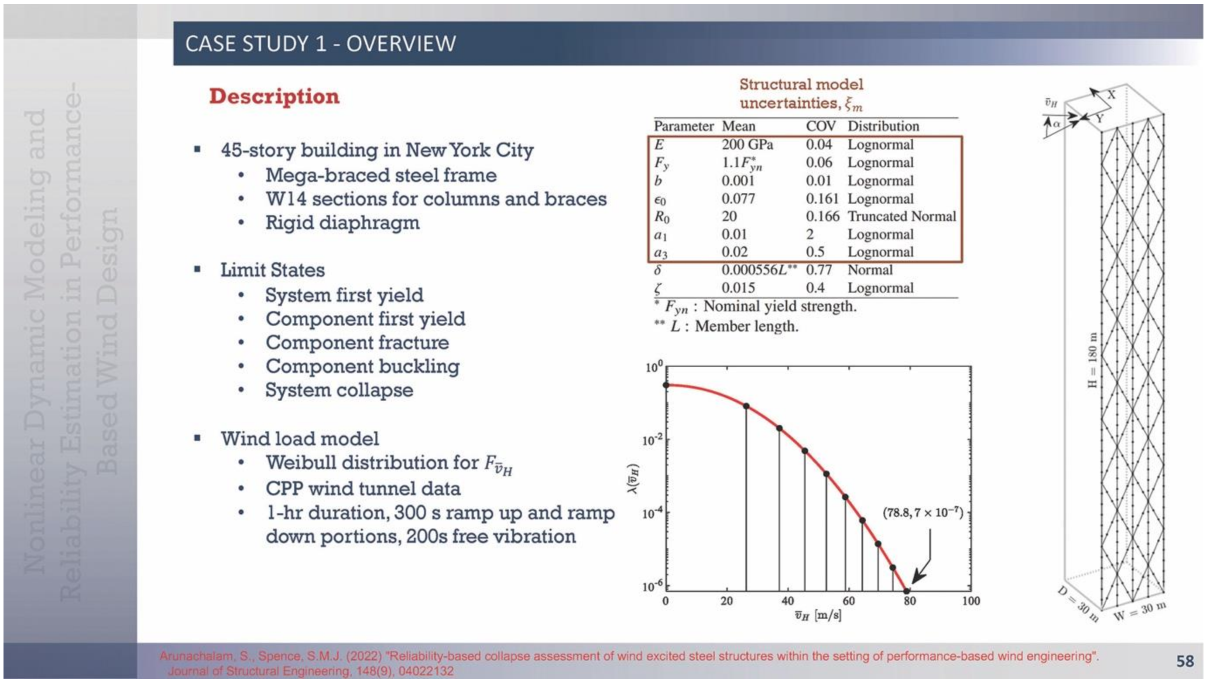


HIGH-FIDELITY STRUCTURAL MODELING

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:

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



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

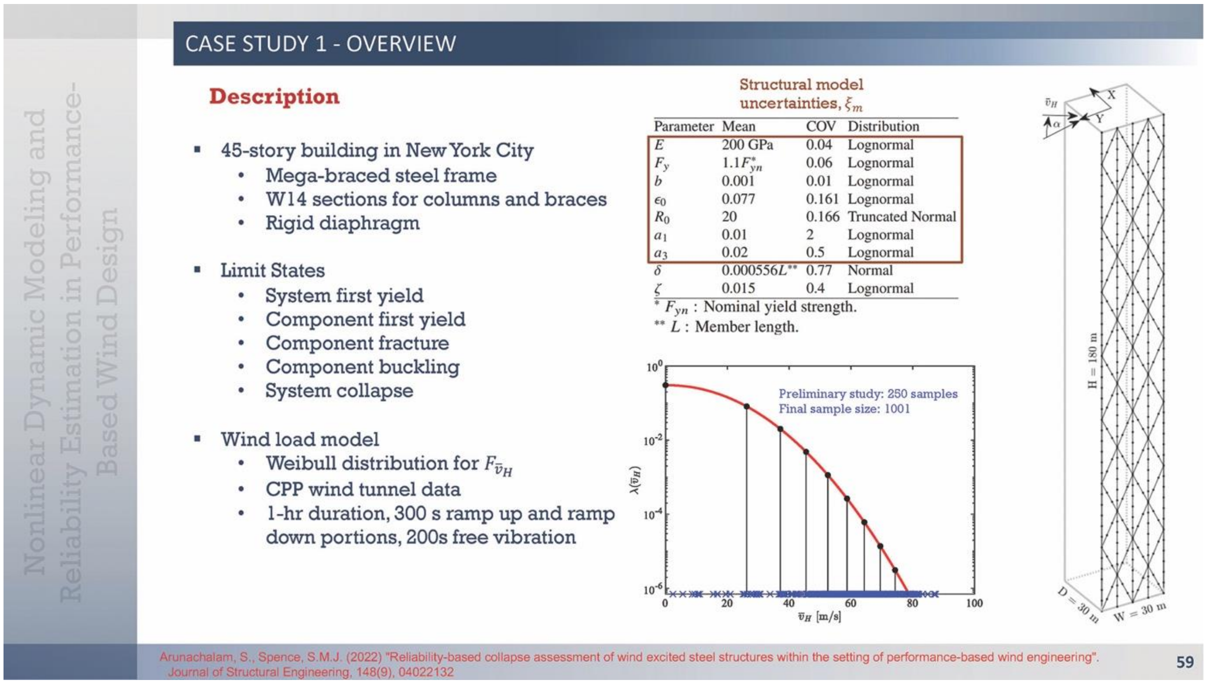
Structural model uncertainties, ξ_m

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



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R_0	20	0.166	Truncated Normal
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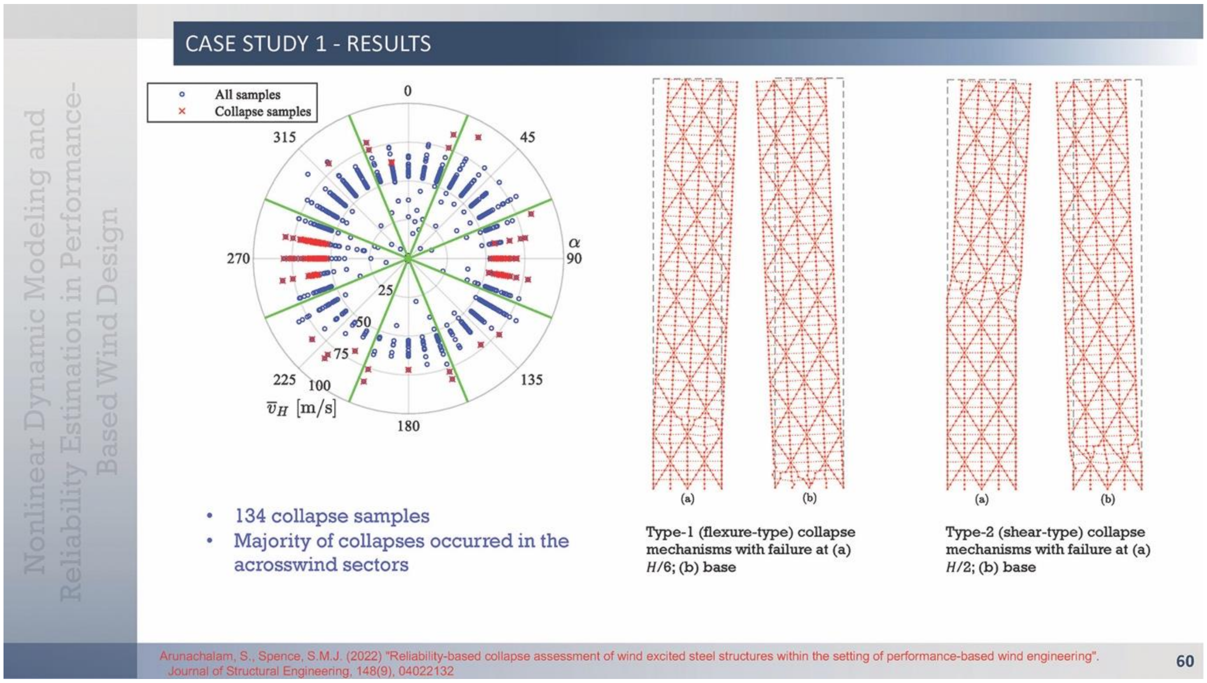


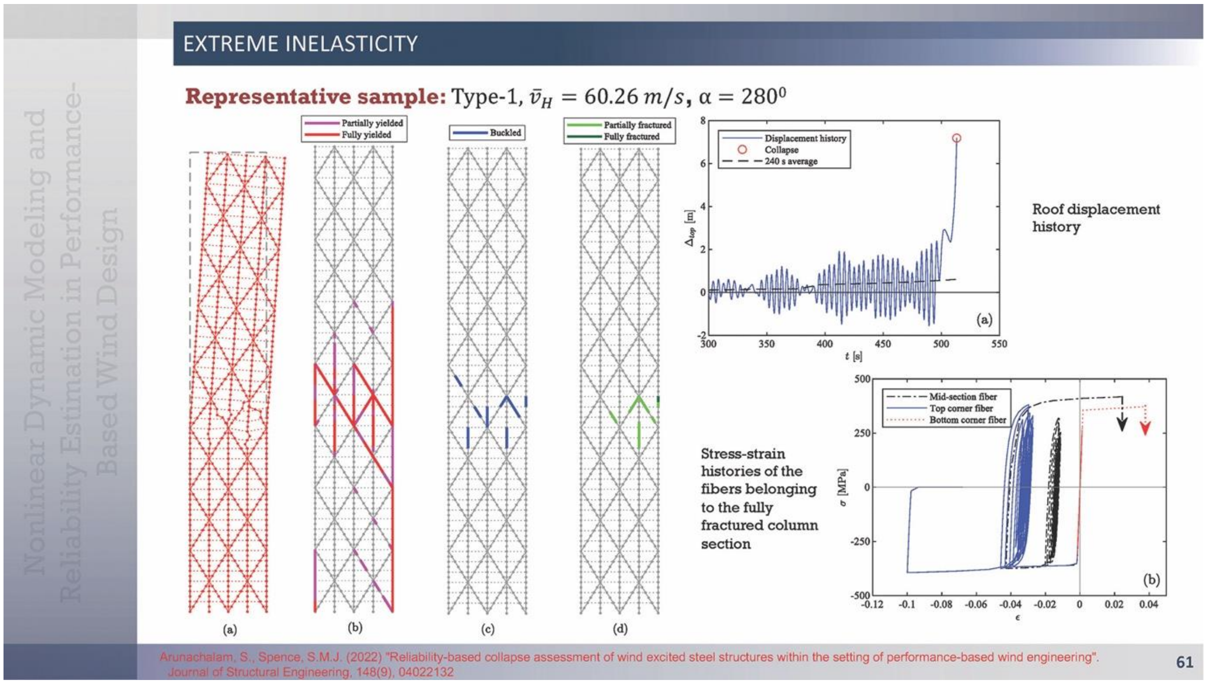
CASE STUDY 1 - RESULTS

- 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



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

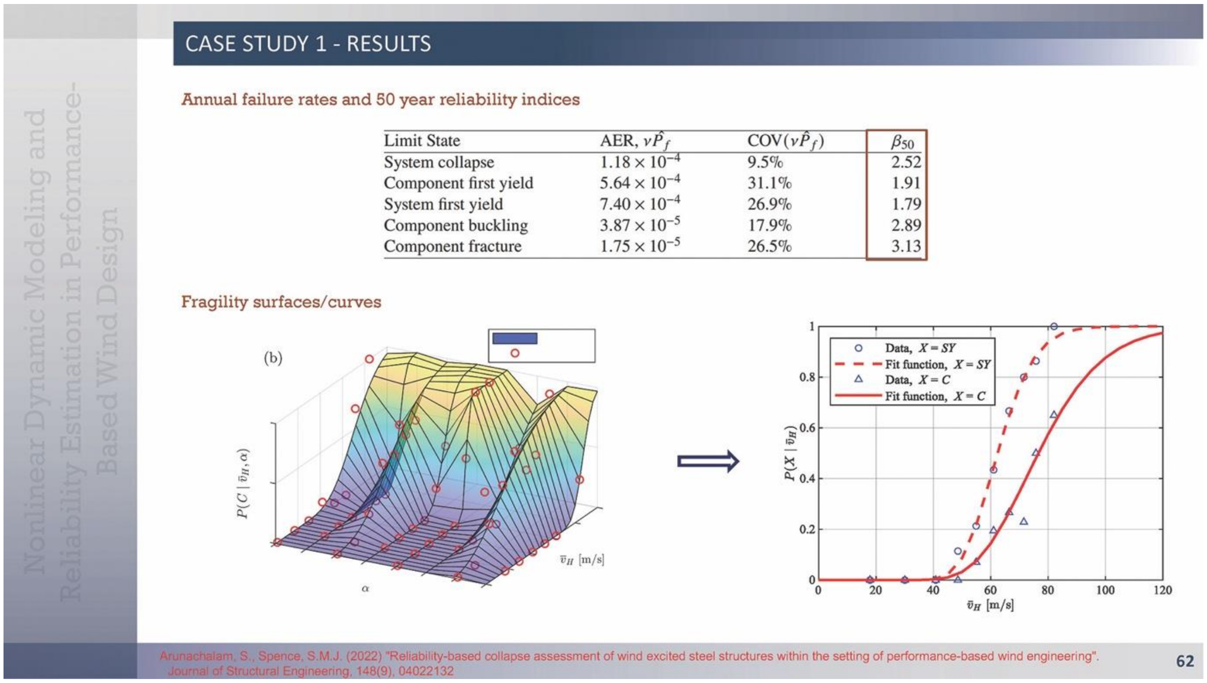
EXTREME INELASTICITY

Representative sample: Type-1, $\bar{v}_H = 60.26\ m/s$, $\alpha = 280^0$

Roof displacement history

Stress-strain histories of the fibers belonging to the fully fractured column section

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



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

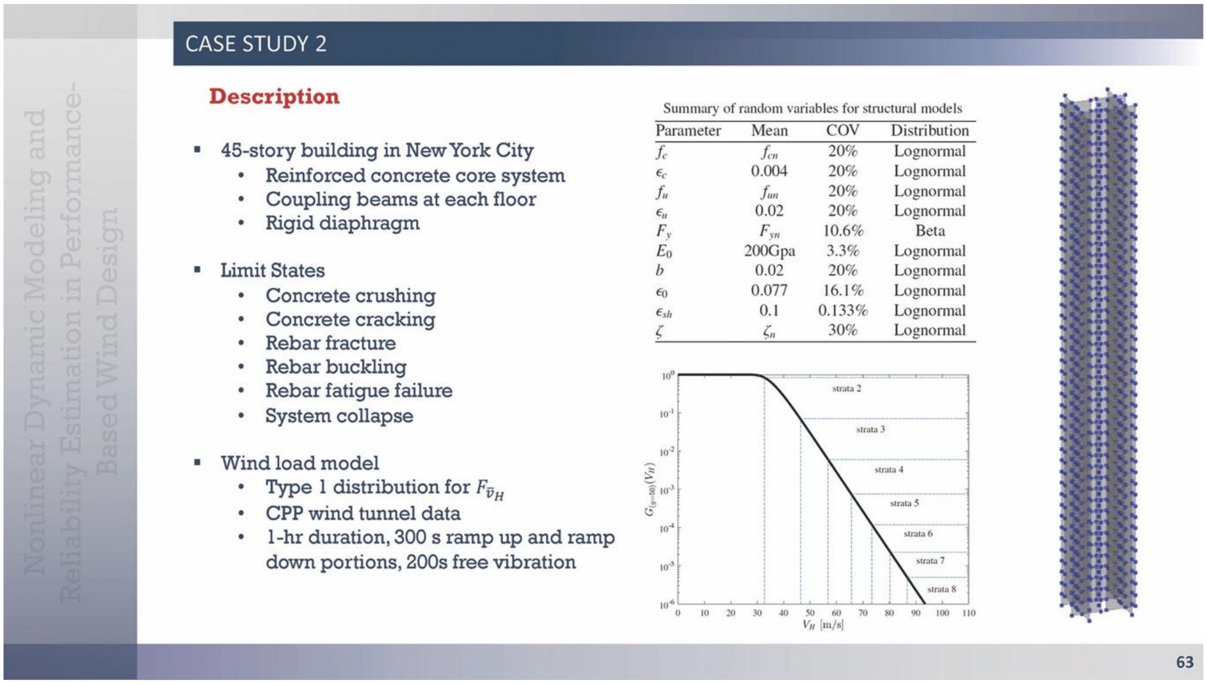
CASE STUDY 1 - RESULTS

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



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

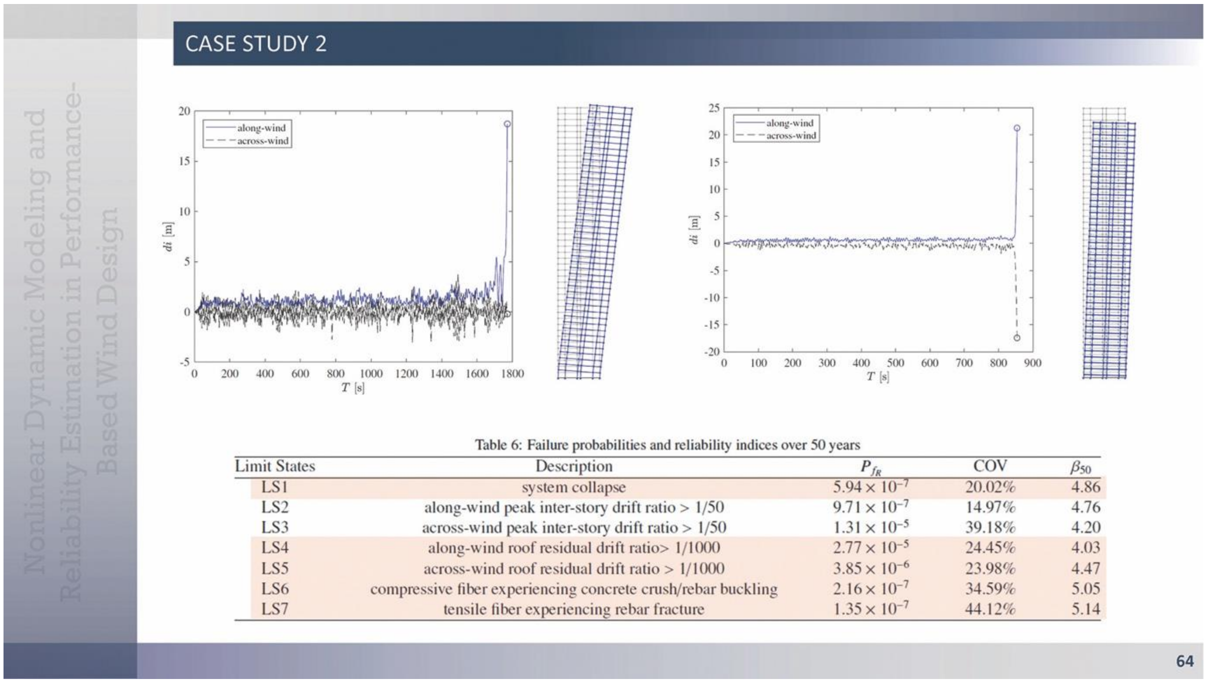
CASE STUDY 2

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

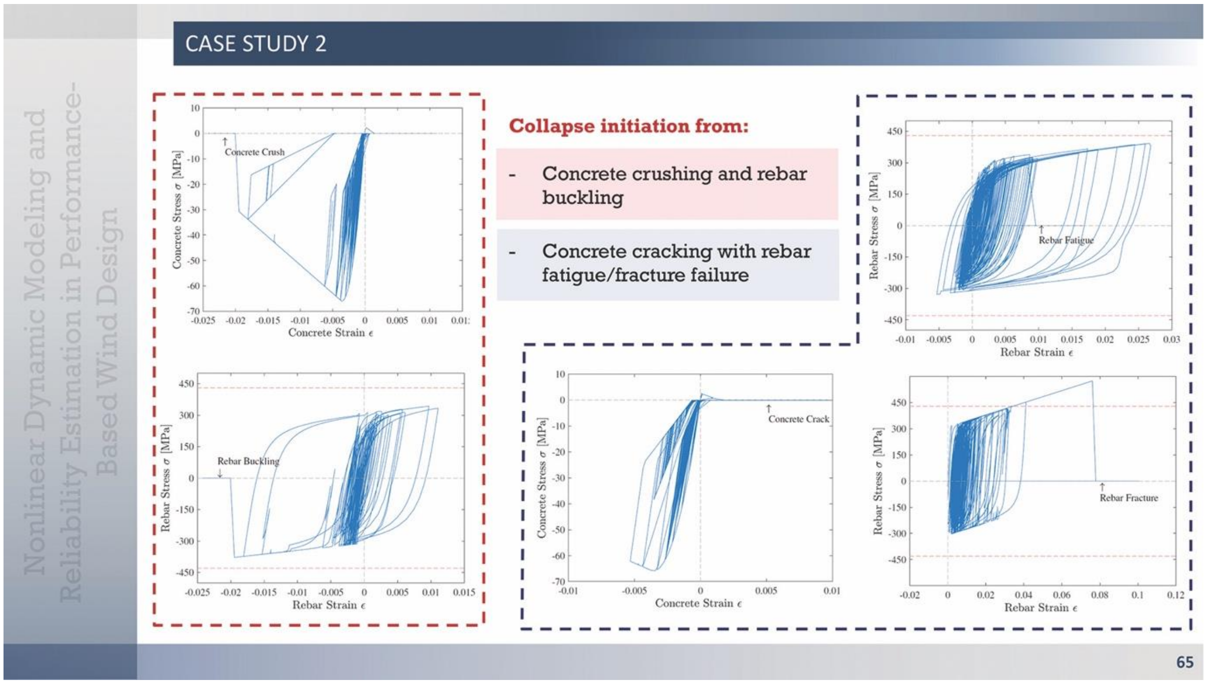


Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design

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



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

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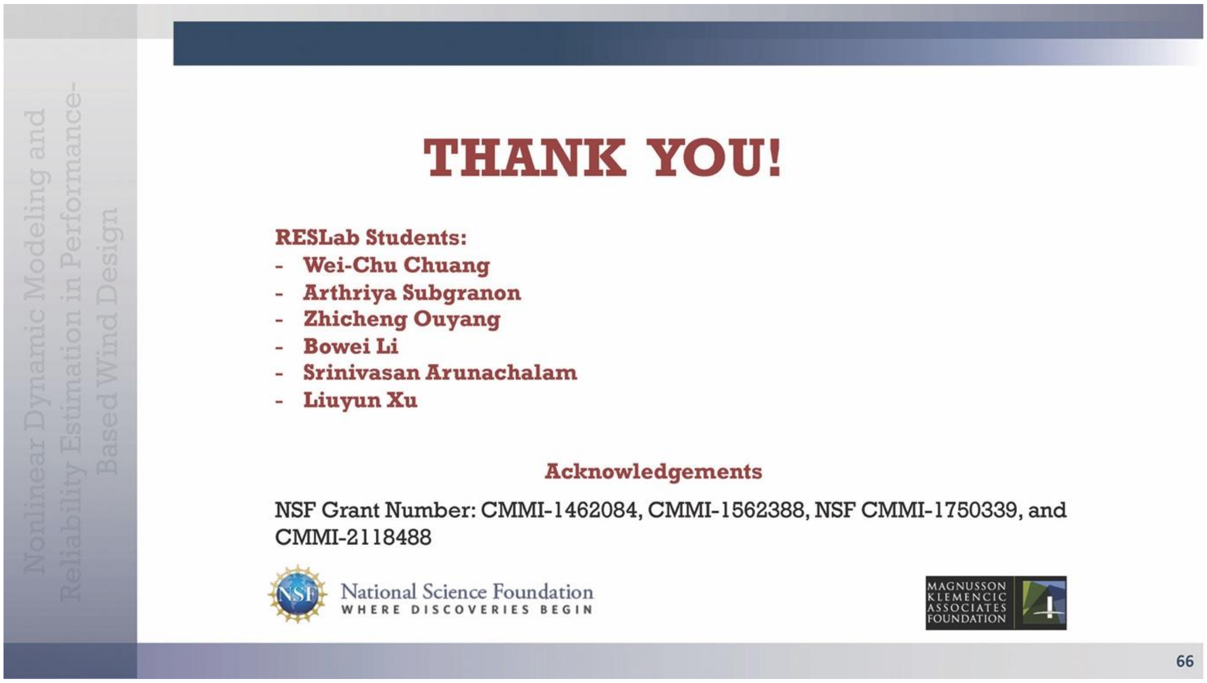

Nonlinear Dynamic Modeling and Reliability Estimation in Performance-Based Wind Design

THANK YOU!

RESLab Students:

- **Wei-Chu Chuang**
- **Arthriya Subgranon**
- **Zhicheng Ouyang**
- **Bowei Li**
- **Srinivasan Arunachalam**
- **Liuyun Xu**

Acknowledgements

NSF Grant Number: CMMI-1462084, CMMI-1562388, NSF CMMI-1750339, and CMMI-2118488

National Science Foundation
WHERE DISCOVERIES BEGIN

MAGNUSSON KLEMENCIC ASSOCIATES FOUNDATION

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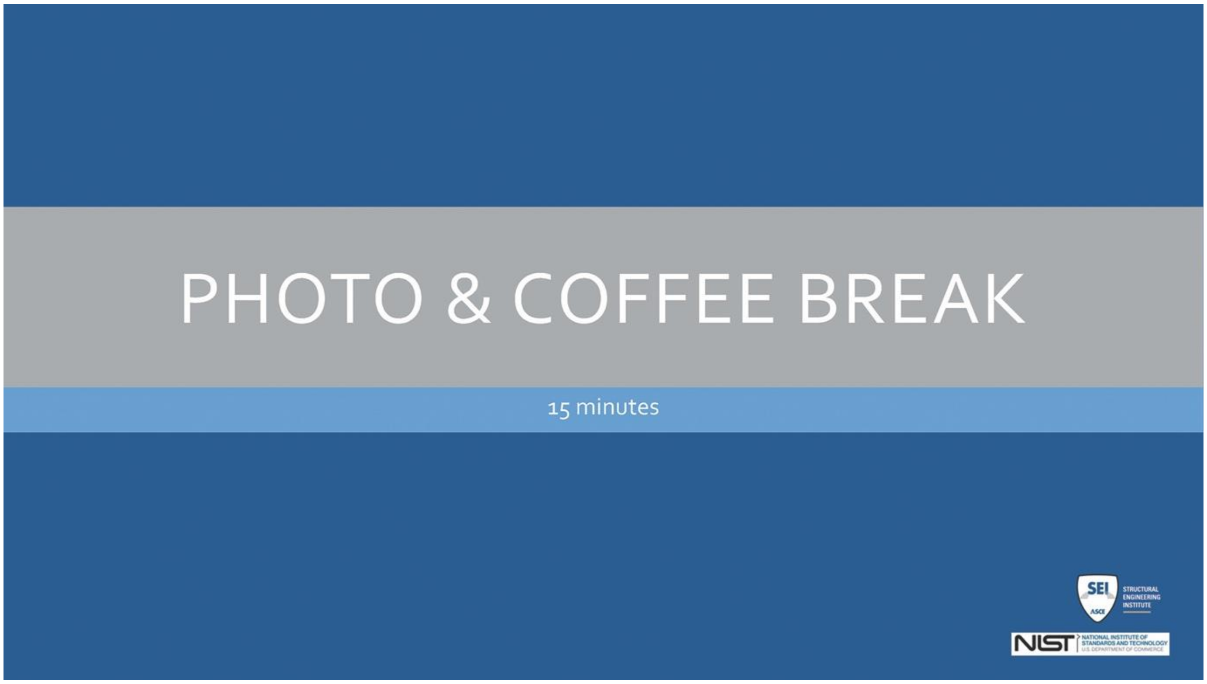
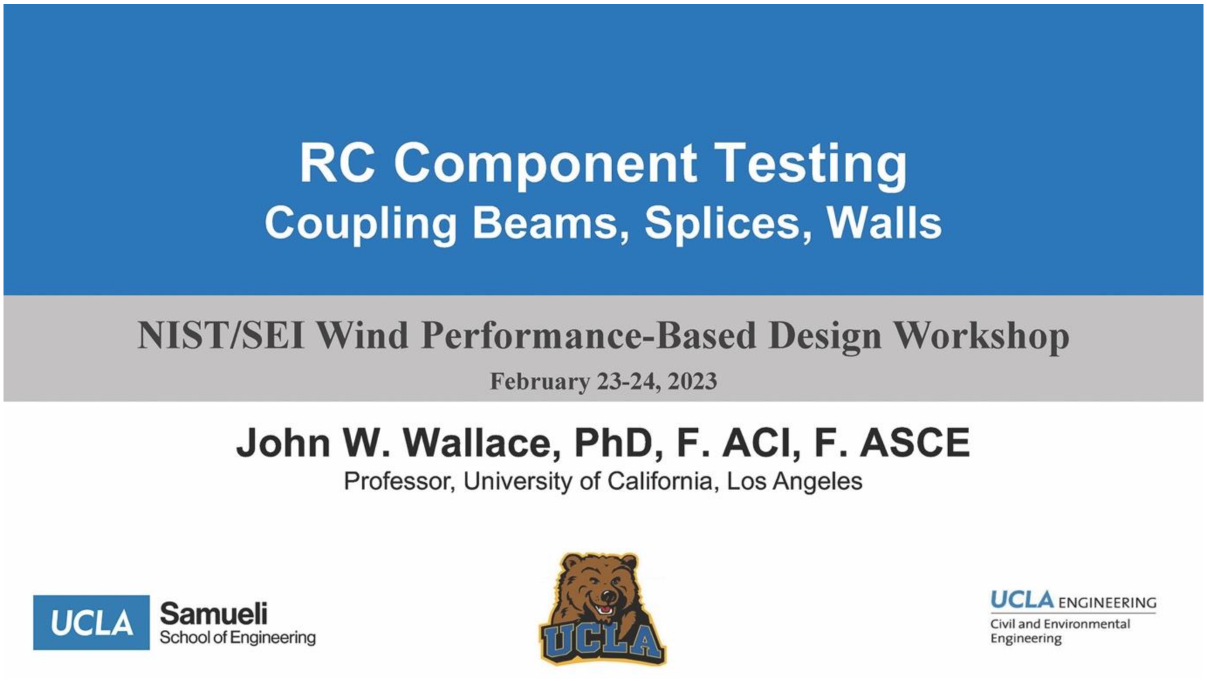


PHOTO & COFFEE BREAK

15 minutes



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

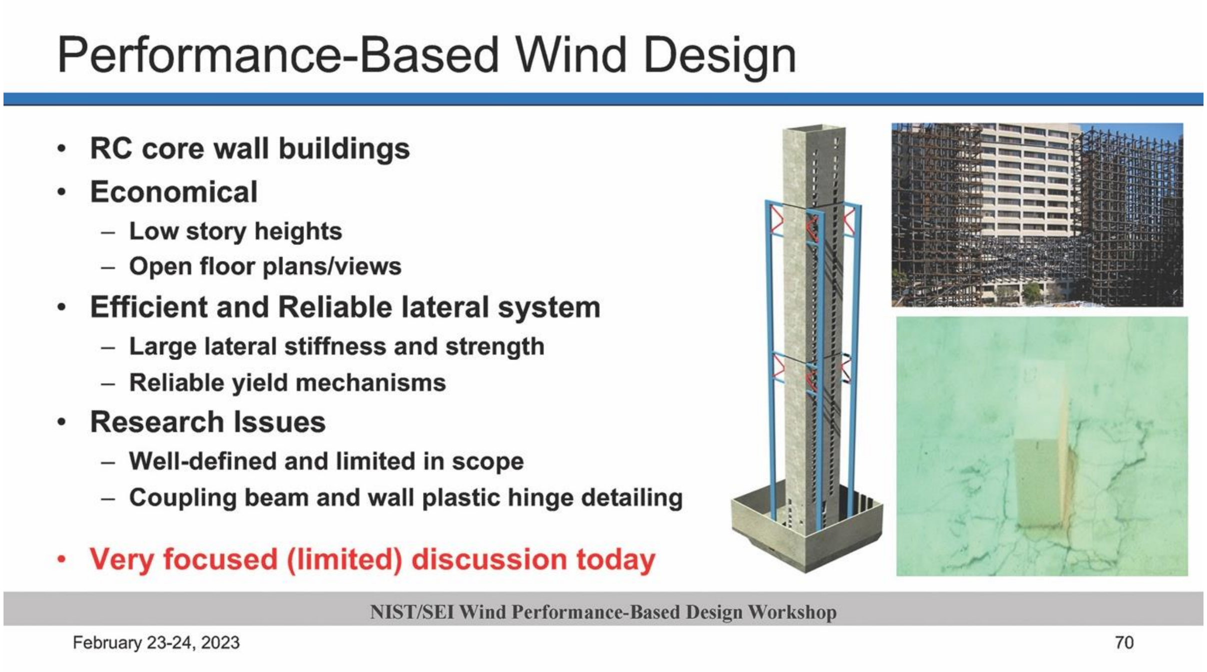
M. Emre Ünal, UCLA

Saman Abdullah, UCLA

Kristijan Kolozvari, CSU Fullerton

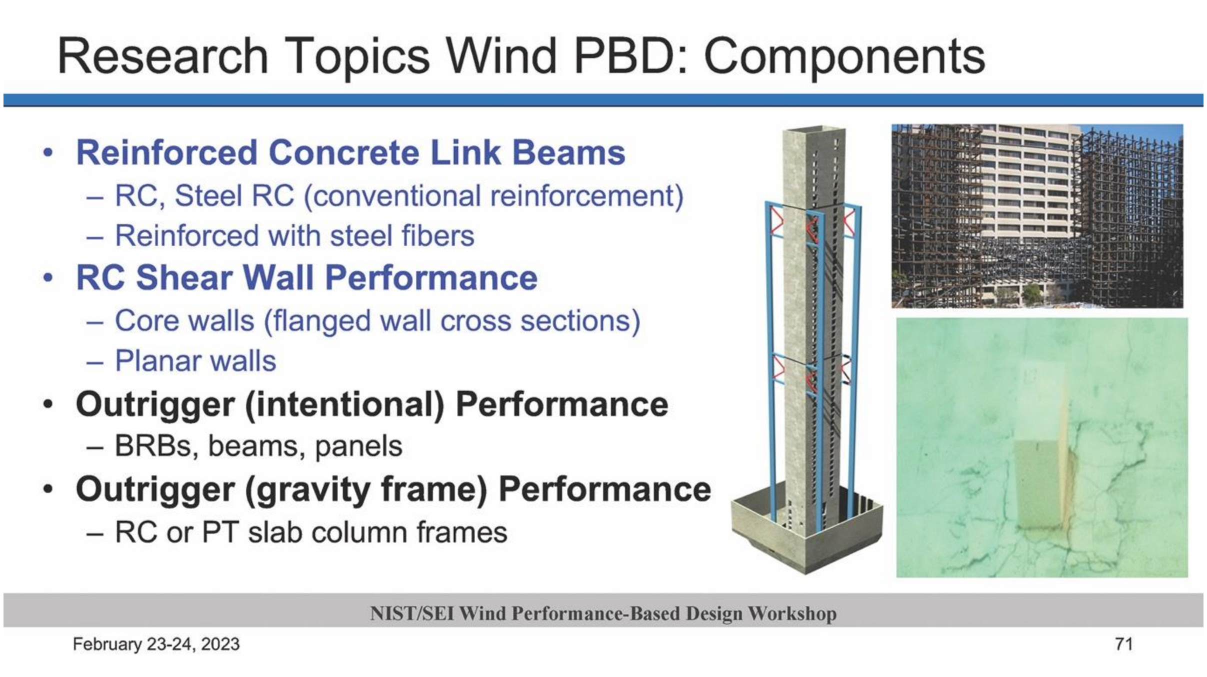
Sunai Kim, CP Pomona

Chris Motter, WSU



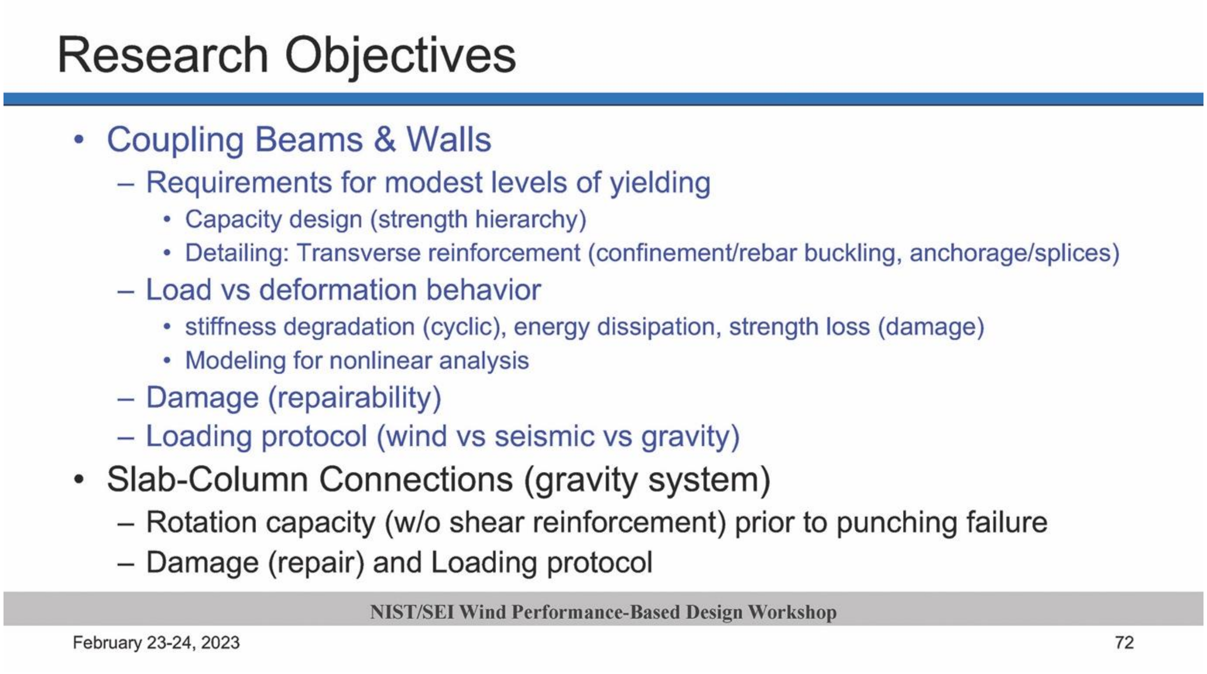
Performance-Based Wind Design

- **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**



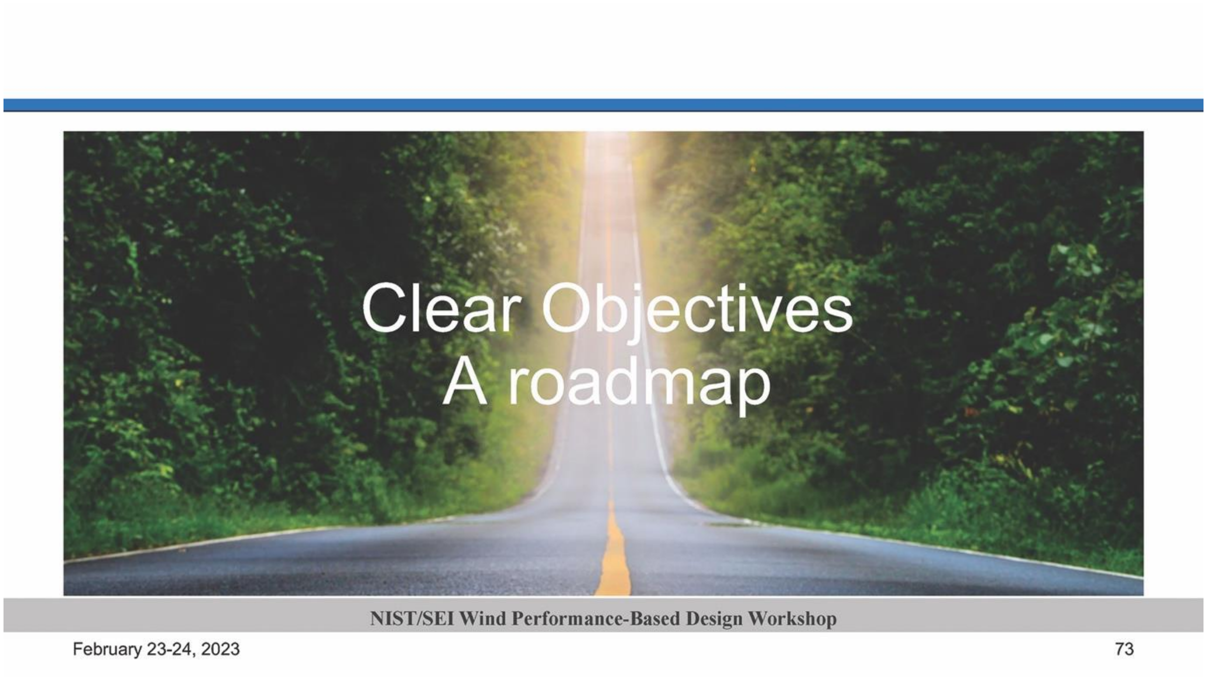
Research Topics Wind PBD: Components

- **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



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



Clear Objectives
A roadmap

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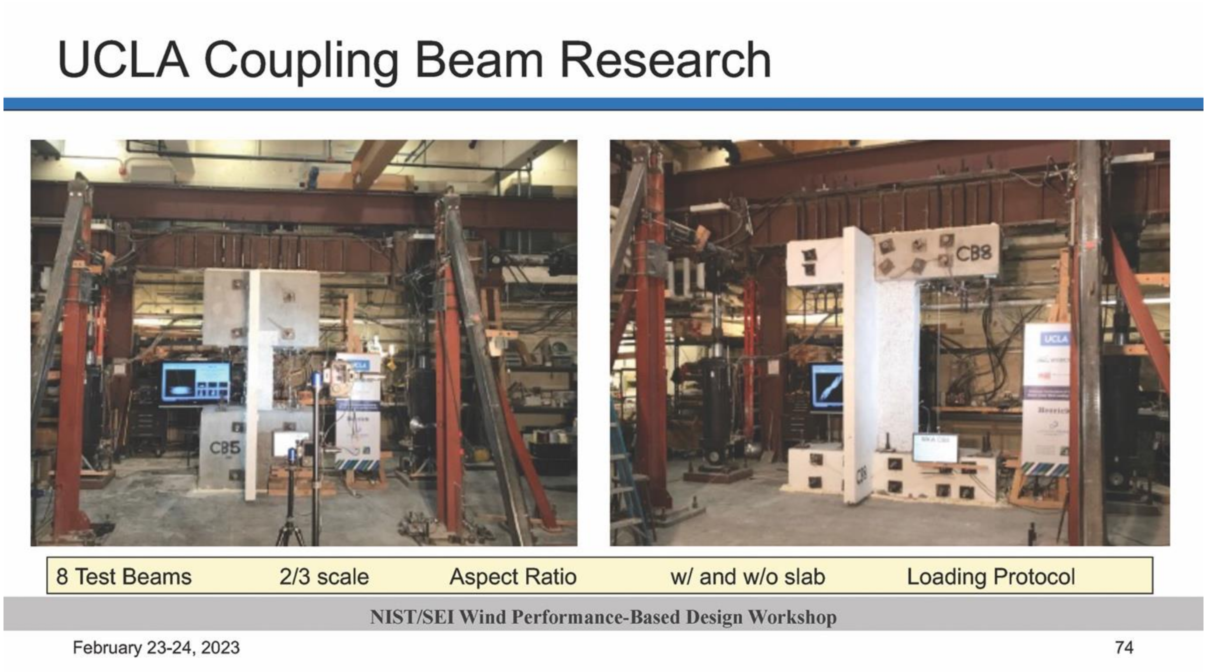

UCLA Coupling Beam Research

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

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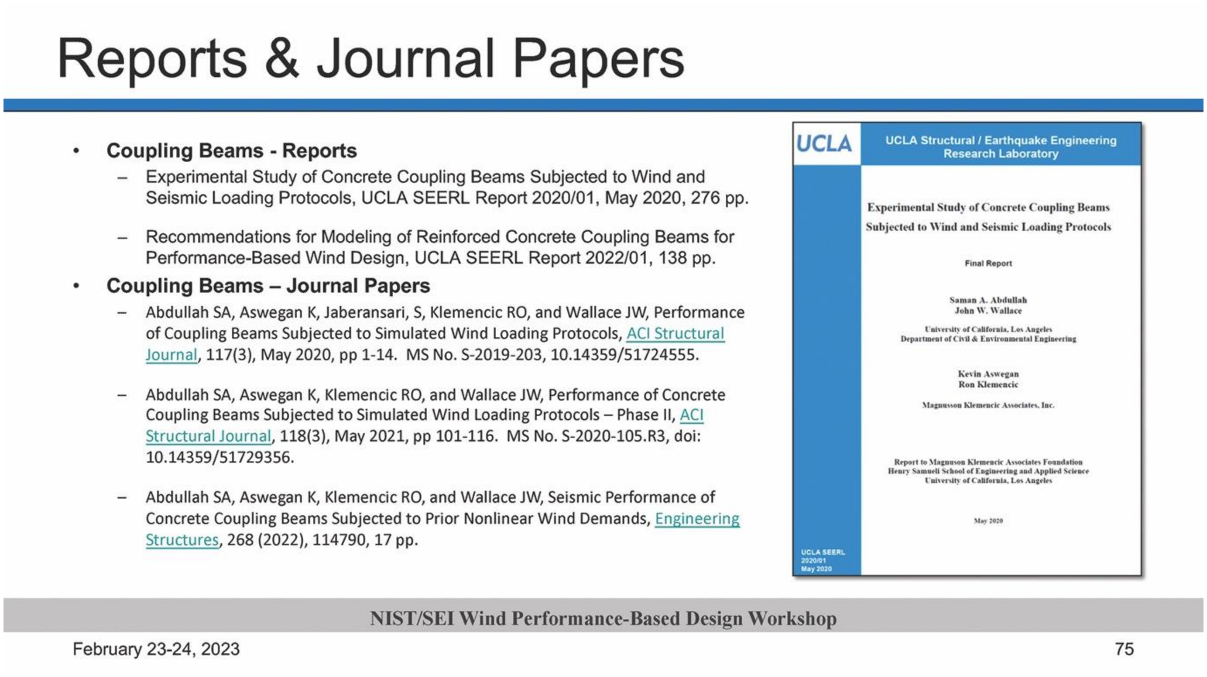

Reports & Journal Papers

- **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

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John W. Wallace

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Department of Civil & Environmental Engineering

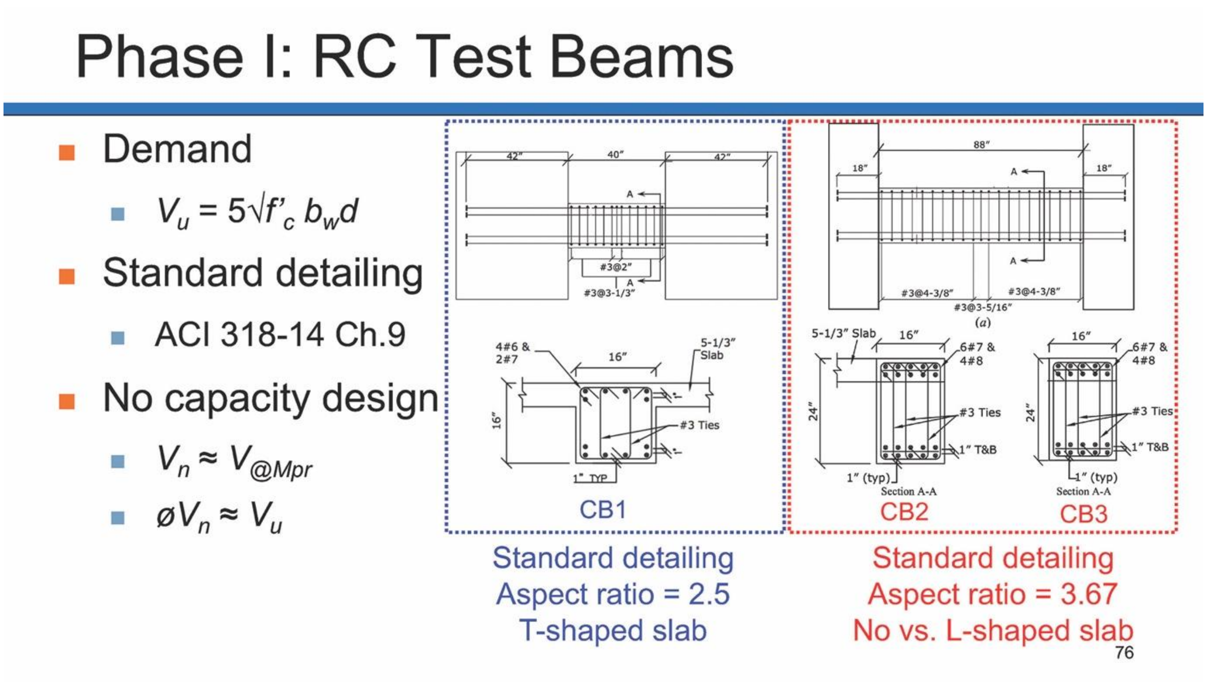
Kevin Aswegan
Ron Klemencic

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

UCLA SEERL
2020/01
May 2020



Phase I: RC Test Beams

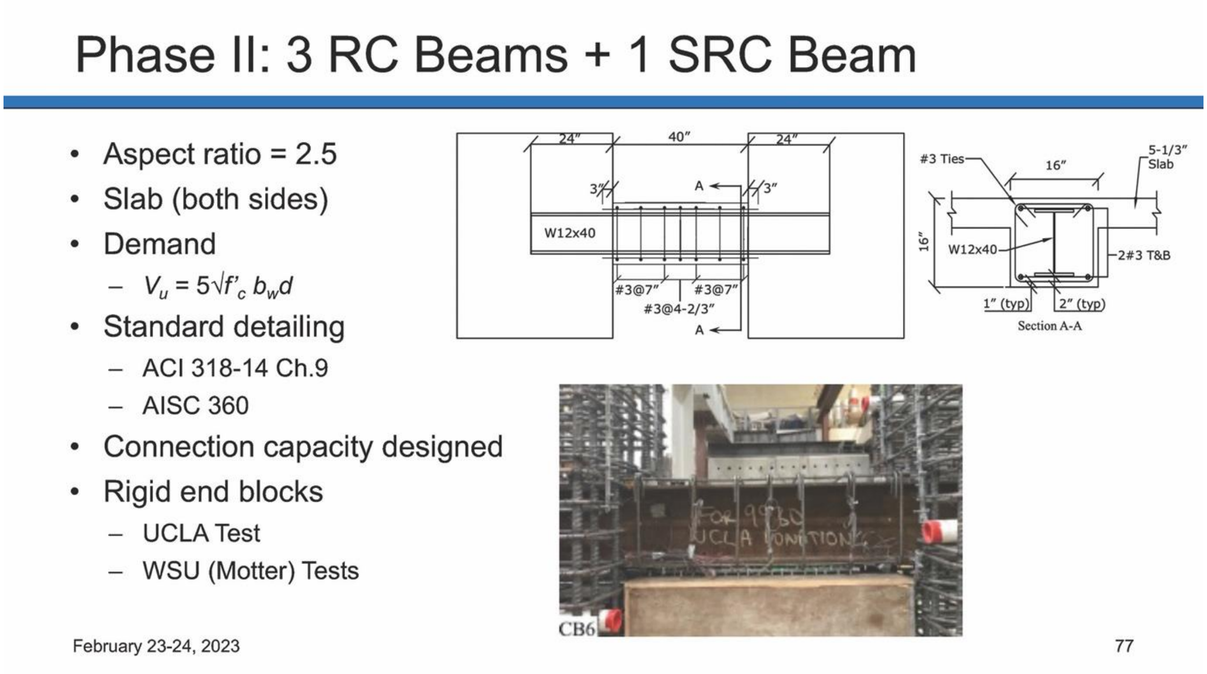
- Demand
  - $V_u = 5\sqrt{f'_c}\, b_w d$
- Standard detailing
  - ACI 318-14 Ch.9
- No capacity design
  - $V_n \approx V_{@Mpr}$
  - $øV_n \approx V_u$

CB1

CB2 CB3

Standard detailing
Aspect ratio = 2.5
T-shaped slab

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



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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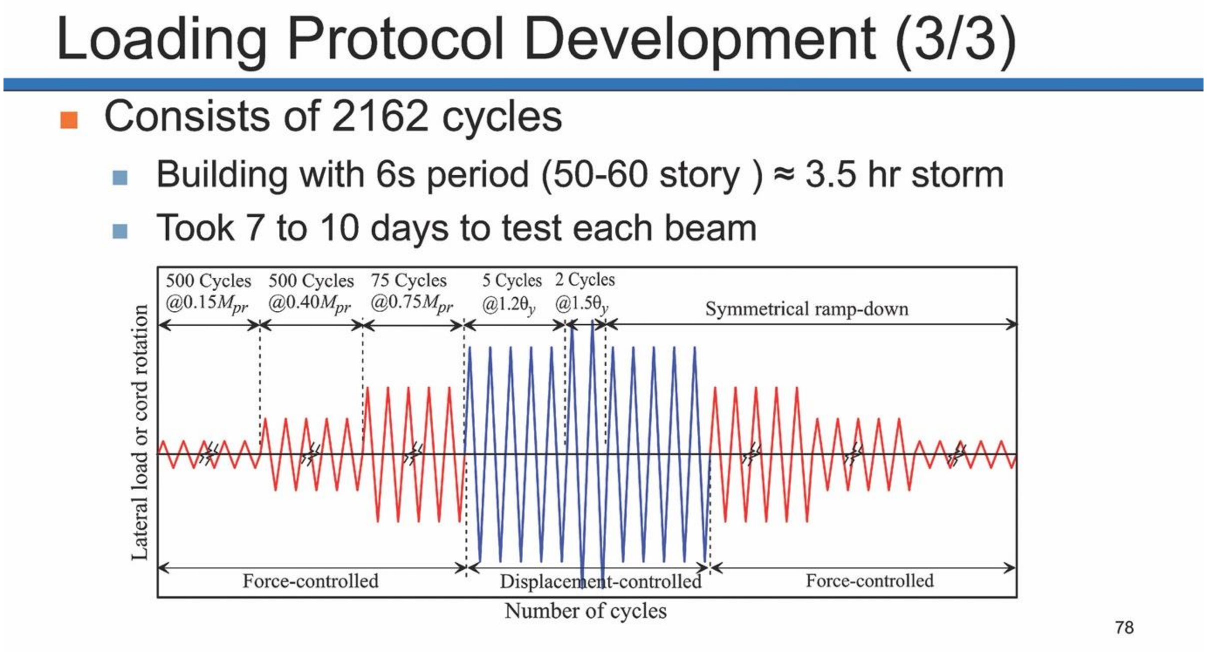
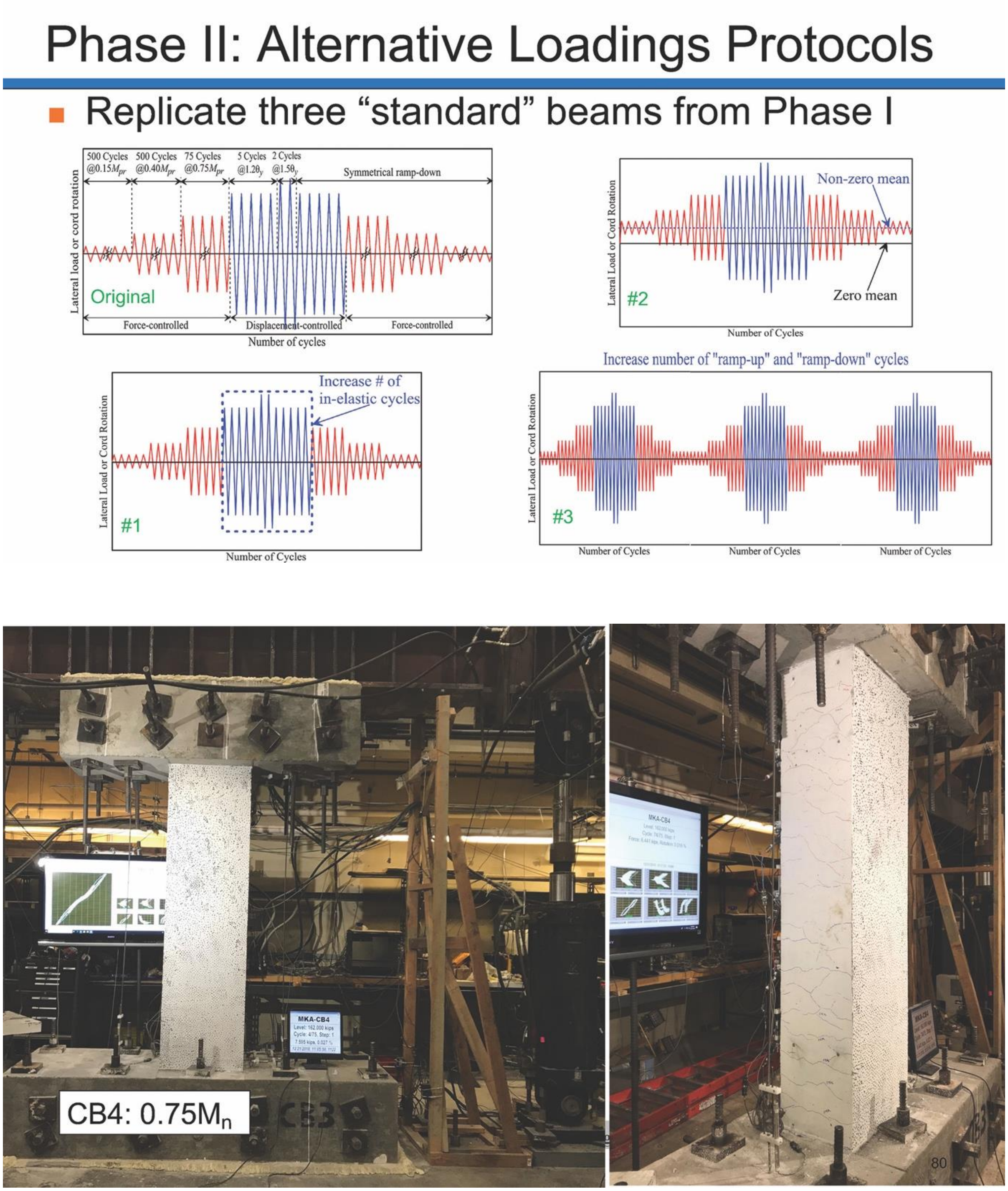


Loading Protocol Development (3/3)

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

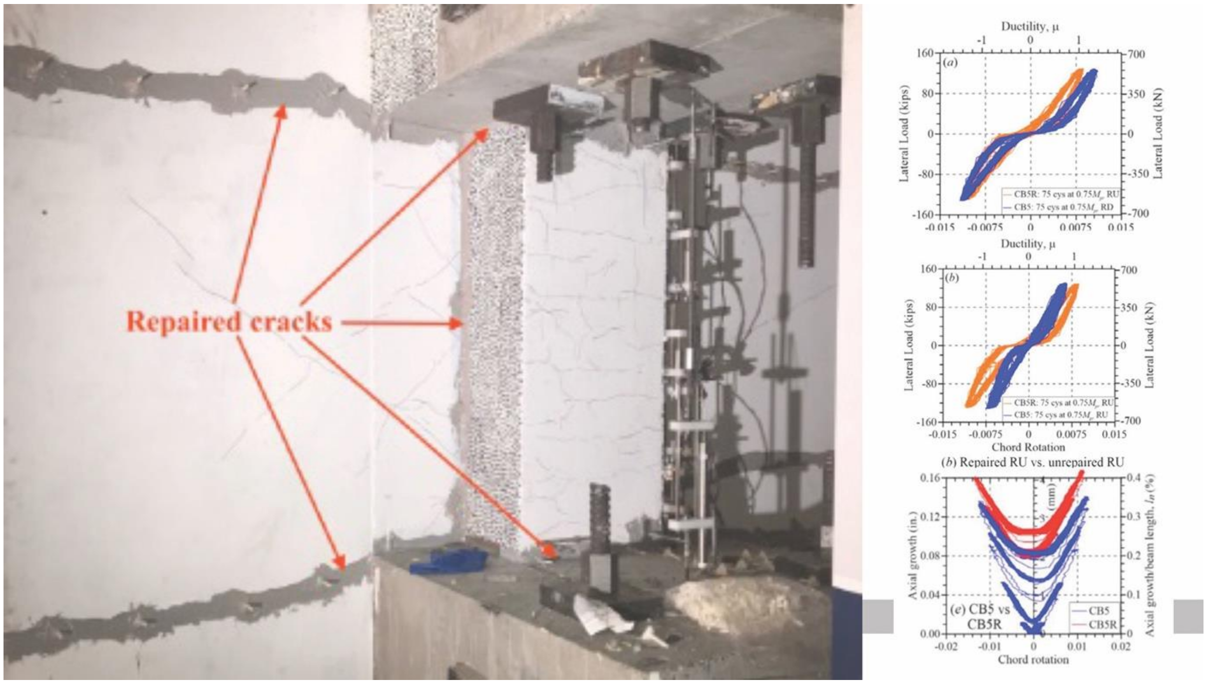


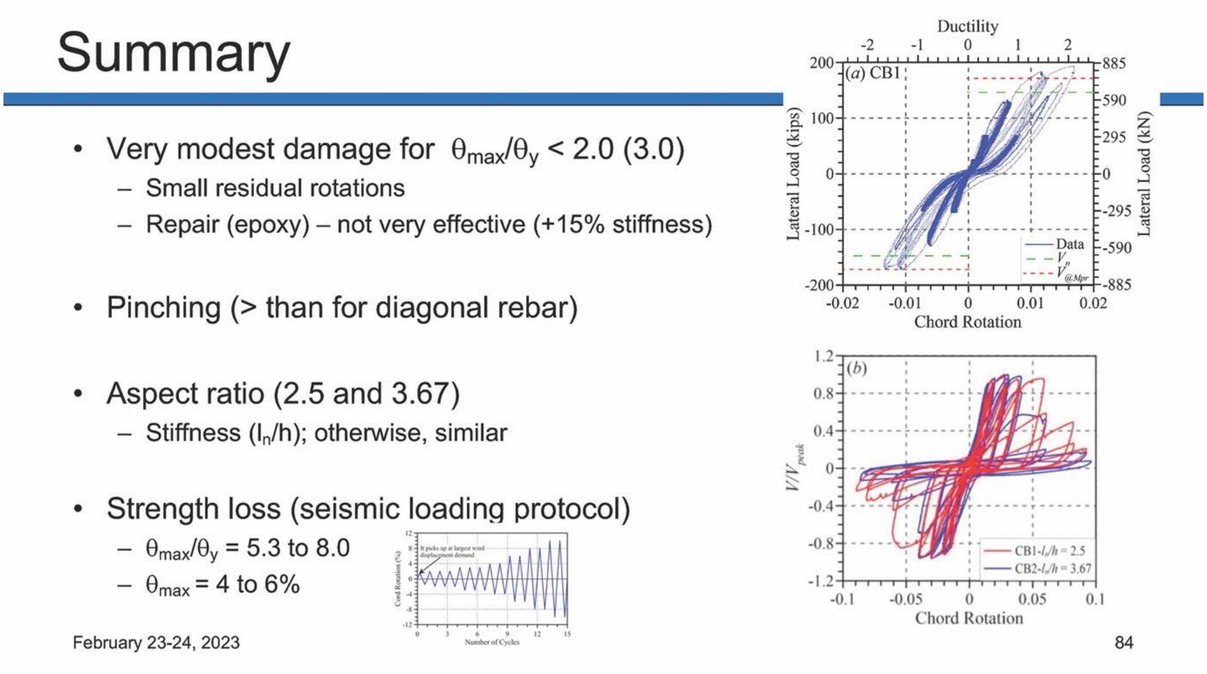
Phase II: Alternative Loadings Protocols

- Replicate three “standard” beams from Phase I


CB2: 1.5θy
MKA-CB2
Level: 1.500 %
Cycle: 1/2, Step: 8
12.285 kips, -0.193 %
81

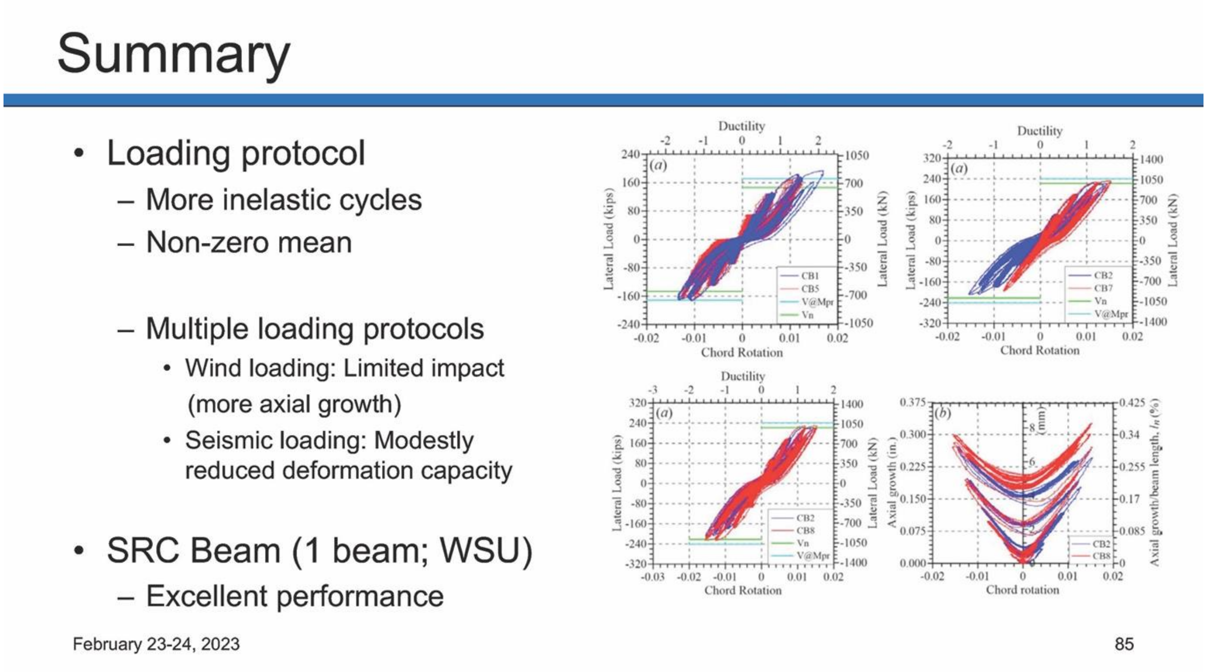

CB2: 2.0θy
MKA-CB2-
Level: 2.000 %
Cycle: 3/3, Step: 8
15.309 kips, -0.042 %
CB2
82





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%



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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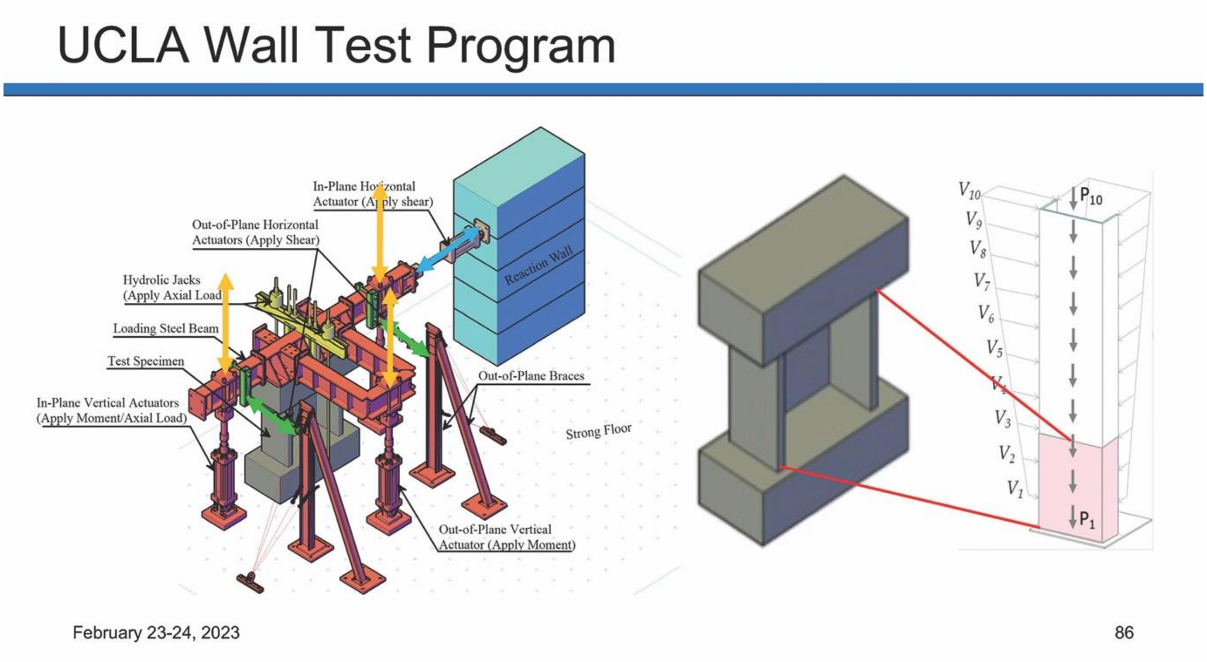

UCLA Wall Test Program

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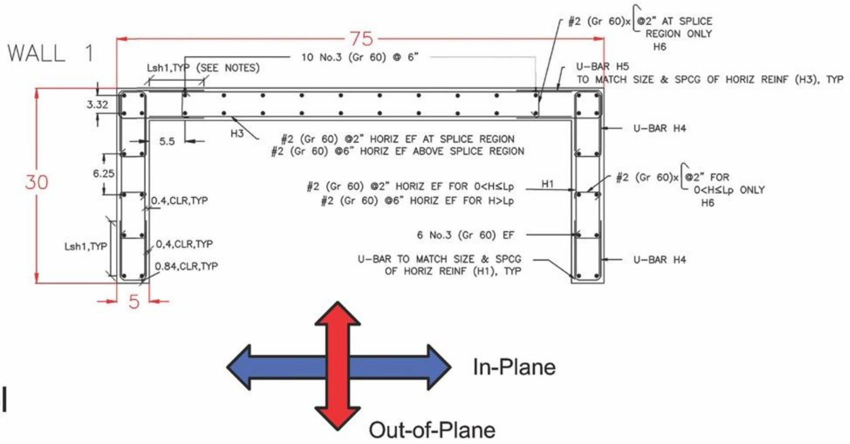
UCLA Wall Test Specimens

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



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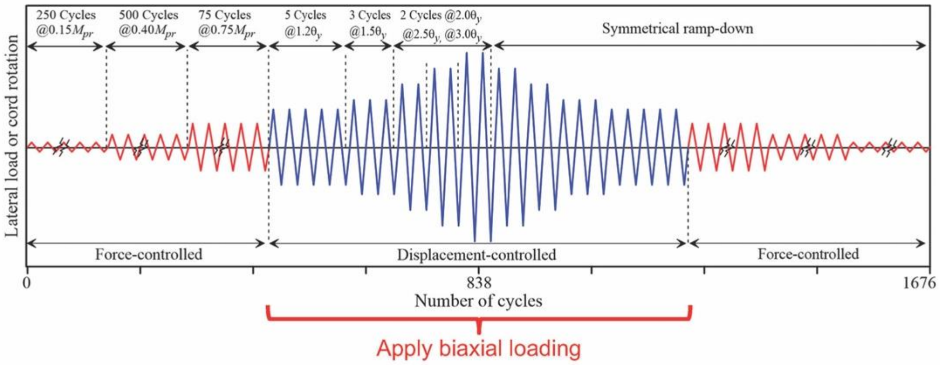
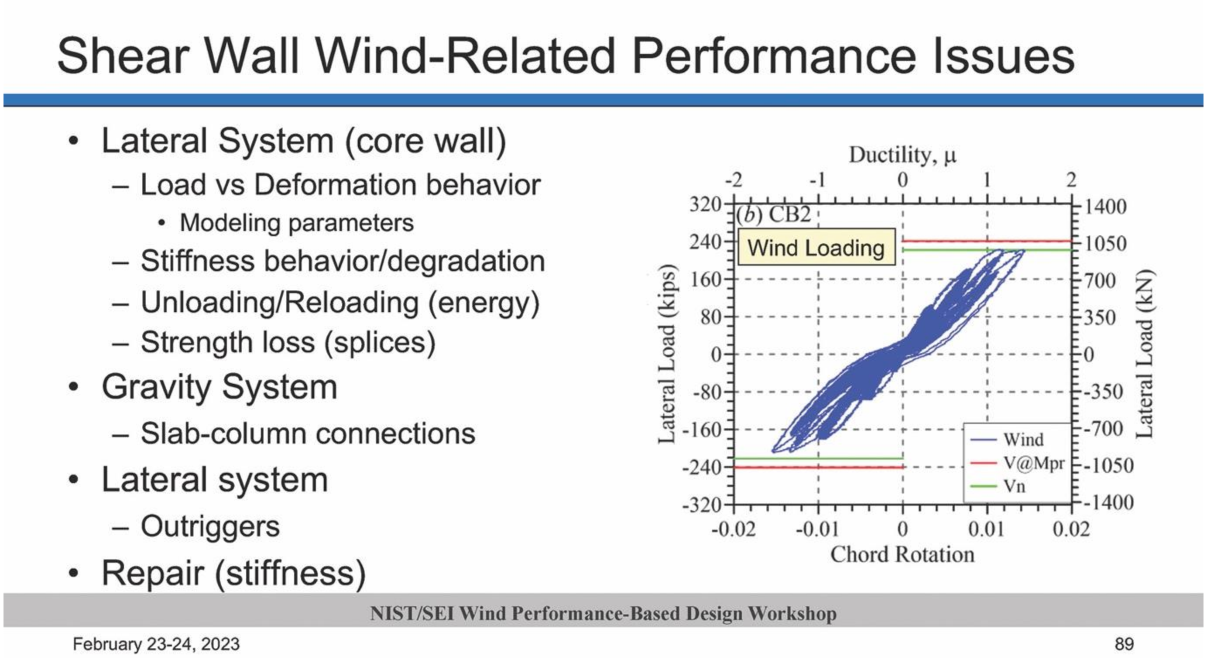
Loading Protocol

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



Apply biaxial loading



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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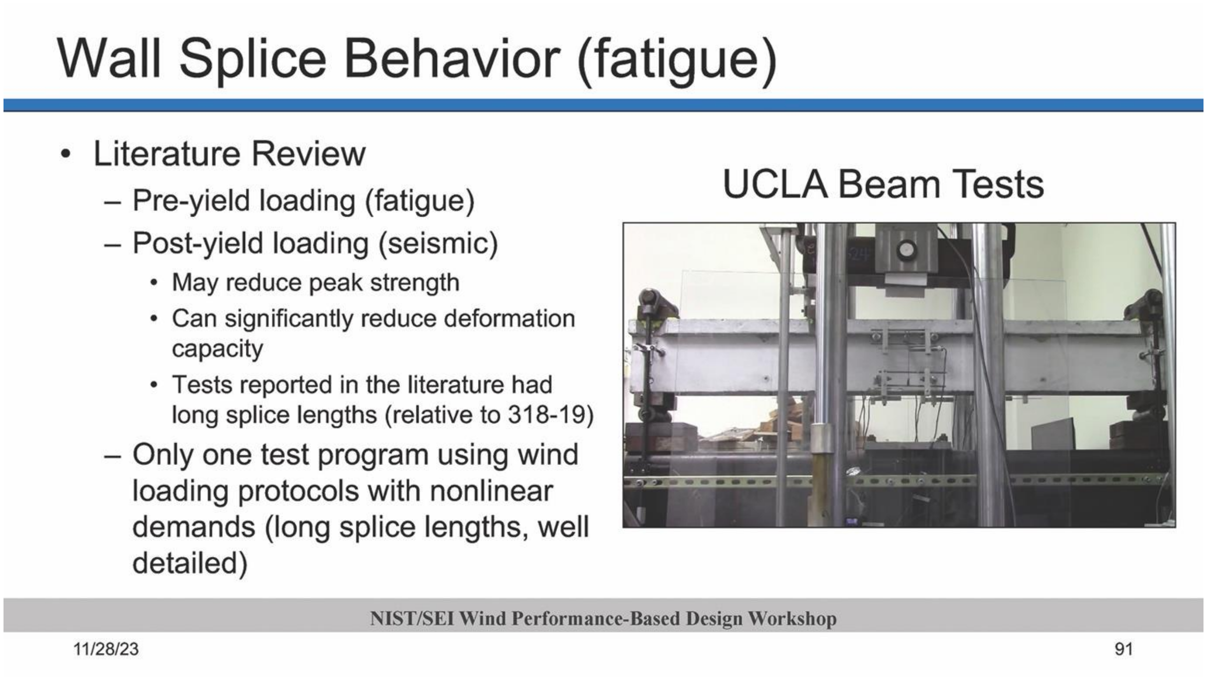

Wall Splice Behavior (fatigue)

- 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

NIST/SEI Wind Performance-Based Design Workshop

11/28/23

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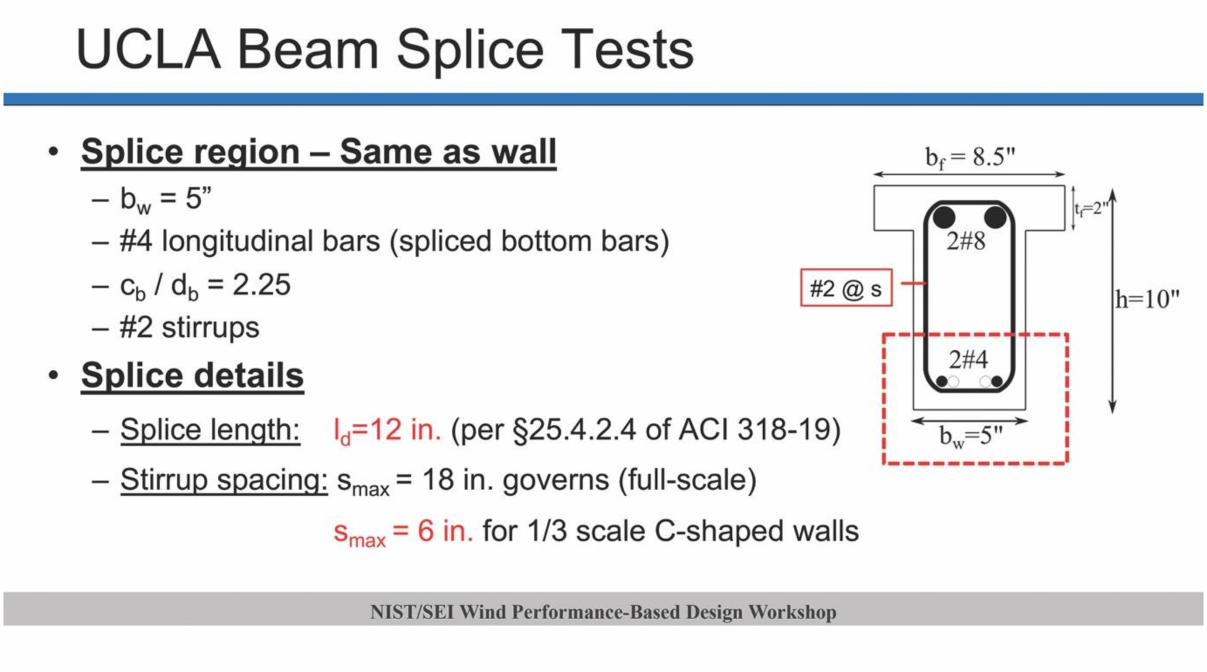

UCLA Beam Splice Tests

- **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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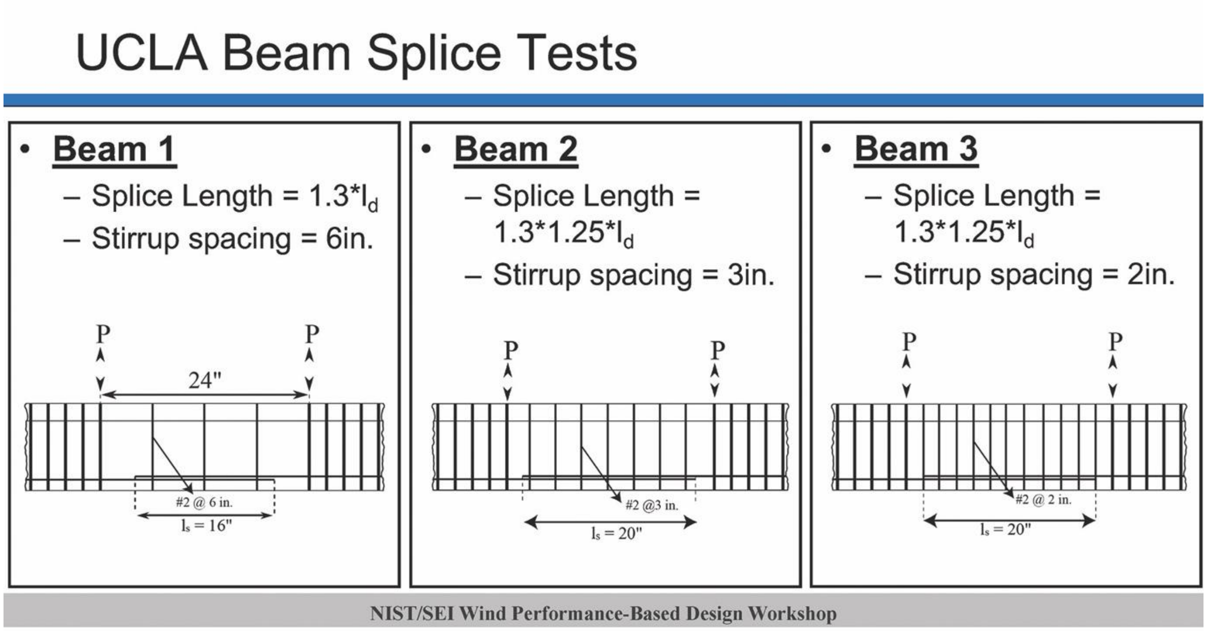

UCLA Beam Splice Tests

- **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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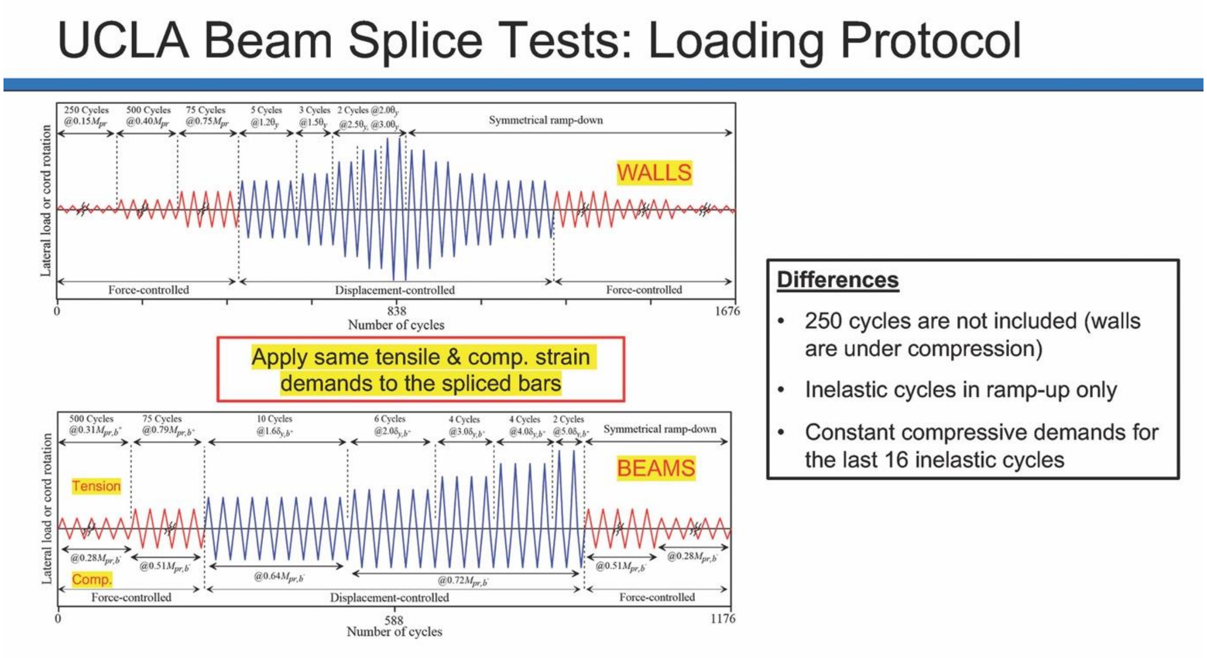
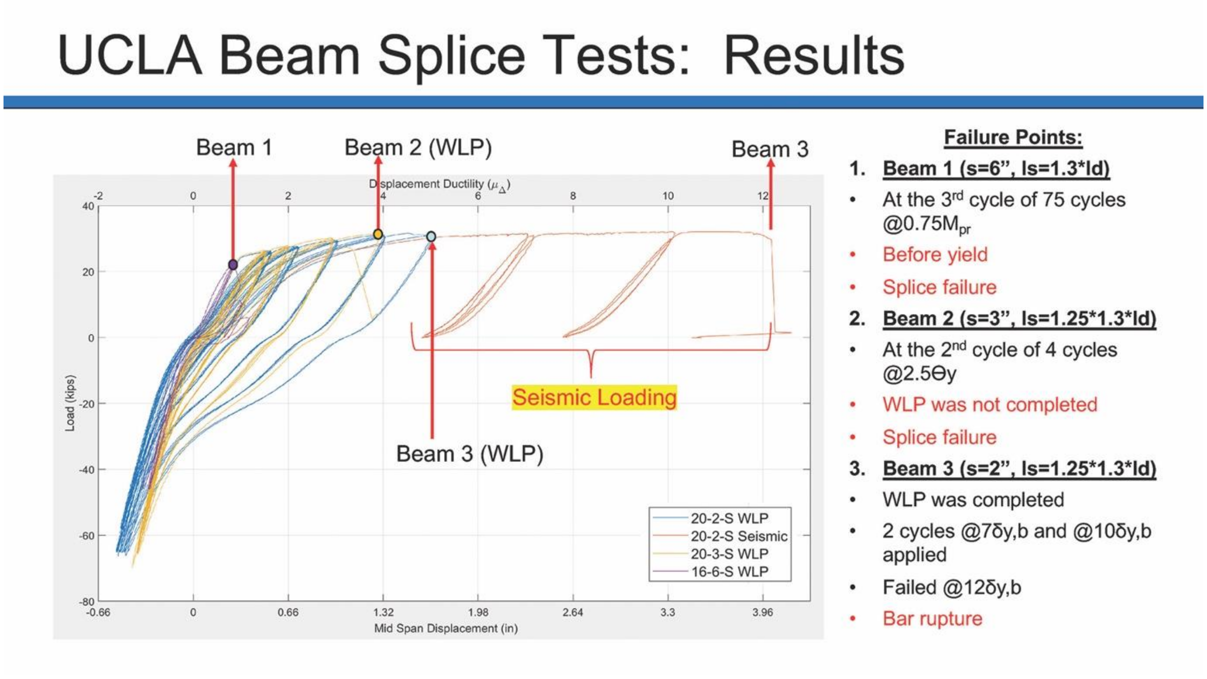


UCLA Beam Splice Tests: Loading Protocol

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

Differences

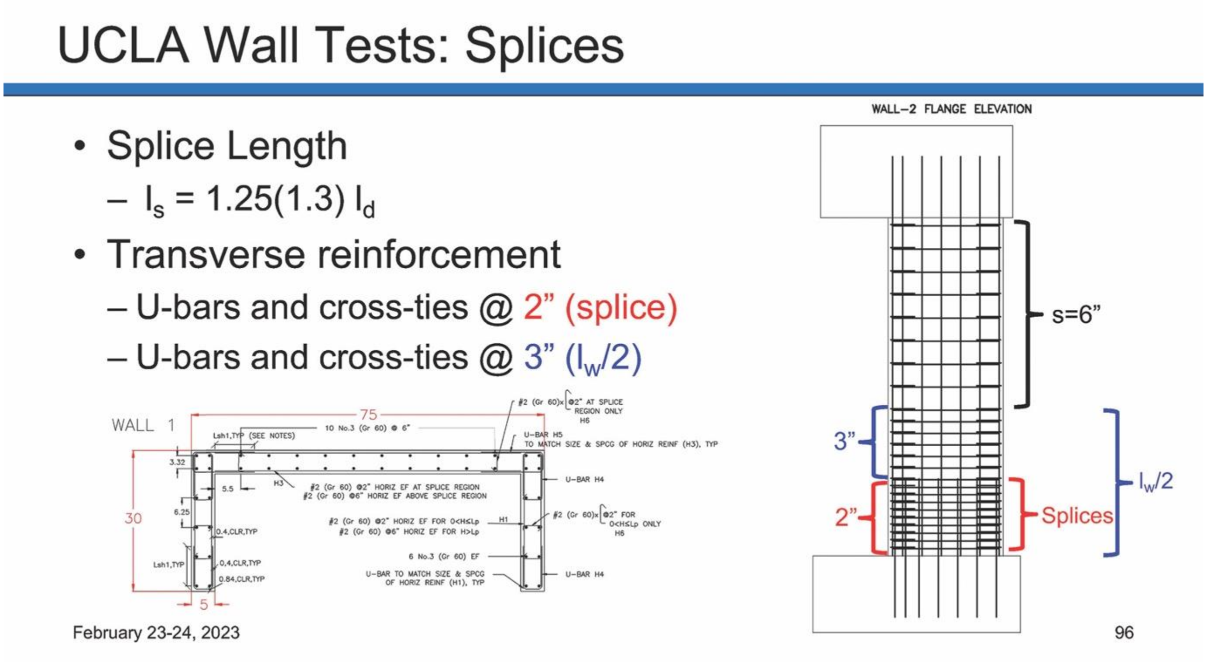
- 250 cycles are not included (walls are under compression)
- Inelastic cycles in ramp-up only
- Constant compressive demands for the last 16 inelastic cycles



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

Final Observation: Instrumentation

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

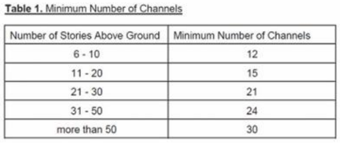
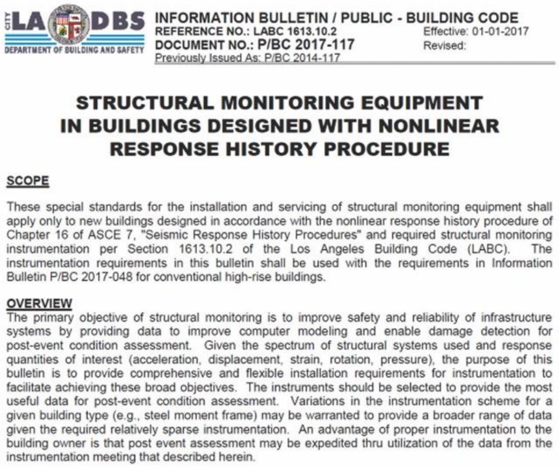


Table 1. Minimum Number of Channels

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



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

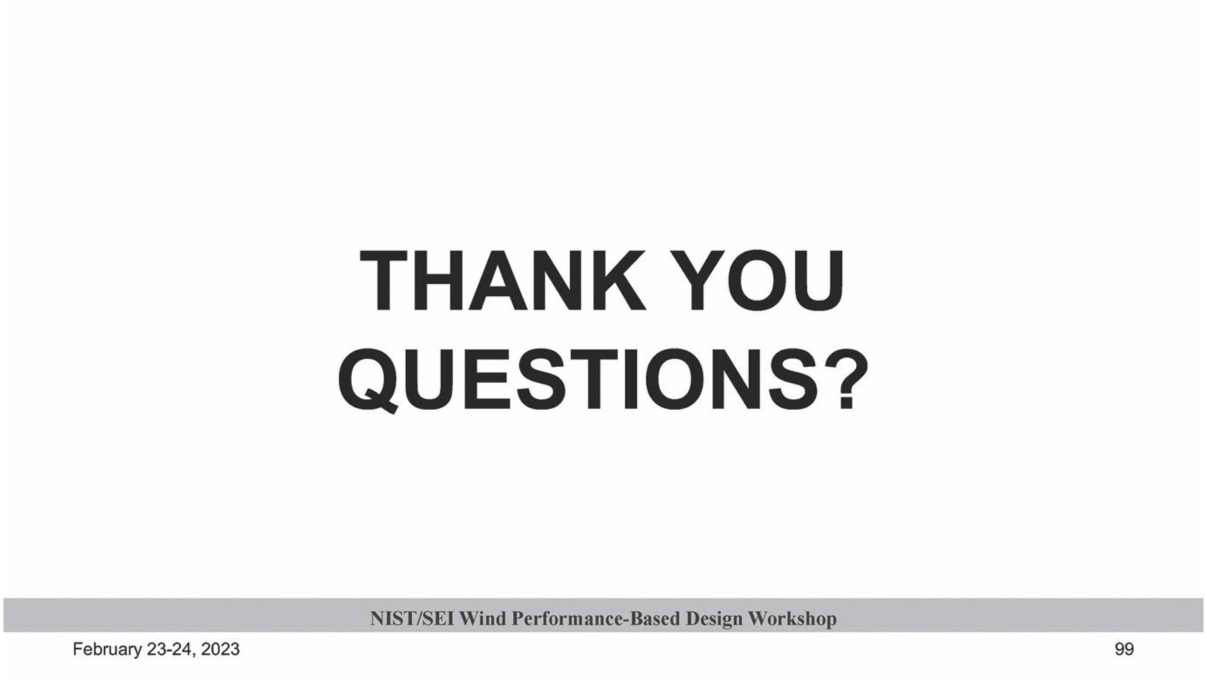
STRUCTURAL MONITORING EQUIPMENT
IN BUILDINGS DESIGNED WITH NONLINEAR
RESPONSE HISTORY PROCEDURE

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.



THANK YOU QUESTIONS?

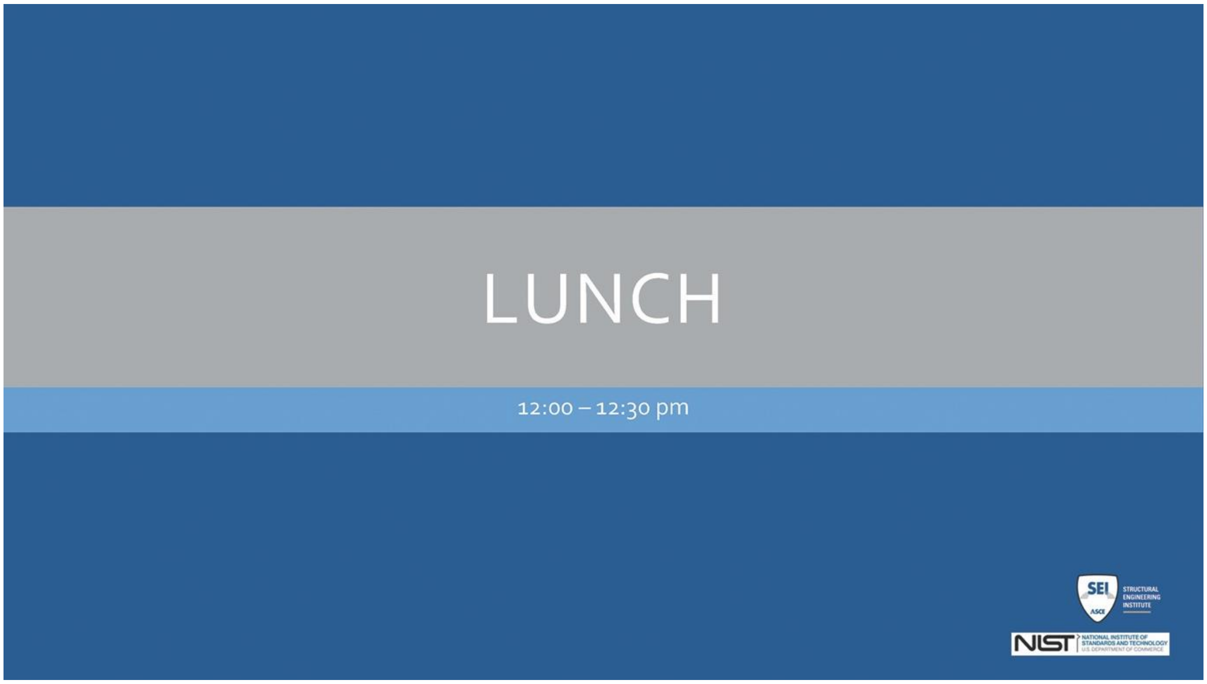
PANEL DISCUSSION

Moderator:

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

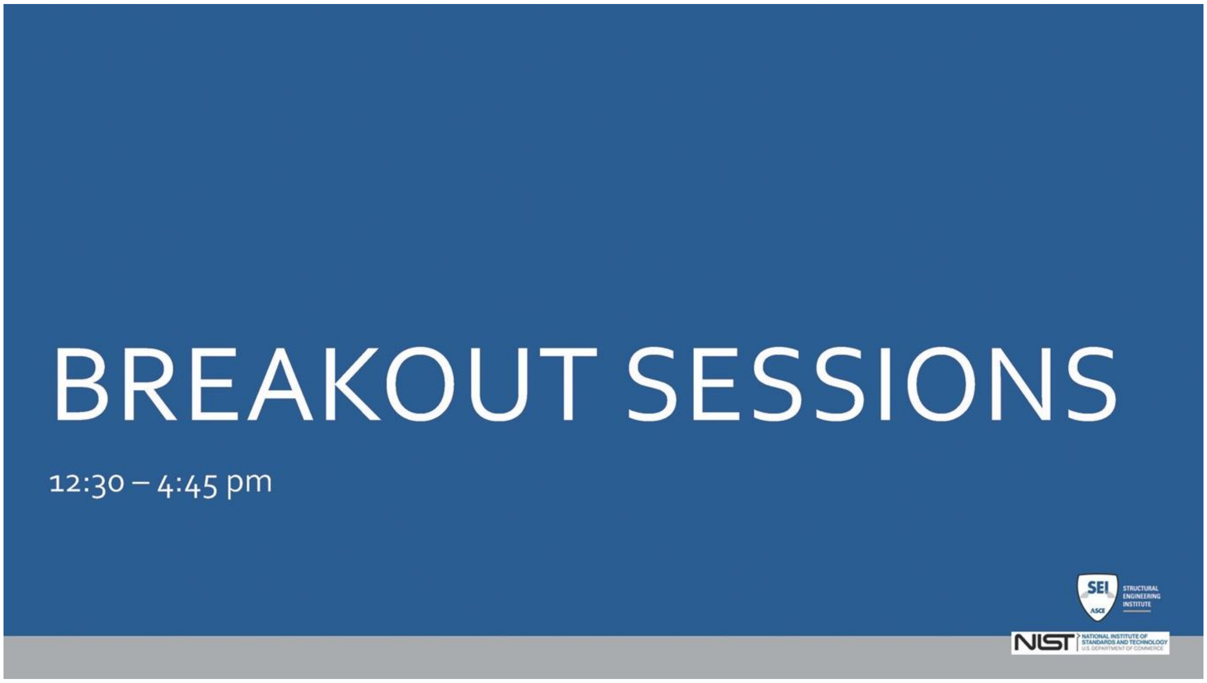
Panelists:

- 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



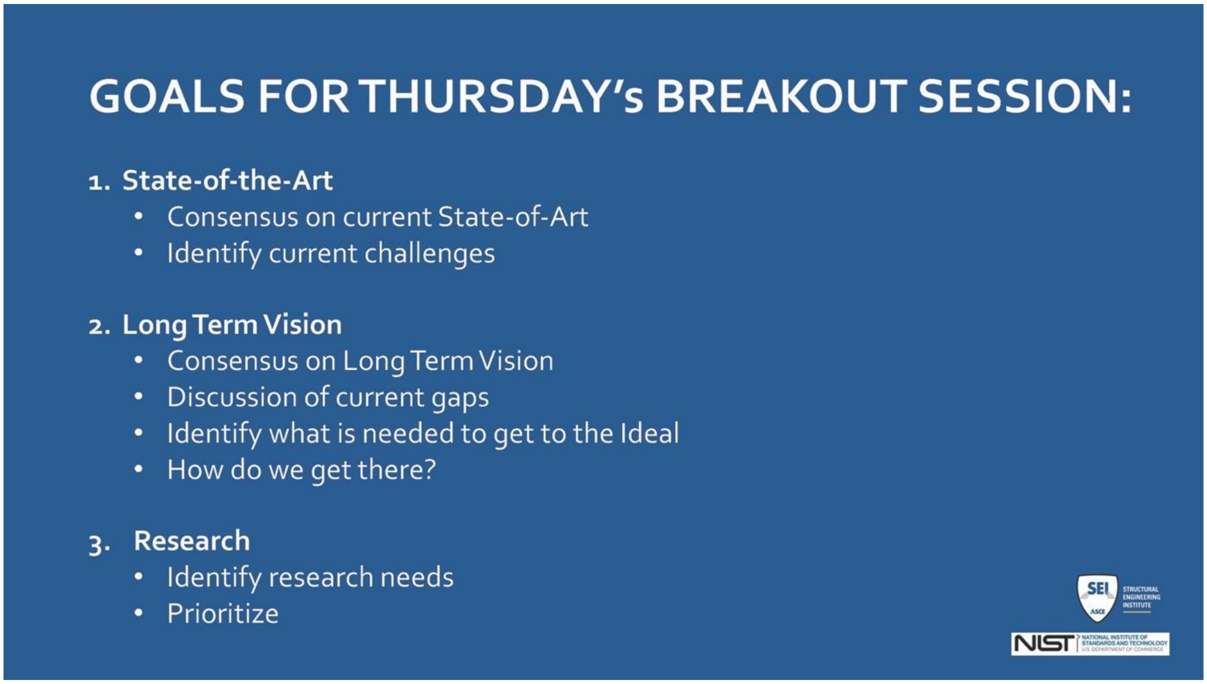
LUNCH

12:00 – 12:30 pm



BREAKOUT SESSIONS

12:30 – 4:45 pm

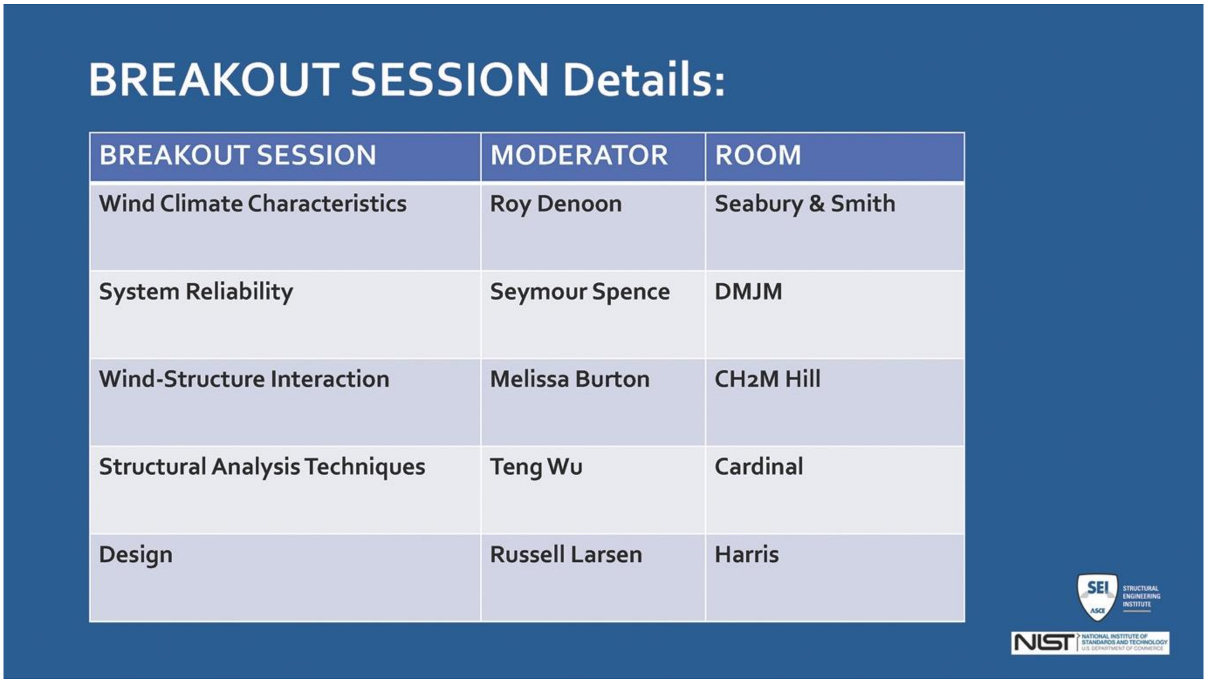


GOALS FOR THURSDAY's BREAKOUT SESSION:

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**

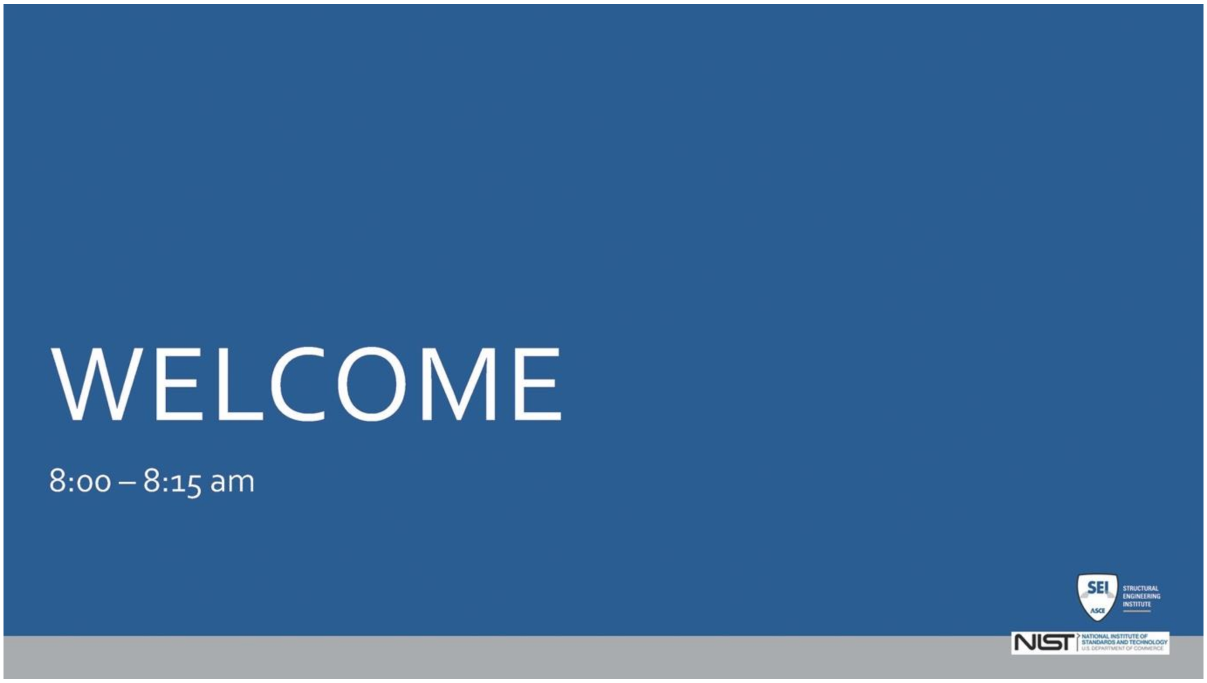
SUMMARY & ADJOURN

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

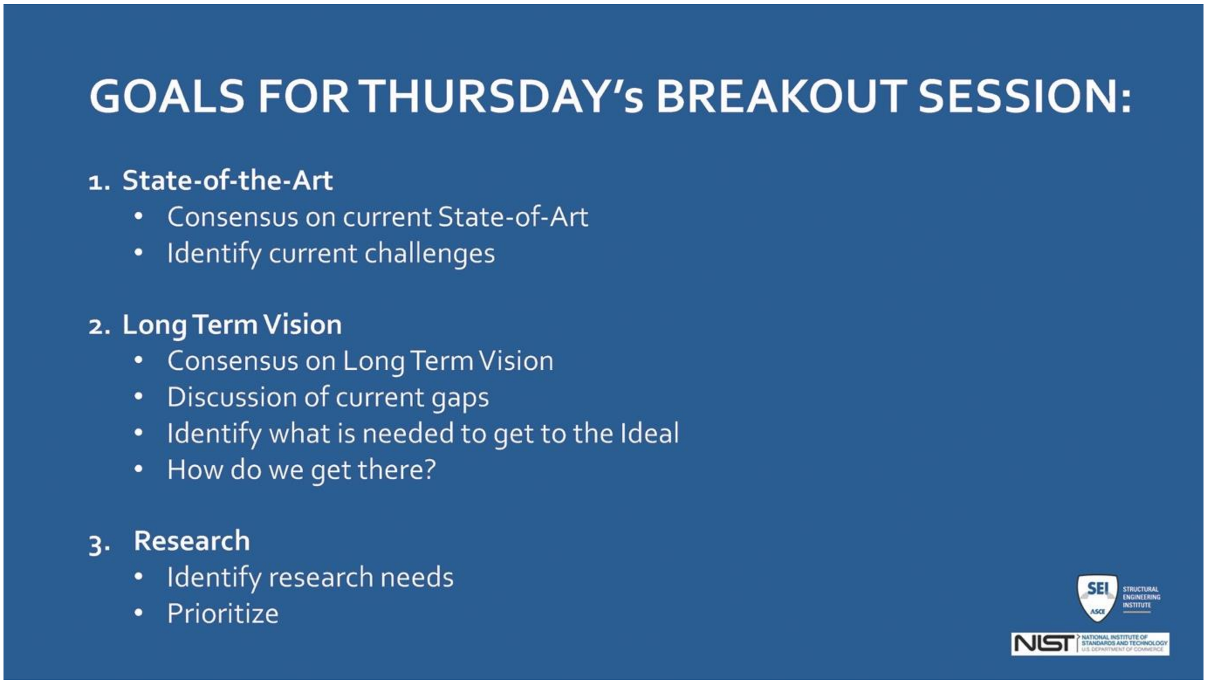
12:00-4:00pm – Workshop Steering Committee Meeting

- 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

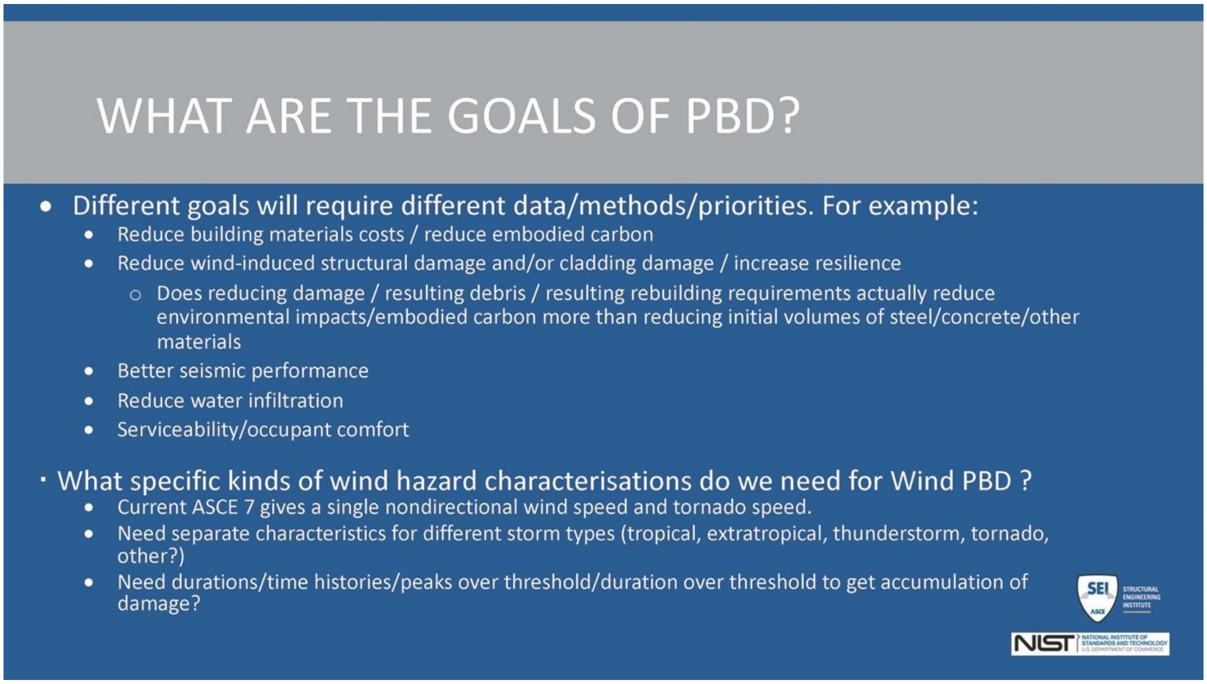


GOALS FOR THURSDAY's BREAKOUT SESSION:

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

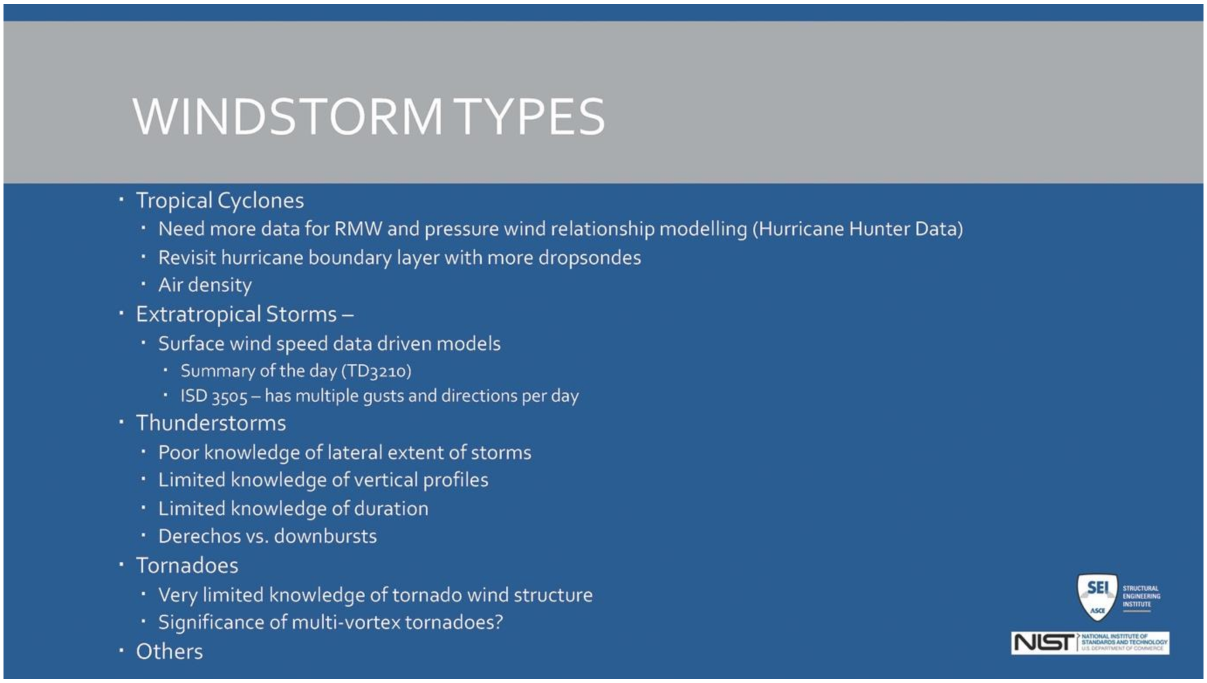
WIND CLIMATE CHARACTERISTICS

Peter Vickery



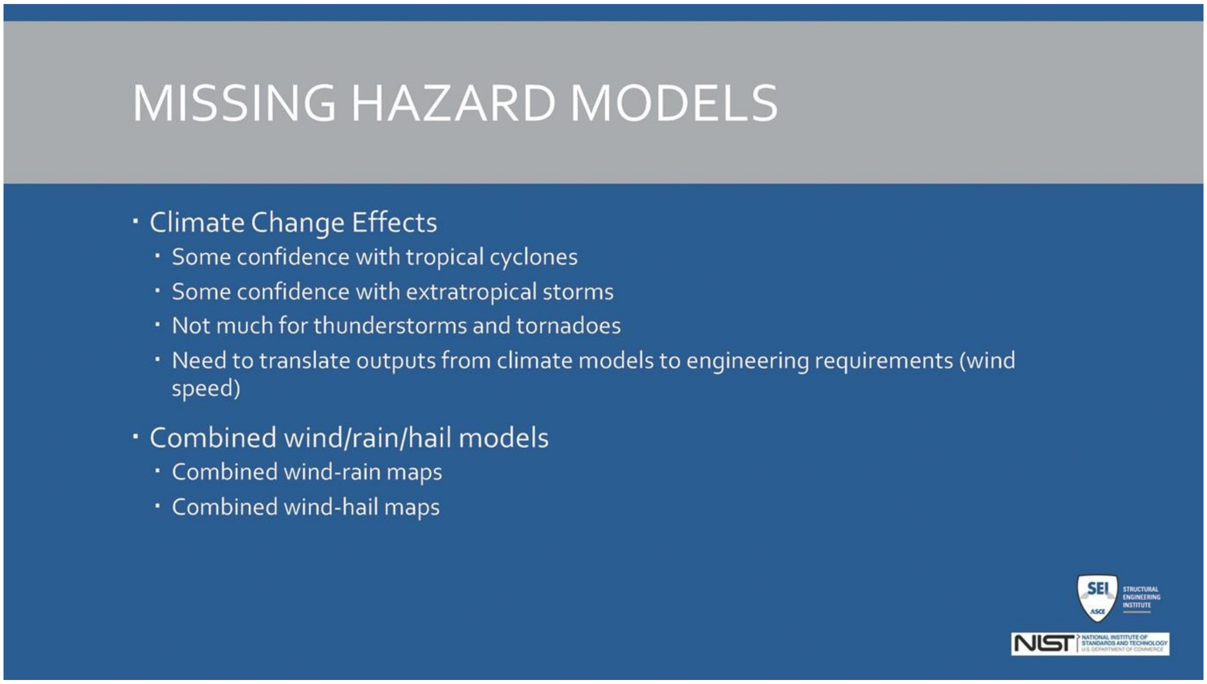
WHAT ARE THE GOALS OF PBD?

- 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?



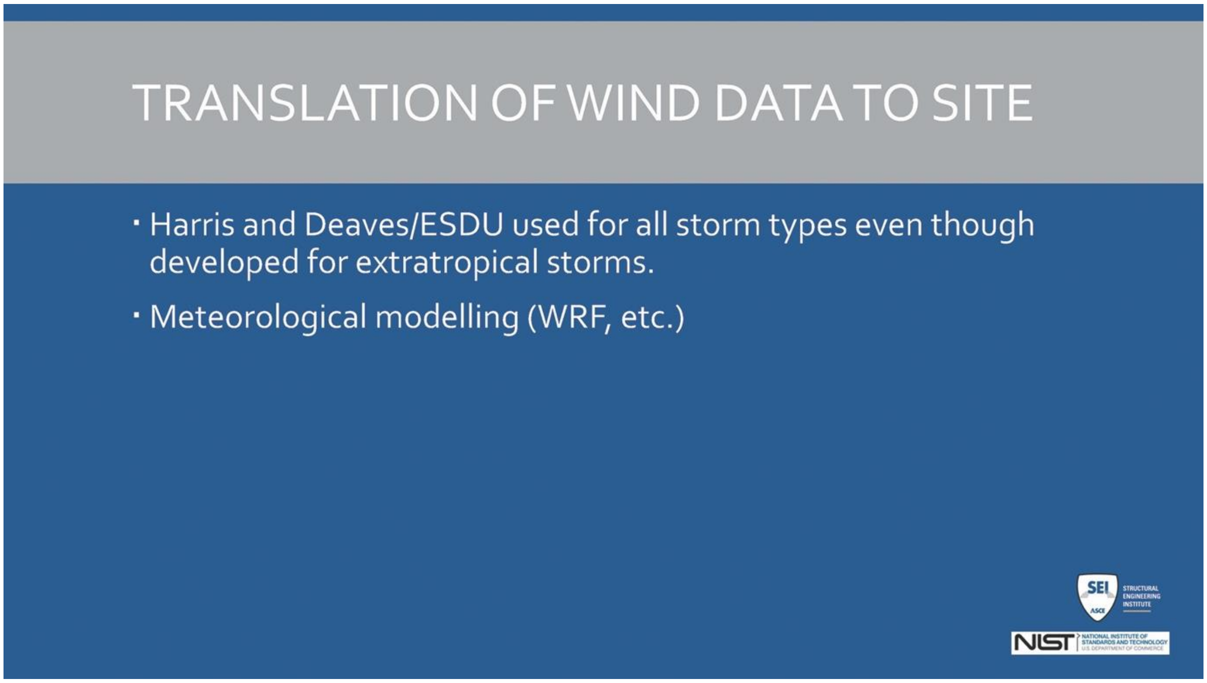
WINDSTORM TYPES

- 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



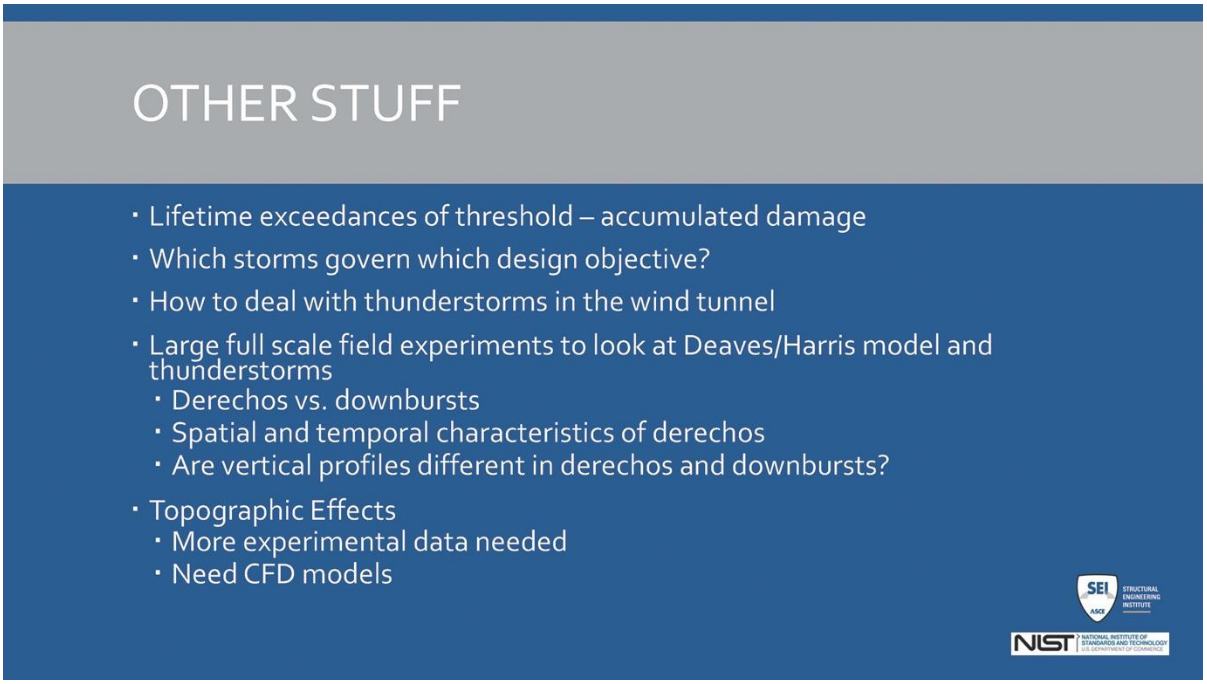
MISSING HAZARD MODELS

- 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



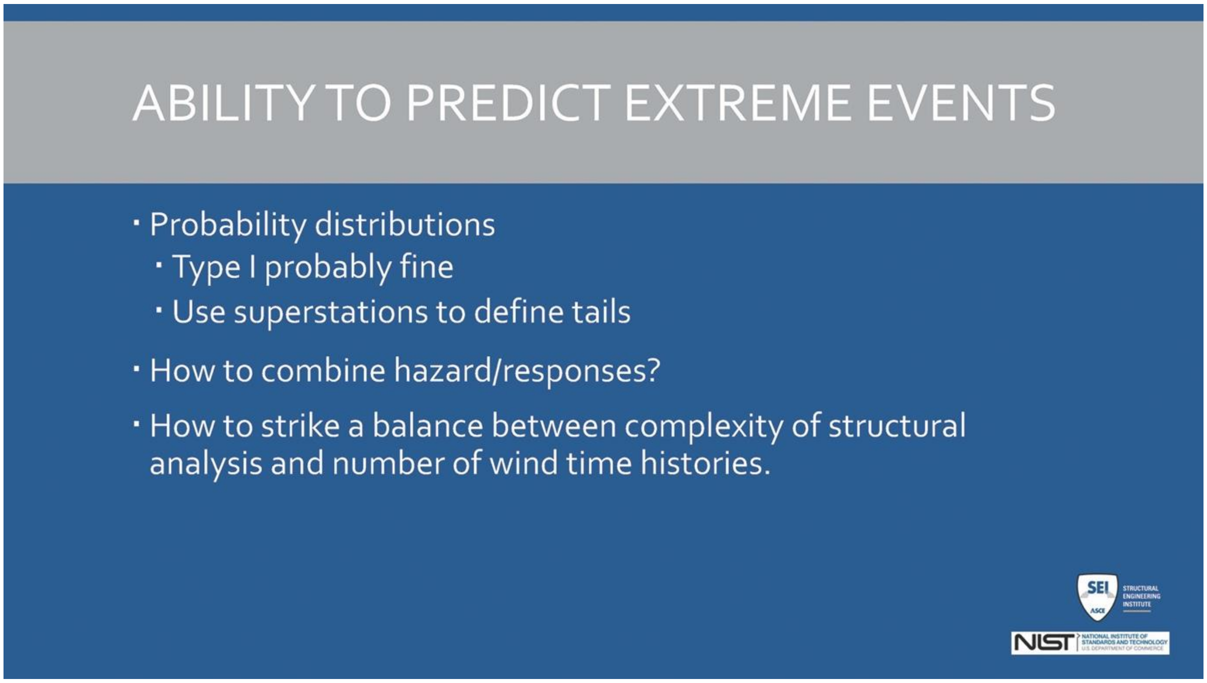
TRANSLATION OF WIND DATA TO SITE

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



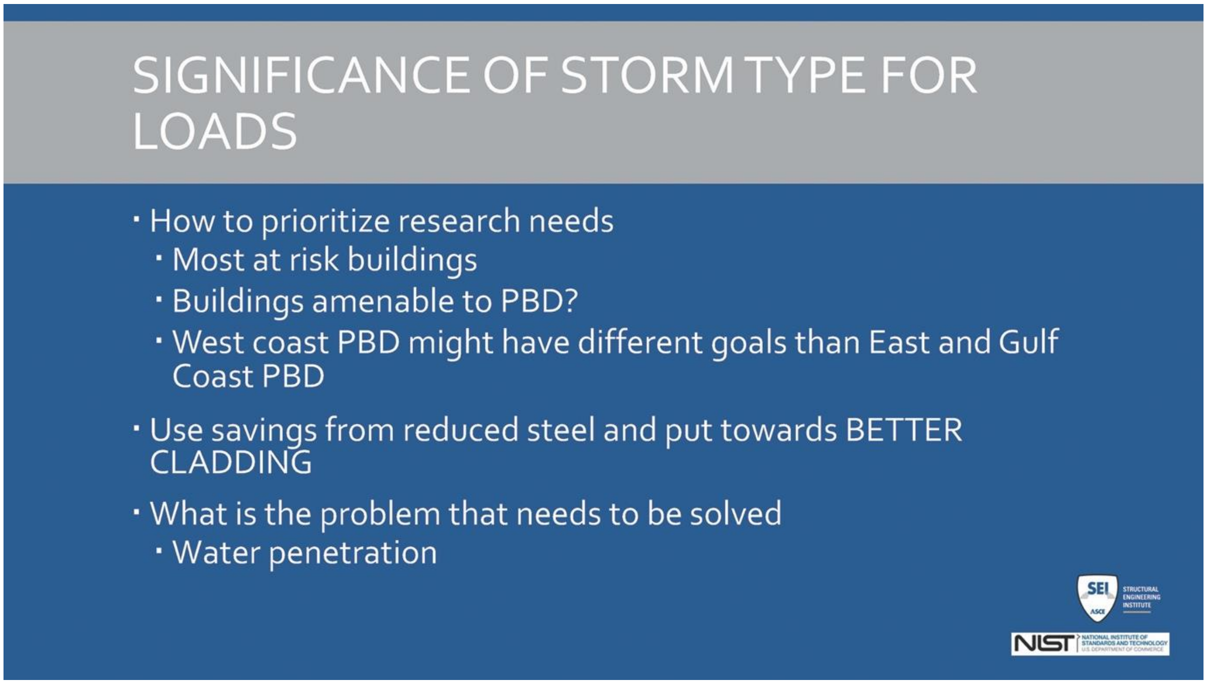
OTHER STUFF

- 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



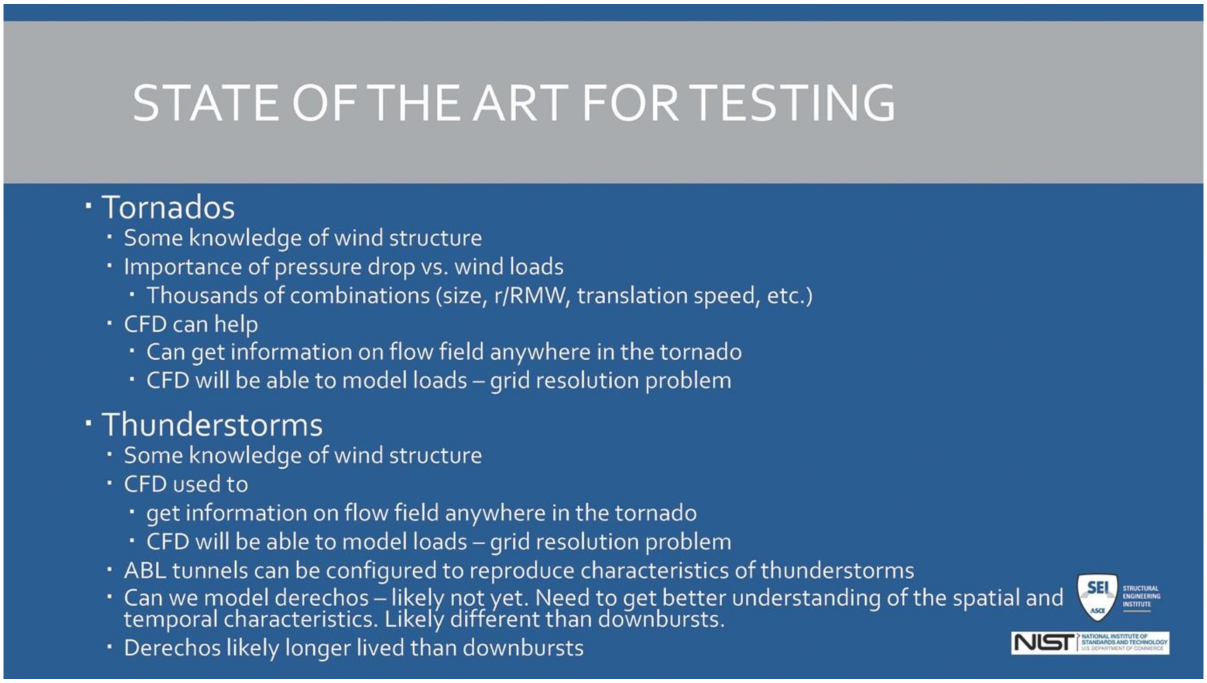
ABILITY TO PREDICT EXTREME EVENTS

- 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.



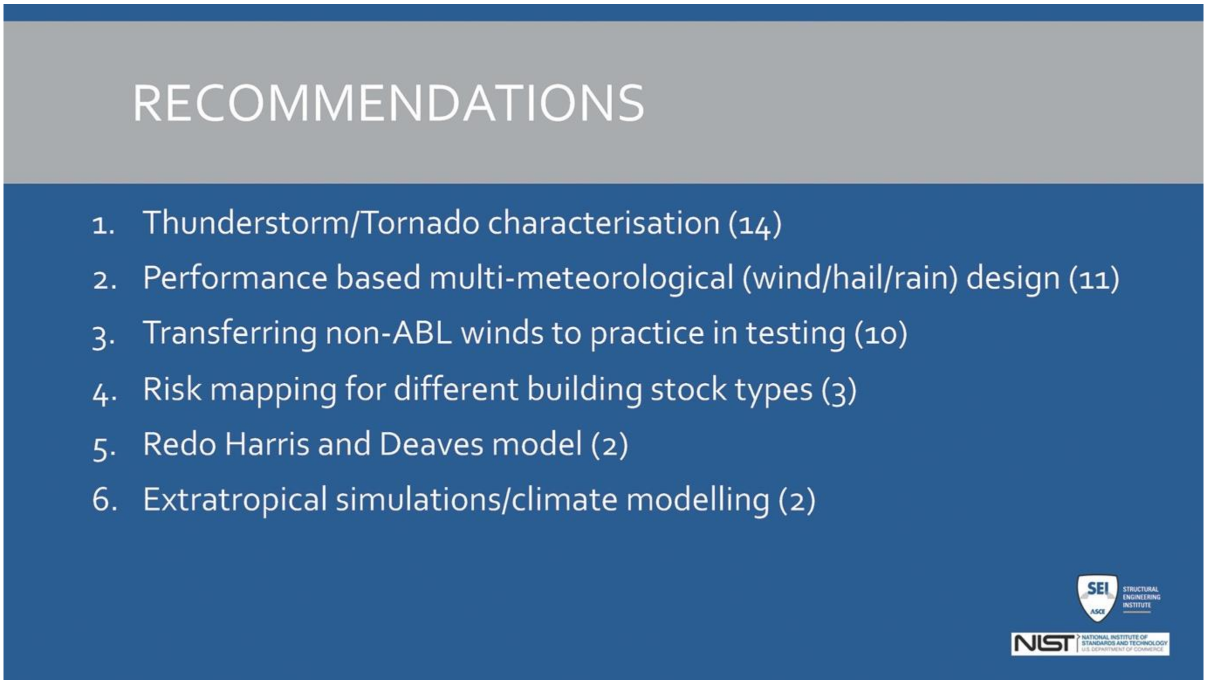
SIGNIFICANCE OF STORM TYPE FOR LOADS

- 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



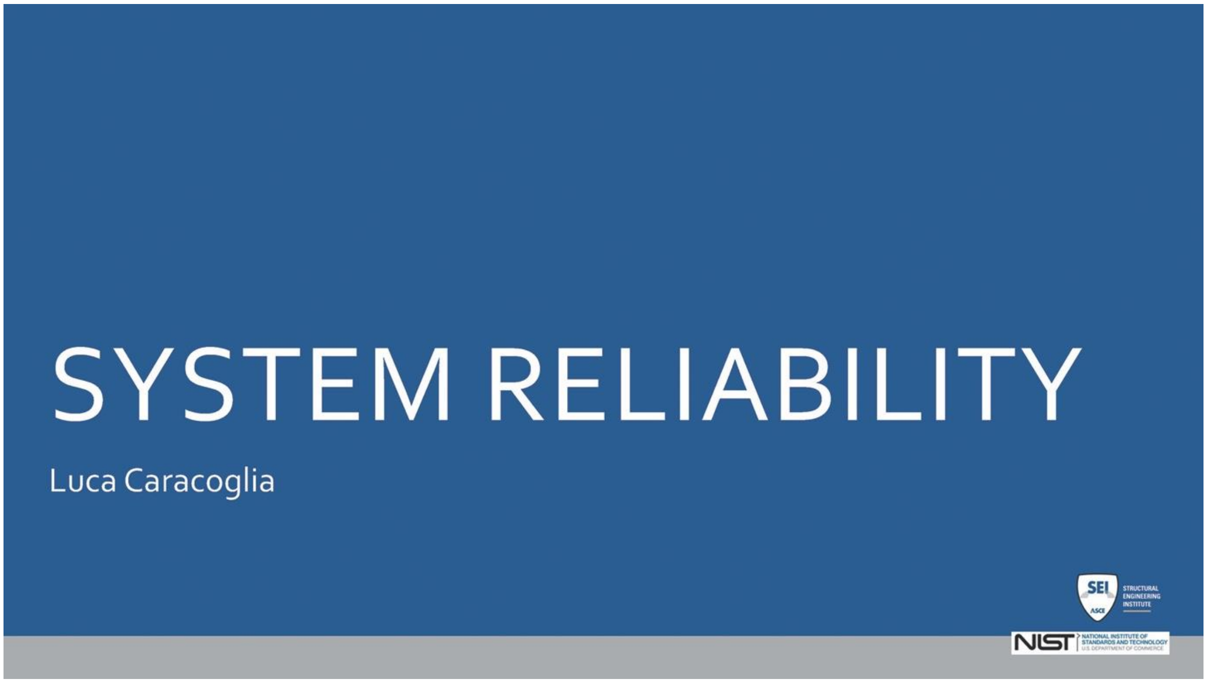
STATE OF THE ART FOR TESTING

- 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)



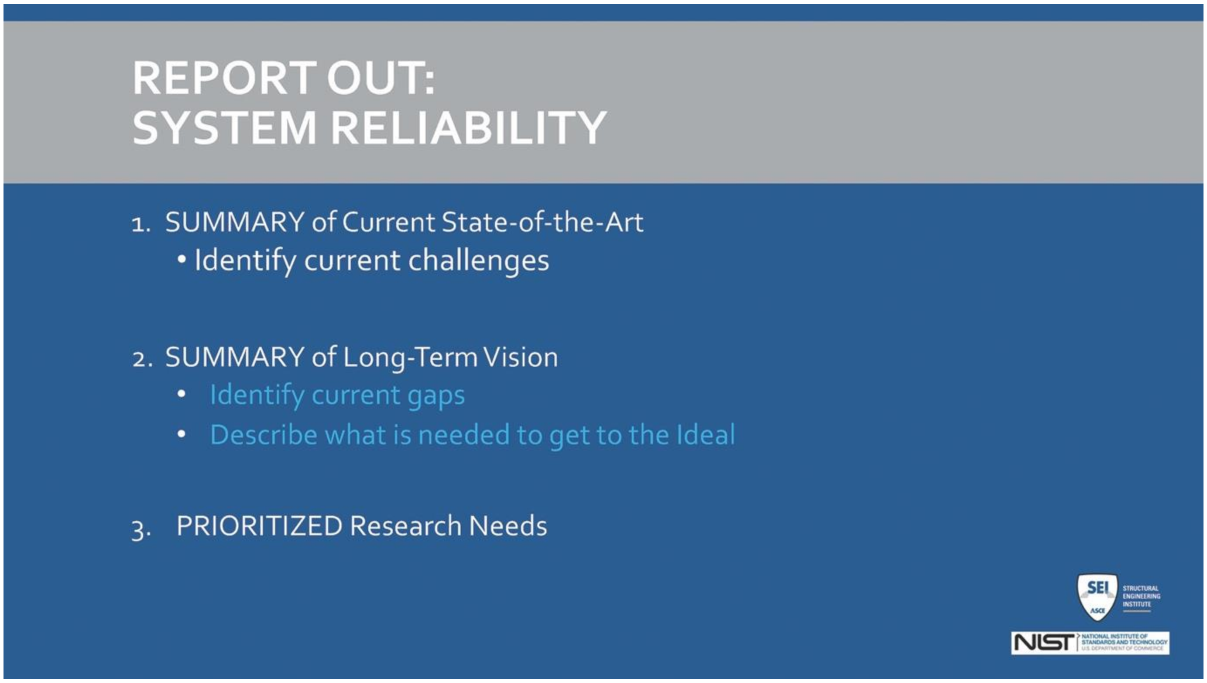
SYSTEM RELIABILITY

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

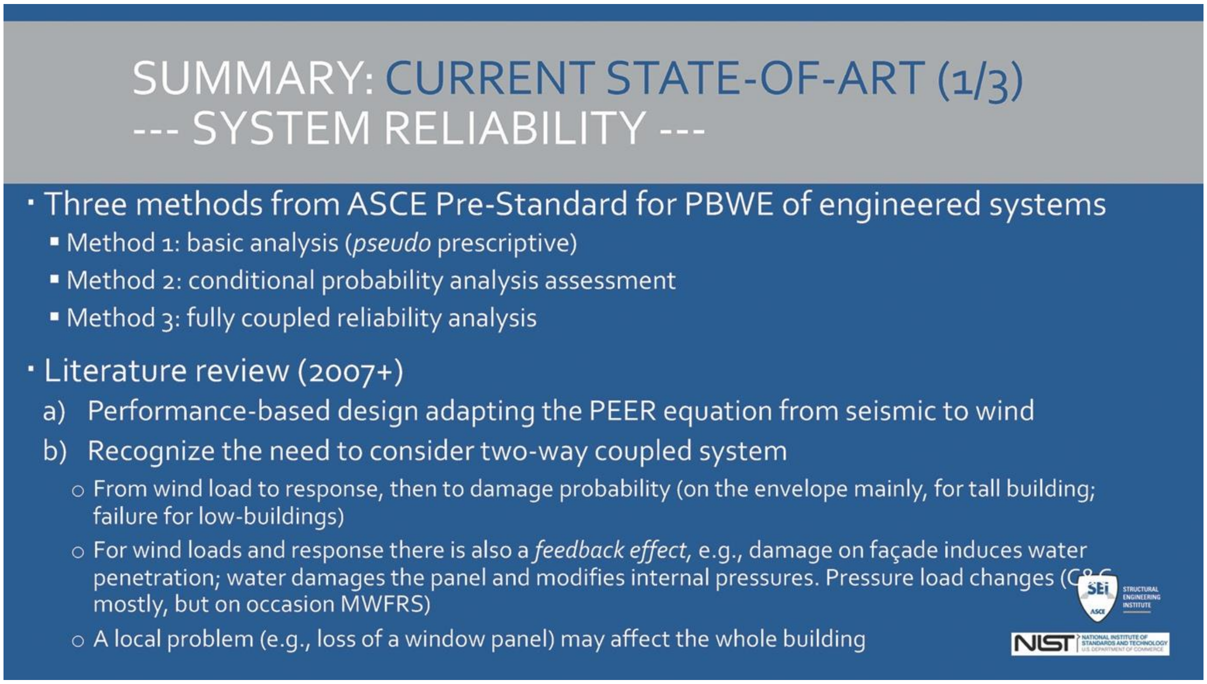


REPORT OUT:
SYSTEM RELIABILITY

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



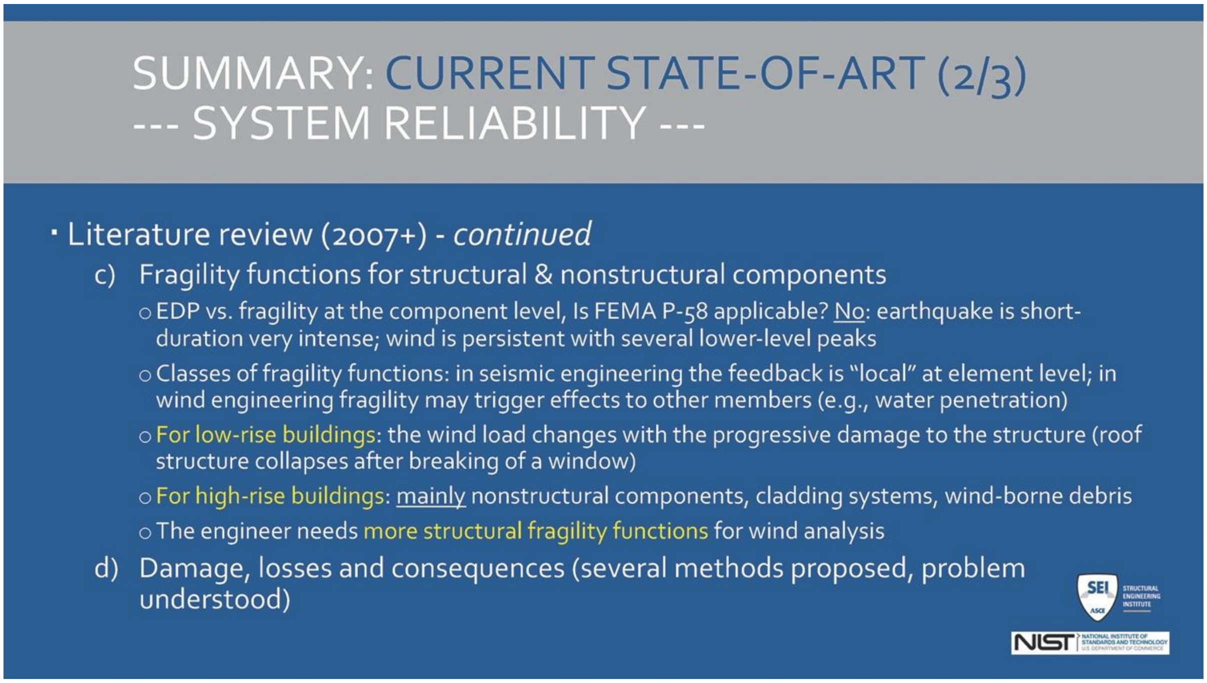
SUMMARY: CURRENT STATE-OF-ART (1/3)
--- SYSTEM RELIABILITY ---

- 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



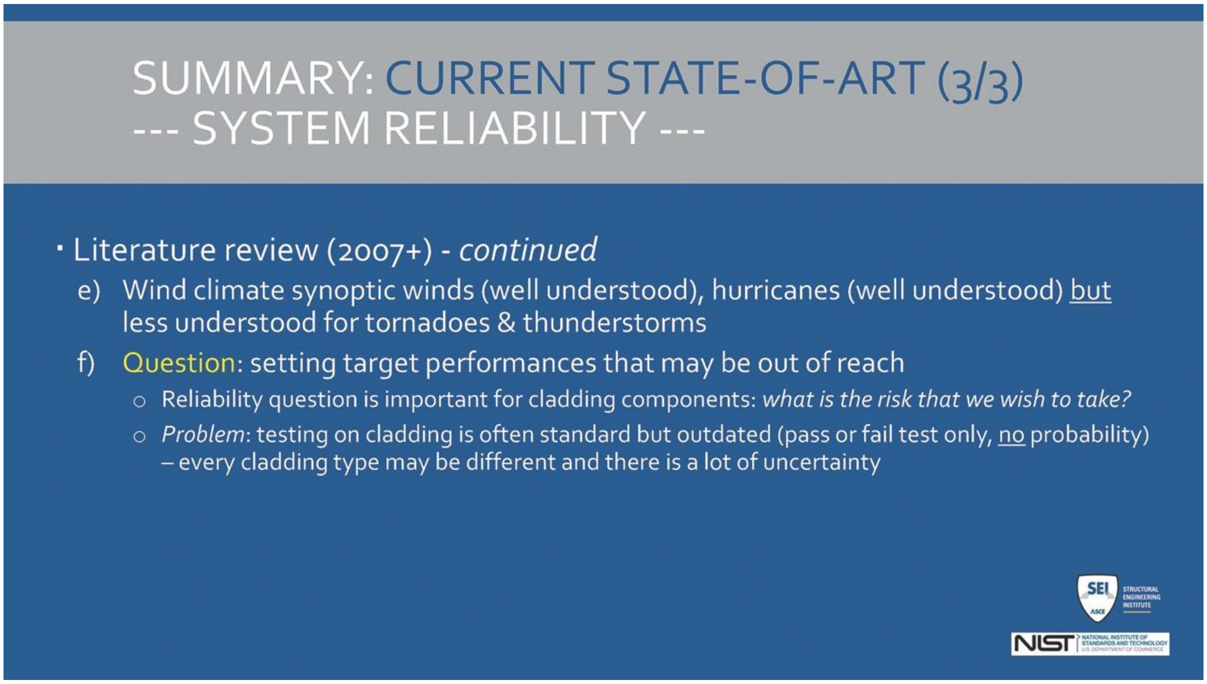
SUMMARY: CURRENT STATE-OF-ART (2/3)
--- SYSTEM RELIABILITY ---

- Literature review (2007+) - *continued*

c) Fragility functions for structural & nonstructural components

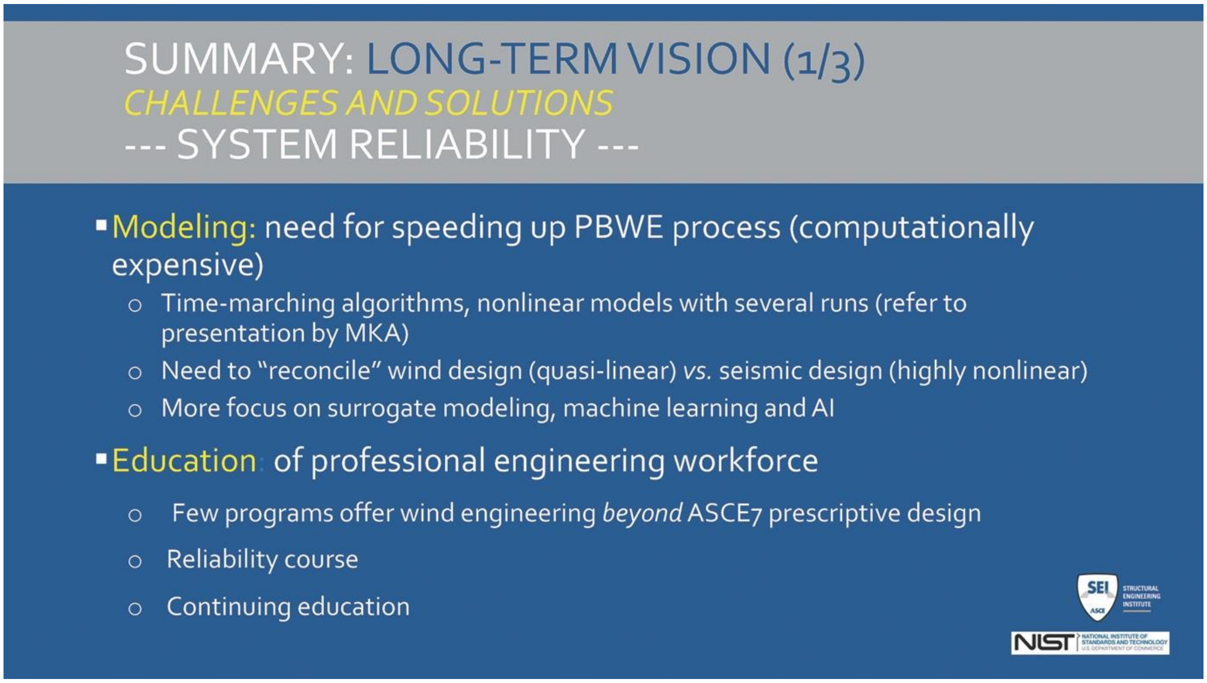
- EDP vs. fragility at the component level, Is FEMA P-58 applicable? No: earthquake is short-duration very intense; wind is persistent with several lower-level peaks
- Classes of fragility functions: in seismic engineering the feedback is "local" at element level; in wind engineering fragility may trigger 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

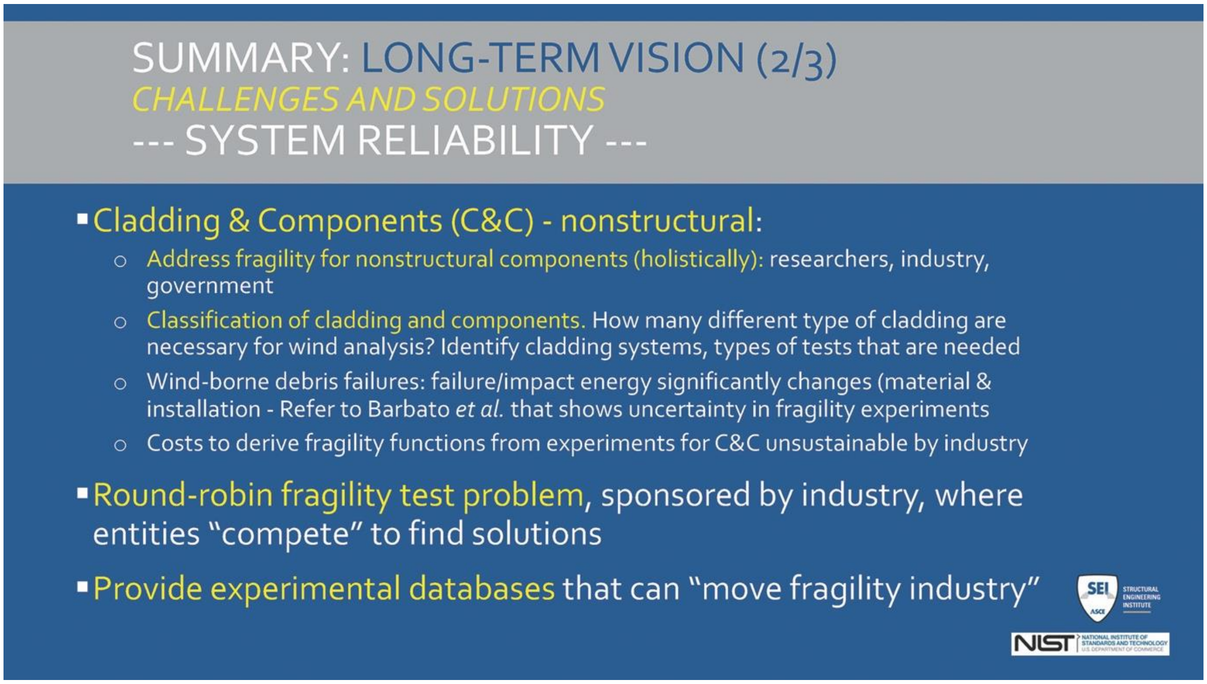


SUMMARY: LONG-TERM VISION (1/3)

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

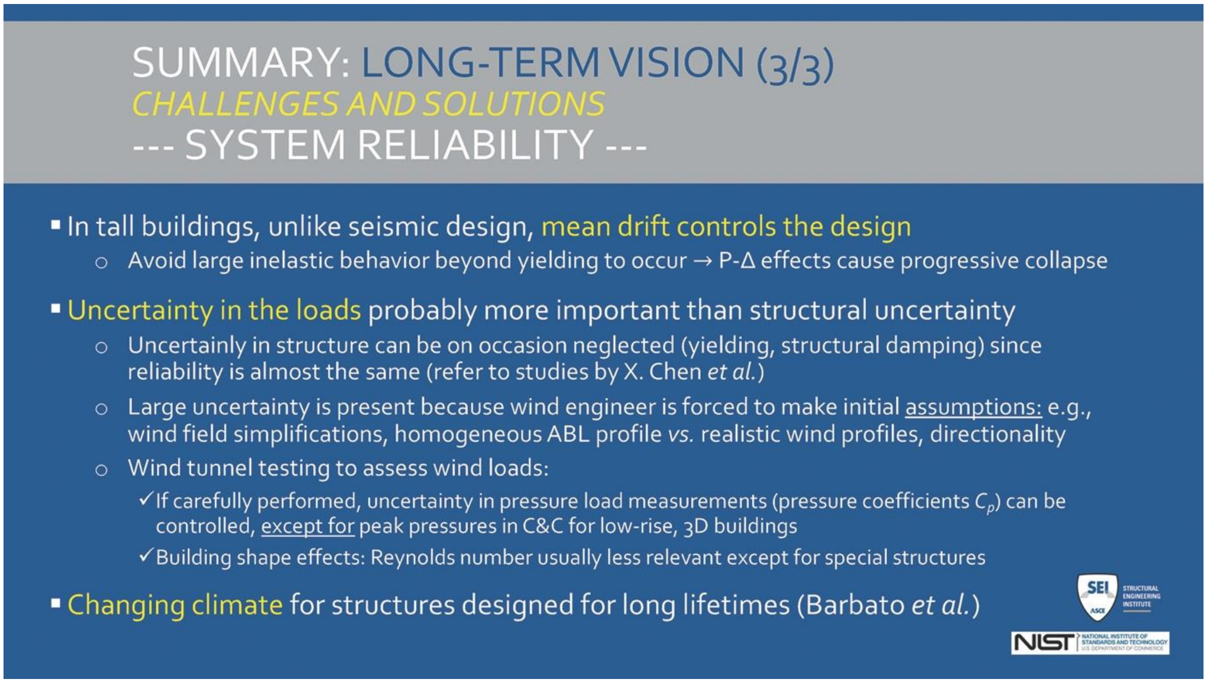


SUMMARY: LONG-TERM VISION (2/3)

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"

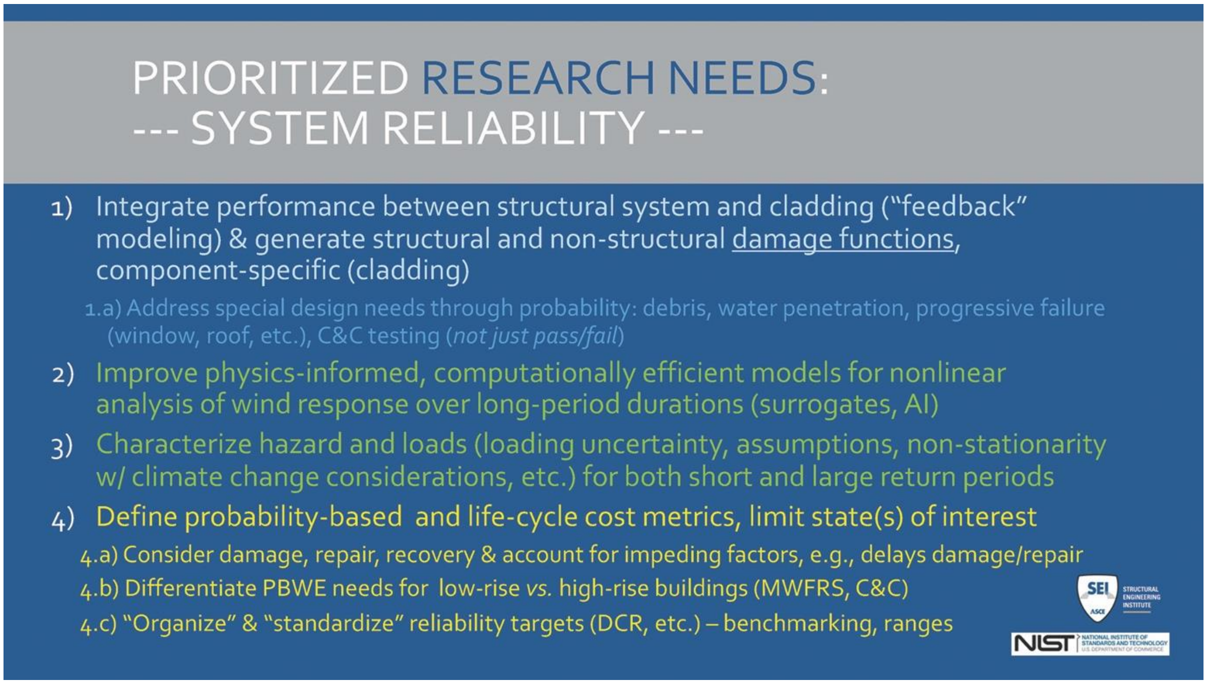


SUMMARY: LONG-TERM VISION (3/3)

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

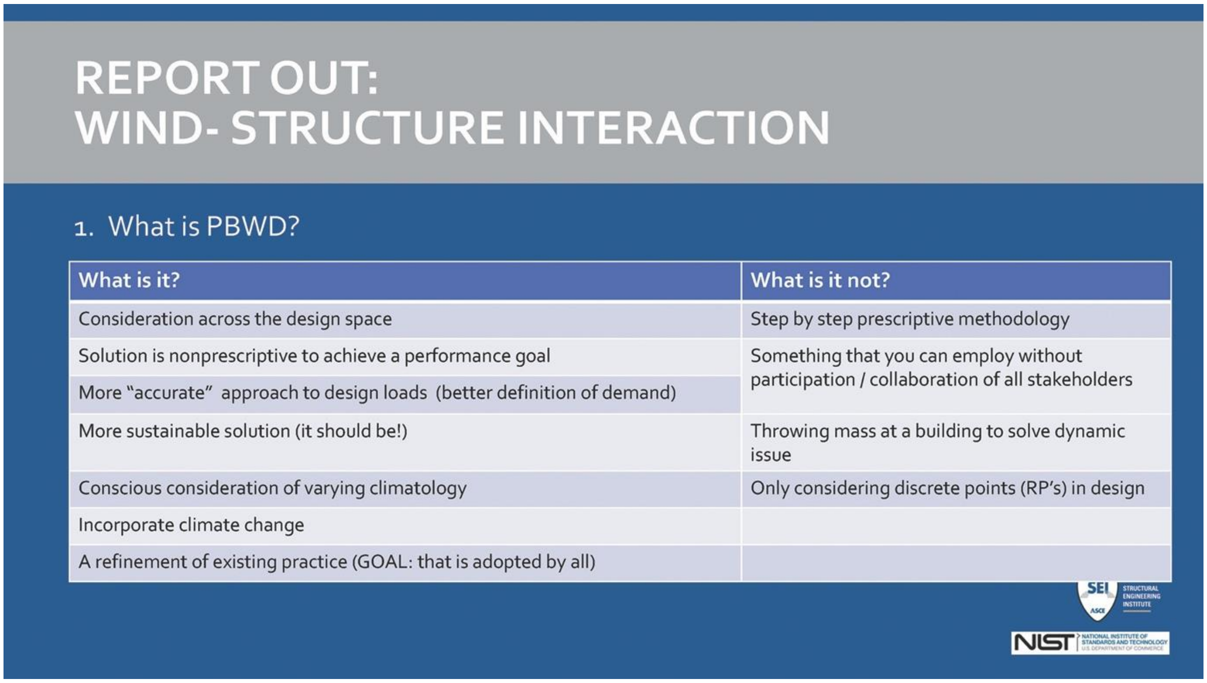
WIND-STRUCTURE INTERACTION

Jason Garber

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.;



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)	

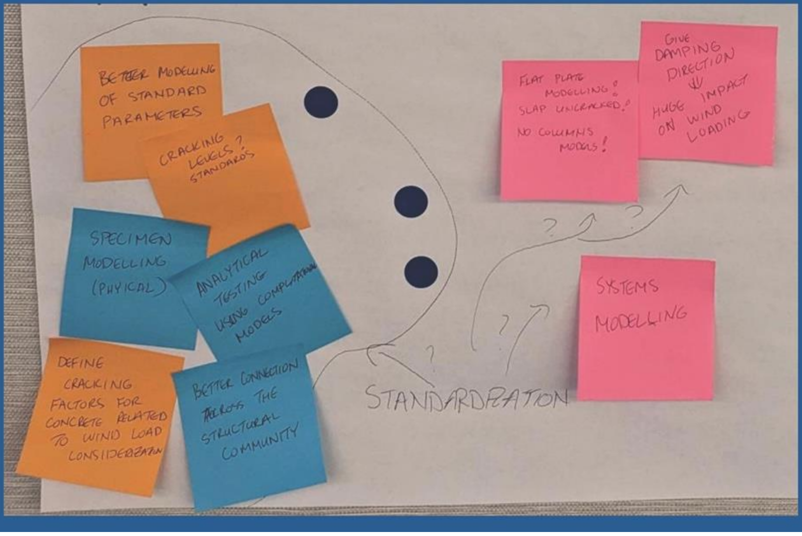
SUMMARY: CURRENT STATE-OF-ART
--- WIND- STRUCTURE INTERACTION ---

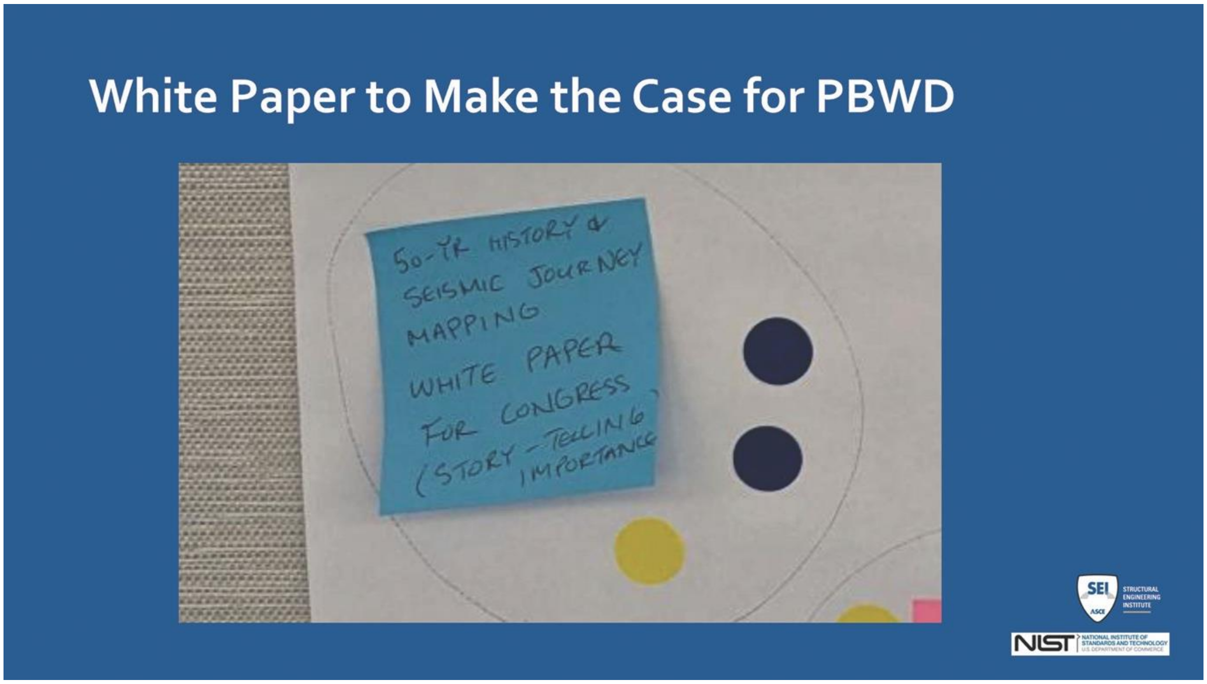
Current challenges:

- Value proposition
- Adoption by many / all

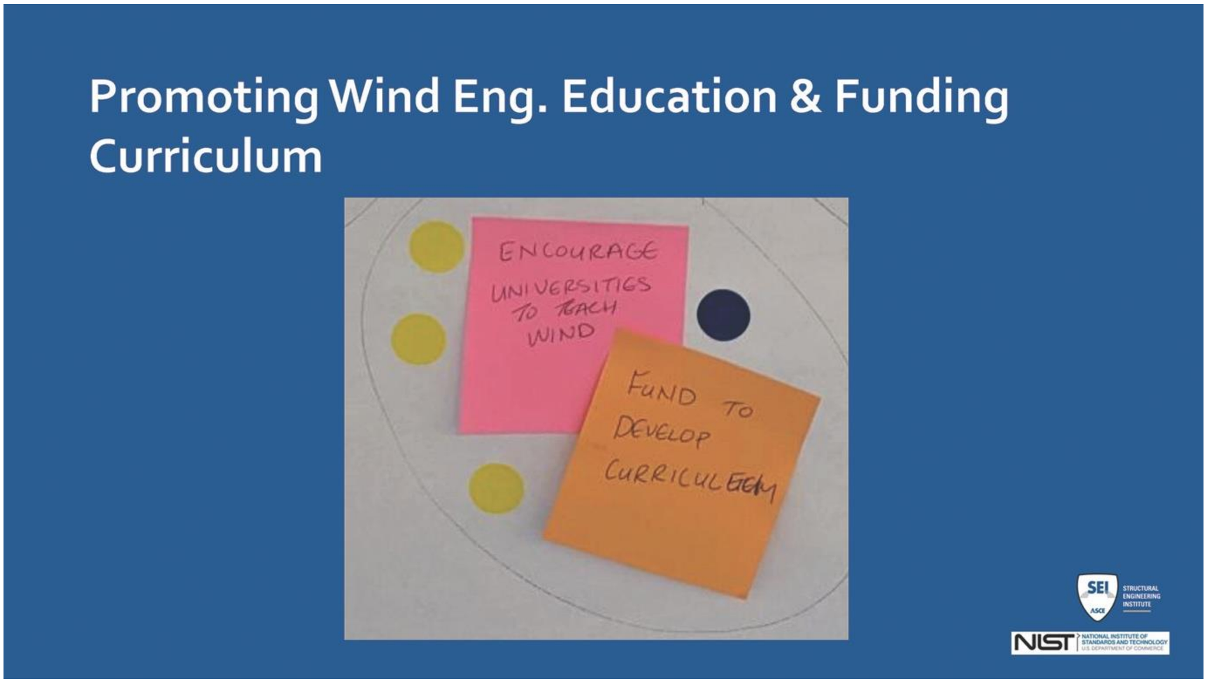
Areas of Consideration
• Time of Peak Demand / Storm Duration
• Complex Structures
• Complex Surroundings
• Computational Requirements
• Required Suites / Progressive Storm after Storm Loading
• Addressing structures where most failures arise
• Load Application / Model + Load Interaction
• Modelling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

Structural and Material Properties

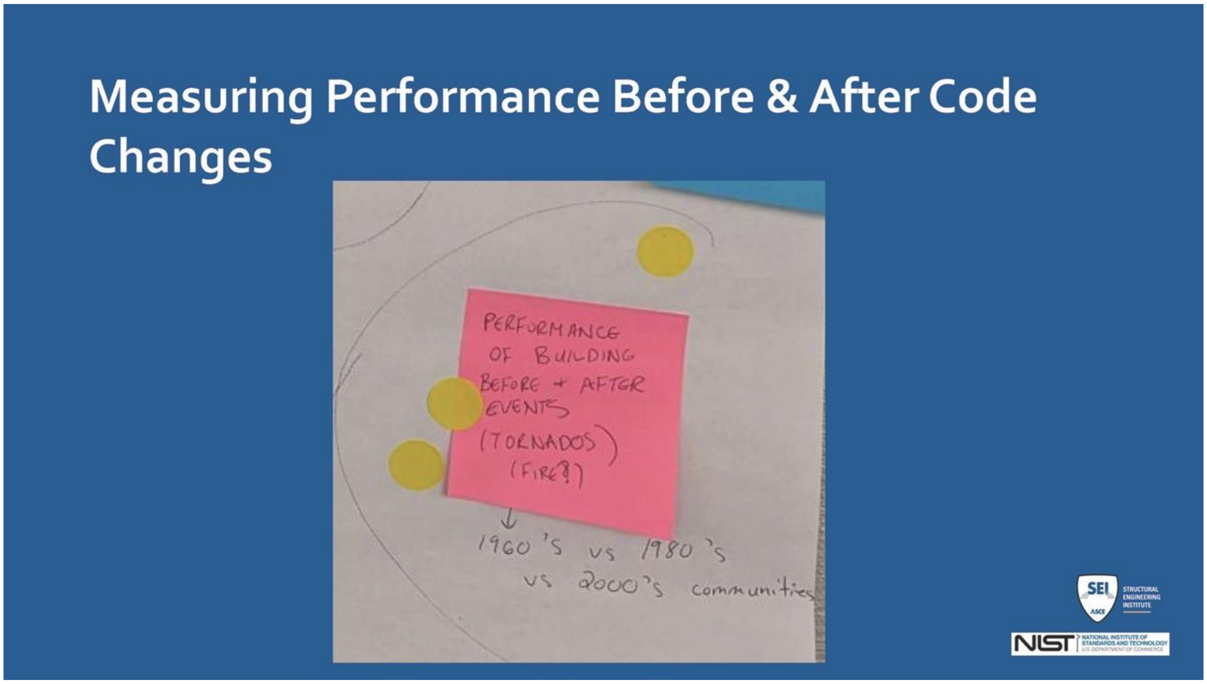




White Paper to Make the Case for PBWD



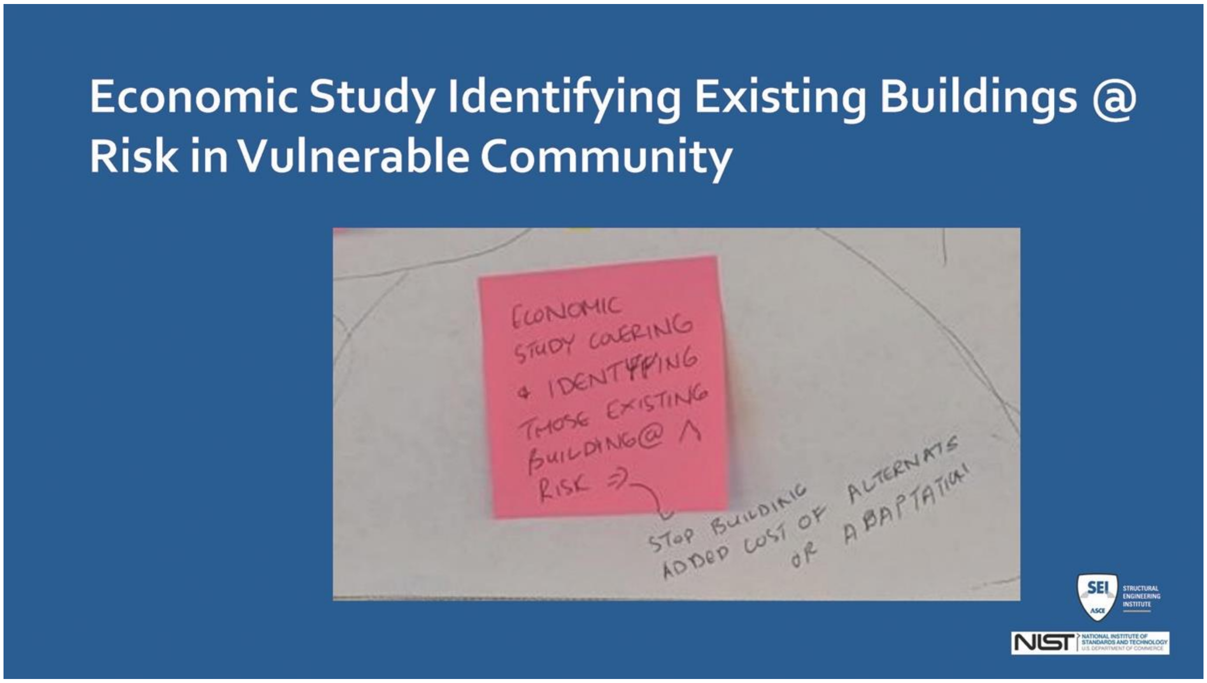
Promoting Wind Eng. Education & Funding Curriculum



Measuring Performance Before & After Code Changes

PERFORMANCE
OF BUILDING
BEFORE + AFTER
EVENTS
(TORNADOS)
(FIRE?)

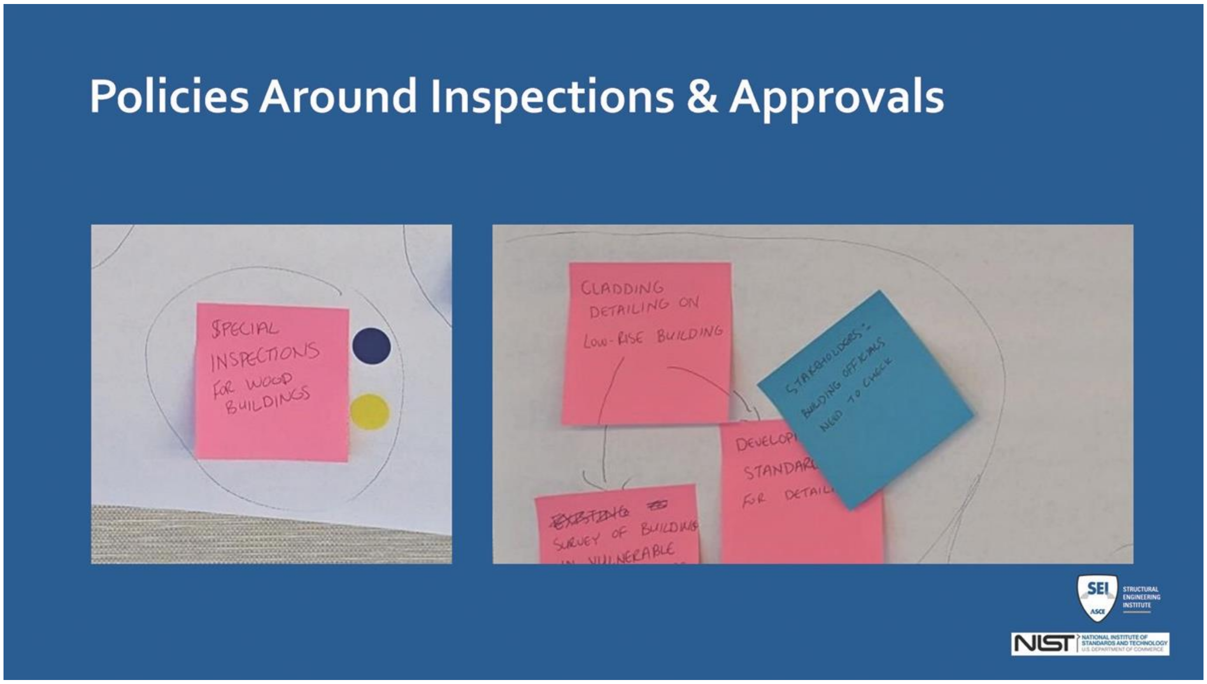
1960'S VS 1980'S
VS 2000'S communities



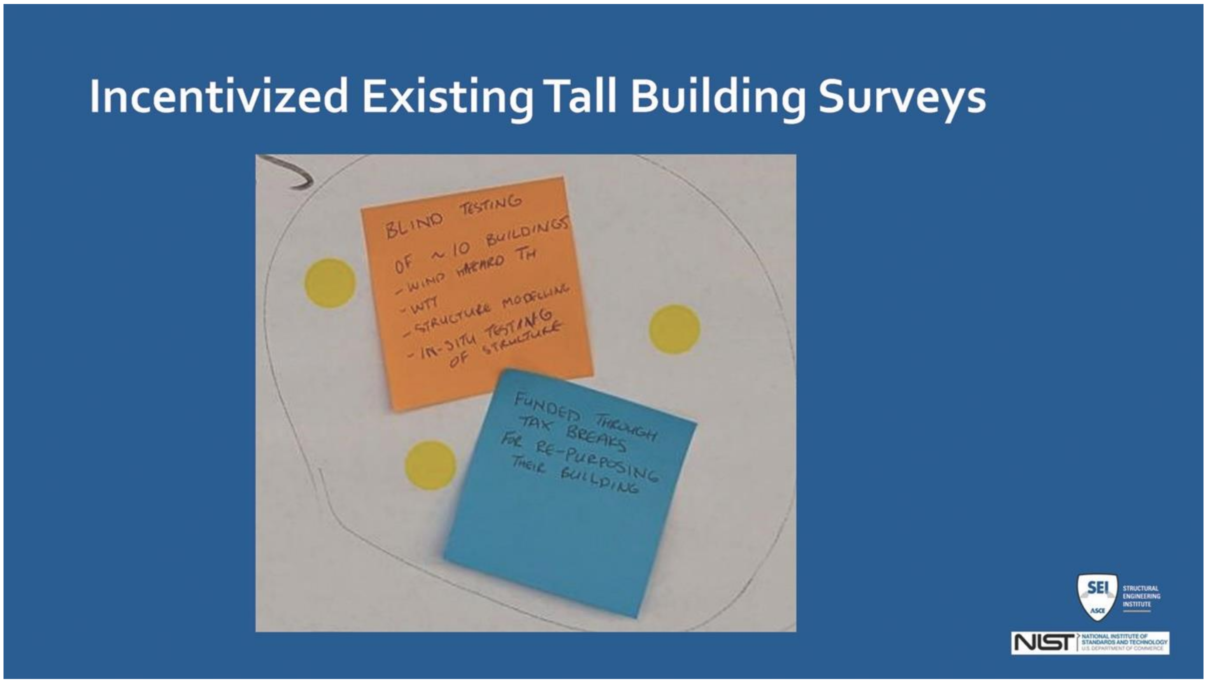
Economic Study Identifying Existing Buildings @ Risk in Vulnerable Community

ECONOMIC
STUDY COVERING
& IDENTIFYING
THOSE EXISTING
BUILDING@
RISK ⇒

STOP BUILDING
ADDED COST OF ALTERNATS
OR ADAPTATION



Policies Around Inspections & Approvals



Incentivized Existing Tall Building Surveys

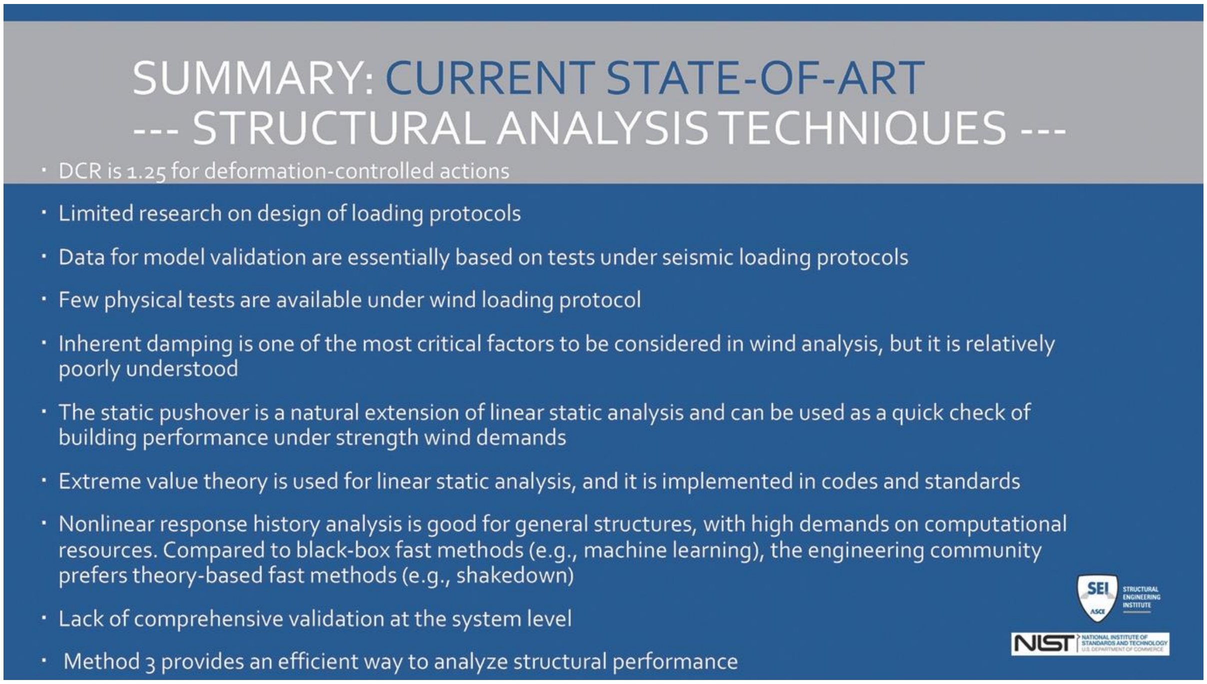
STRUCTURAL ANALYSIS TECHNIQUES

Ricardo Medina

BREAKOUT SESSION Participants:

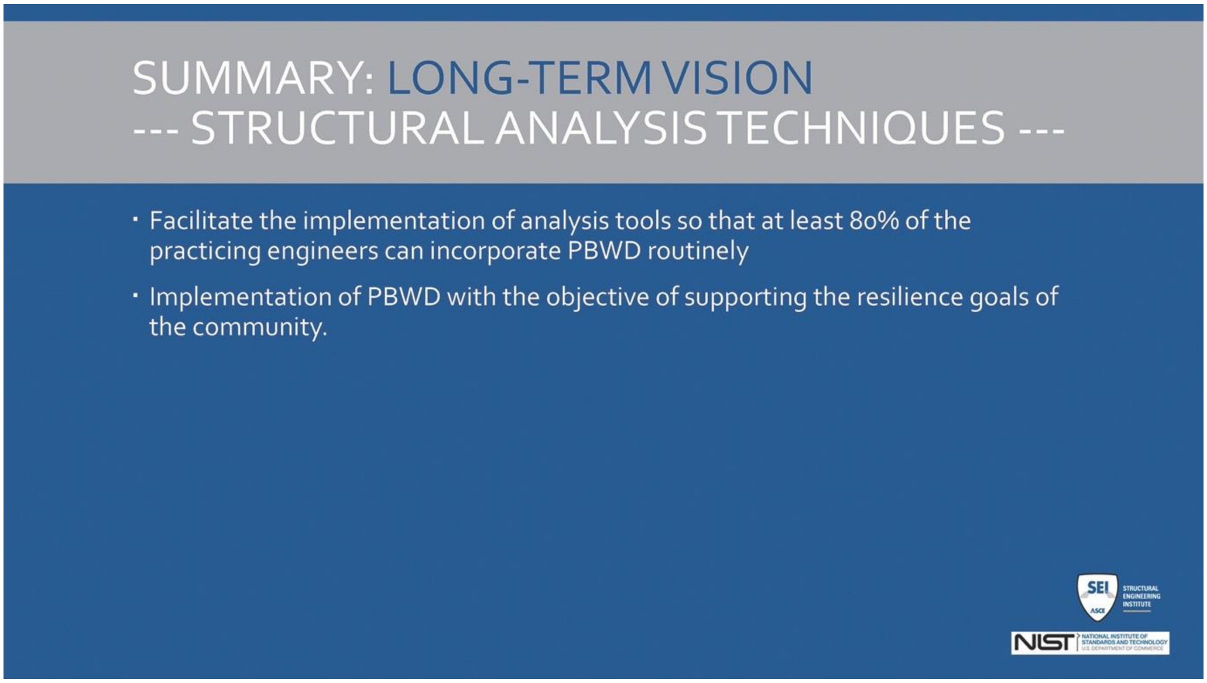
Moderator: Teng Wu
Scribe: Baichuan Deng
Reporter: Ricardo Medina

- 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

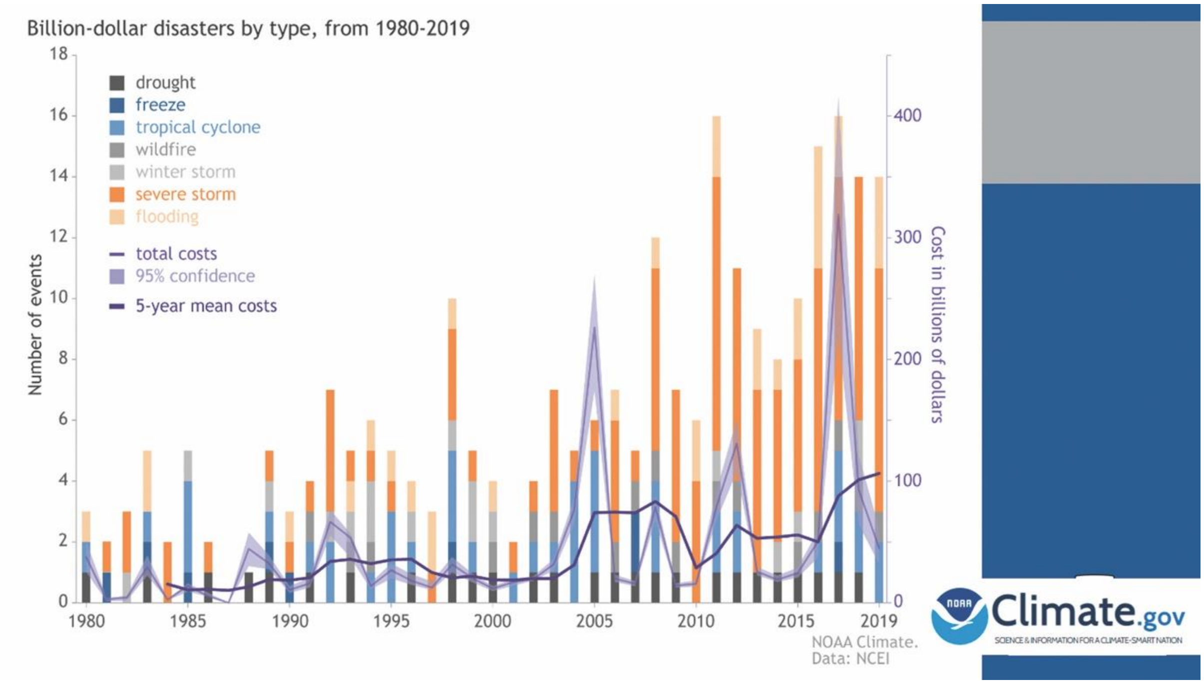
BREAKOUT SESSION Participants:

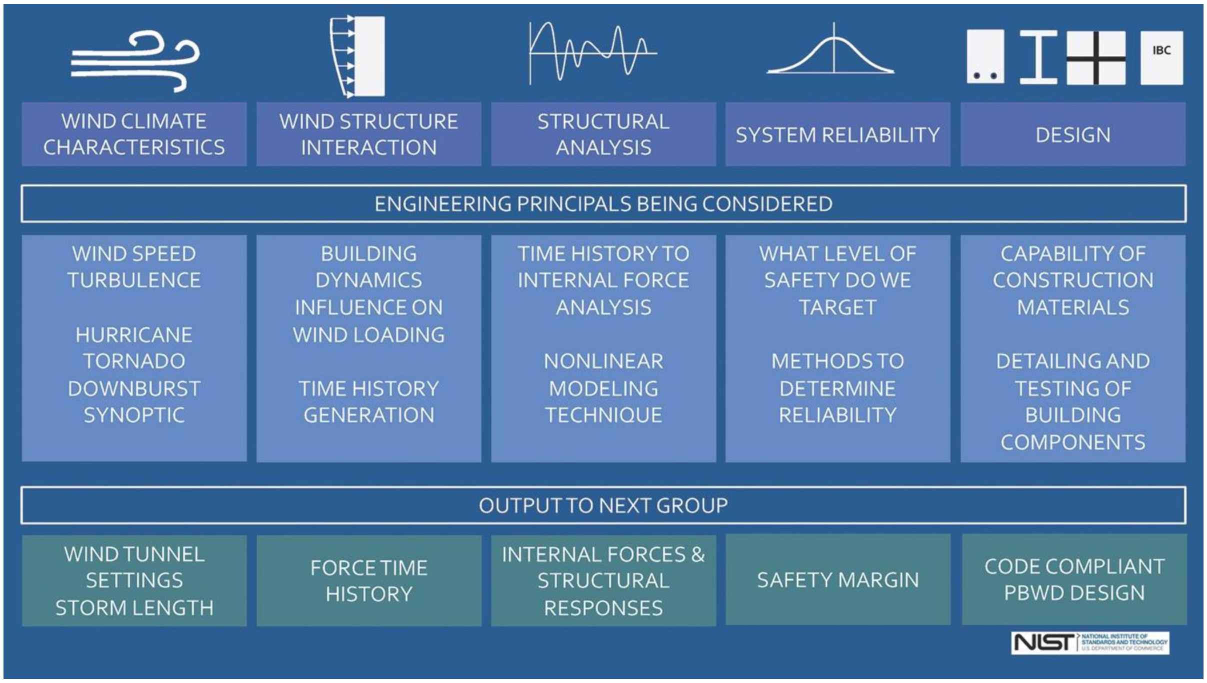
Moderator: Russell Larsen
Scribe: Juliana Rochester
Reporter: Juliana & Tom

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

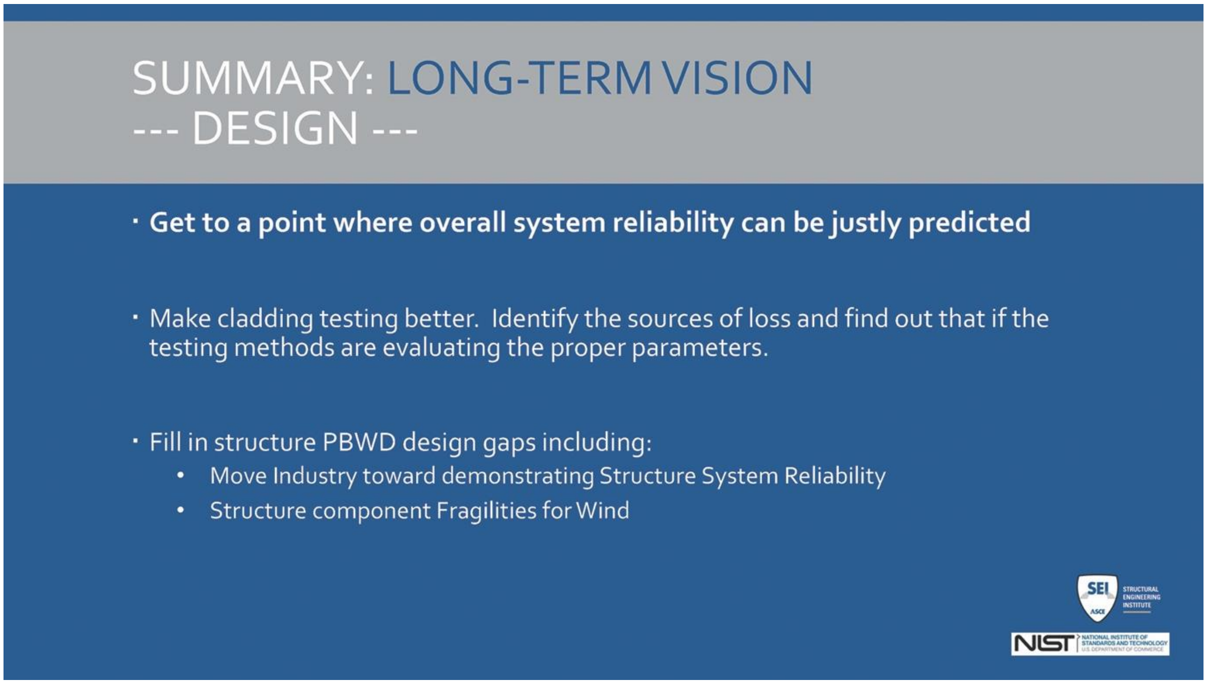
SUMMARY: CURRENT STATE-OF-ART --- DESIGN ---

- 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
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



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

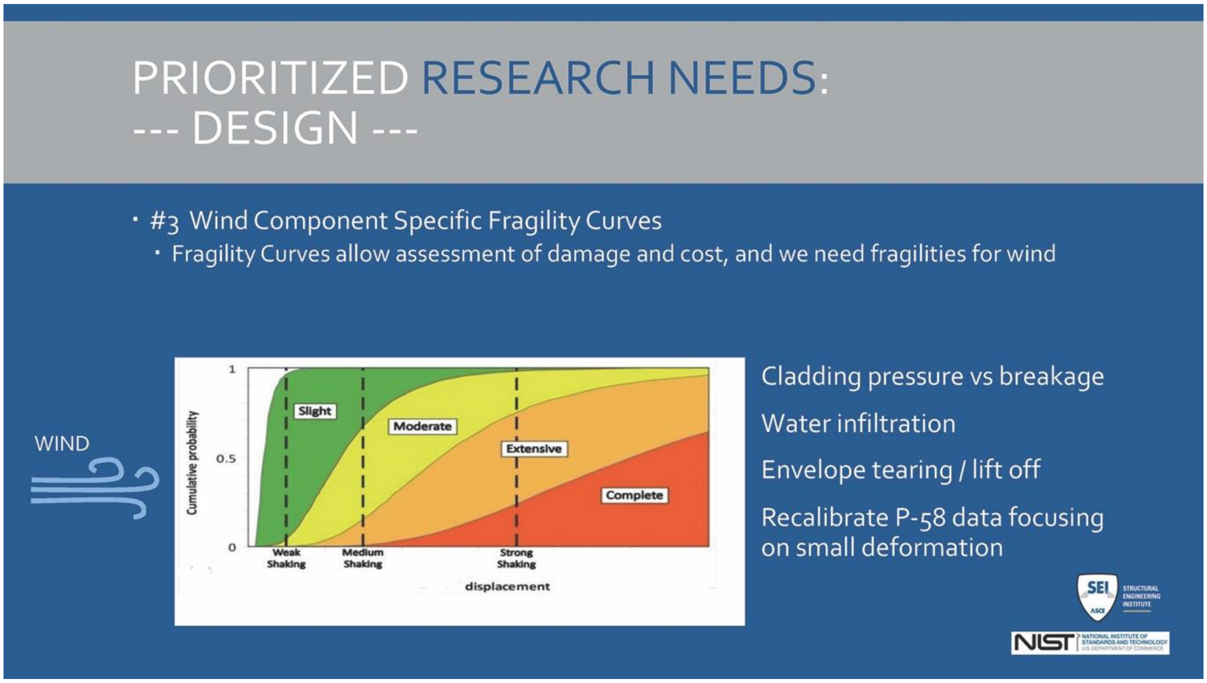
PRIORITIZED RESEARCH NEEDS:
--- DESIGN ---

- #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 ---

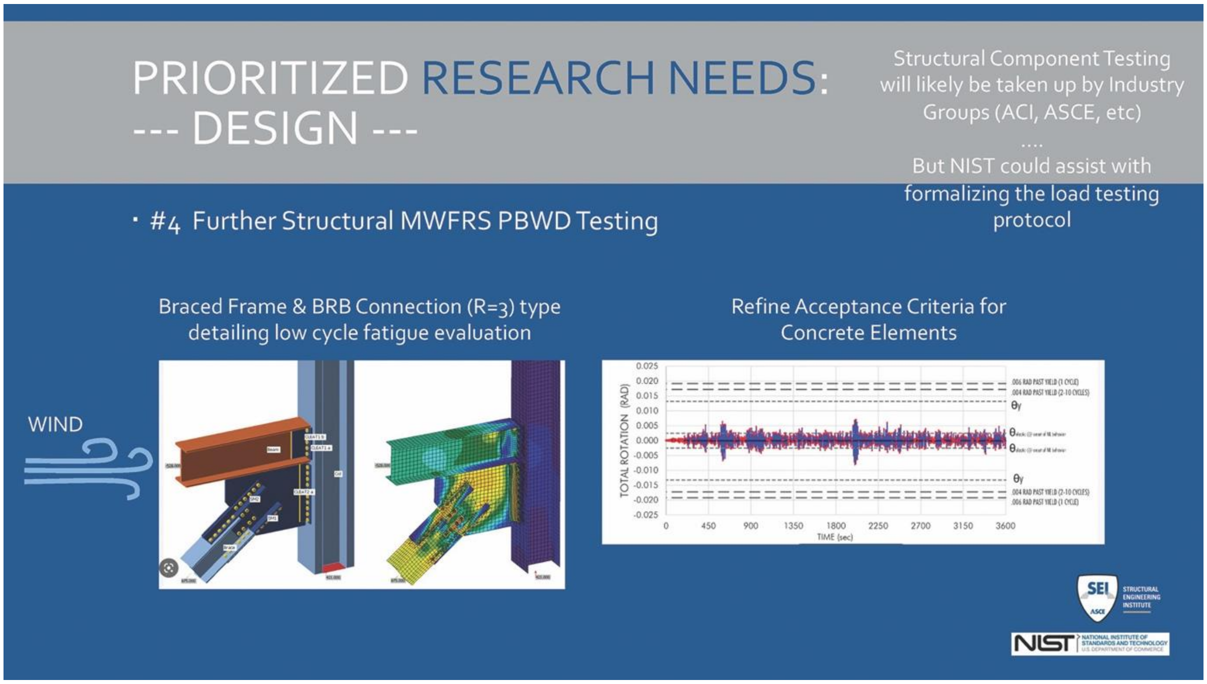
- #3 Wind Component Specific Fragility Curves
  - Fragility Curves allow assessment of damage and cost, and we need fragilities for wind

Cladding pressure vs breakage

Water infiltration

Envelope tearing / lift off

Recalibrate P-58 data focusing on small deformation



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

COFFEE BREAK

10 minutes

PANEL DISCUSSION – 30 MINUTES

Moderator:

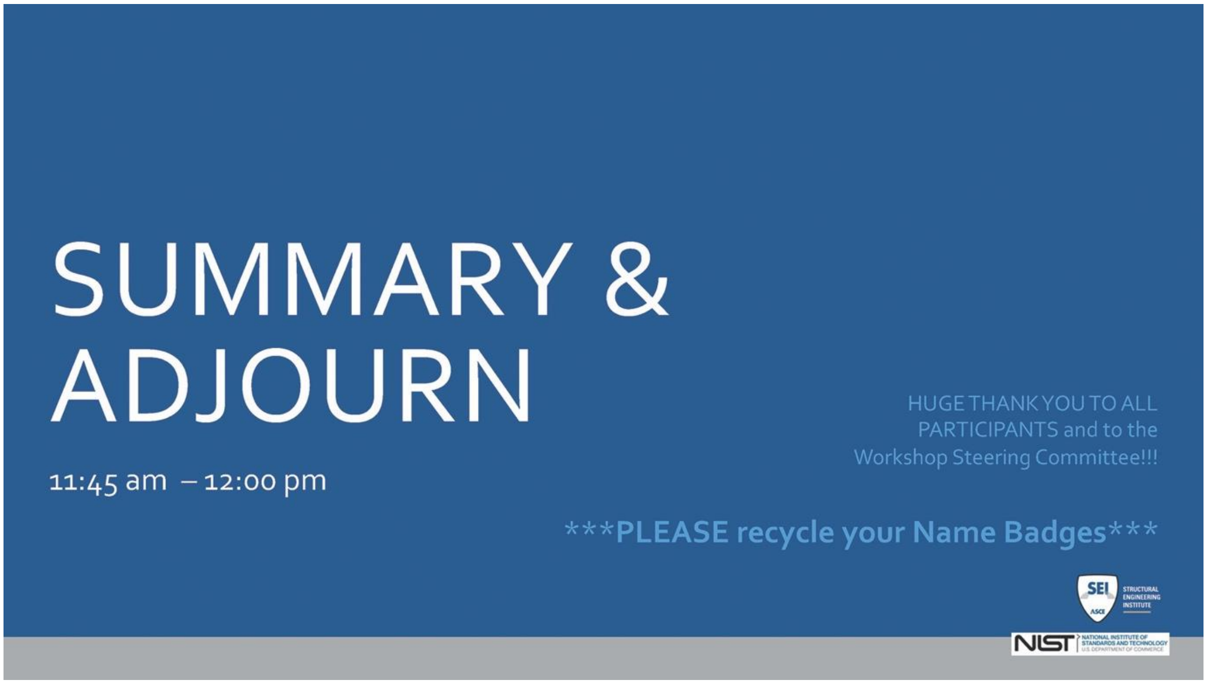
Don Scott, P.E., S.E. – Workshop Director

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*****

SEI ASCE STRUCTURAL ENGINEERING INSTITUTE

NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY U.S. DEPARTMENT OF COMMERCE

B.3. Breakout Session Participants

B.3.1. Computational Fluid Dynamics Design Tools

Moderator: **Ahsan Kareem**, F.EMI, Dist.M.ASCE; University of Notre Dame
Scribe: **Fei Ding**, Postdoctoral Scholar; NHERI SimCenter University of California, Berkeley
Participants:

- Stefano Capra, C.Eng.; MICMechE; Head of Department Advanced CFD Simulations, Ramboll
- Yunjae Hwang, Ph.D.; Postdoctoral Research, NIST
- Aleksander Jemcov, Ph.D.; Associate Research Professor, University of Notre Dame
- Arif Masud, University of Illinois at Urbana-Champaign
- Wesam Mohamed, M.E.Sc; University of Illinois at Urbana-Champaign
- Huy Pham, A.M.ASCE; Virginia Tech
- Don Scott, P.E., S.E., F.SEI, F.ASCE; President, Don Scott Consulting
- Richard Szoeke-Schuller, SimScale GmbH
- Jian-Xun Jason Wang, Ph.D.; Assistant Professor, University of Notre Dame

B.3.2. Verification and Validation Benchmark Testing

Moderator: **Ted Stathopoulos**, P.E., F.SEI, F.ASCE; Concordia University
Scribe: **Theodore Potsis**, Ph.D. Candidate; Concordia University
Participants:

- Girma Bitsuamlak, Ph.D., A.M.ASCE; University of Western Ontario
- Tsinuel Geleta, Ph.D. Candidate; Boundary Layer Wind Tunnel Laboratory and WindEEE Research Institute at Western University
- Hassan Hemida, Ph.D.; Professor, University of Birmingham, UK
- Harry Kabodha; University Student Researcher, University of Arkansas
- Claudio Mannini, Ph.D.; Assistant Professor, University of Florence (Italy)
- Joy Pauschke, Ph.D., P.E.; Program Director, NSF
- Adam Pintar, Statistician, NIST
- R. Panneer Selvam, Ph.D., P.E., F.ASCE; University Professor, University of Arkansas
- Xiaoyun Shao, P.E., M.ASCE; Professor in Structural Engineering, Western Michigan University, Department of Civil and Constructing Engineering
- Chao Sun, P.E., M.ASCE; Professor
- Yoshihide Tominaga, Ph.D.; Professor, Nigata Institute of Technology

- DongHun Yeo, Ph.D., P.E., M.ASCE; NIST

B.3.3. System Reliability and Risk

Moderator: **Melissa Burton**, Ph.D., C.Eng., M.ASCE; Arup

Scribe: **Jennifer Goupil,** P.E., F.SEI, F.ASCE; Managing Director Structural Engineering Institute and ASCE Chief Resilience Officer/**Rubina Ramponi**, Ph.D., C.Eng, MCIBSE; Arup

Participants:

- Bianca Augustin, ASCE/SEI
- David Banks, Ph.D., P.Eng., M.ASCE; President, CPP Inc.
- Lakshmana Doddipatla, Ph.D., A.M.ASCE; FM Global
- Jason Garber, M.E.Sc, P.Eng., M.ASCE; Technical Director, Principal, RWDI
- Hiroto Kataoka, Ph.D., Eng.; Senior Expert, Technology Research Institute, Obayashi Corporation
- Milad Roohi, Ph.D., A.M.ASCE; Assistant Professor, University of Nebraska-Lincoln

B.3.4. Storm Type and Generation

Moderator: **Catherine Gorle**, Aff.M.ASCE; Stanford University
Scribe: **Mattia Ciarlatani**, Ph.D. Candidate; Stanford University
Participants:

- Bilal Alhawamdeh, Ph.D., A.M.ASCE; Western Michigan University
- Yanlin Guo, Ph.D.; Colorado State University
- Fred Haan, Ph.D., A.M.ASCE; Professor of Engineering, Calvin University
- Faiaz Khaled, Ph.D.; Postdoctoral Research Associate, University of Illinois Urbana–Champaign
- Marc Levitan, Ph.D., A.M.ASCE; NIST
- Lance Manual, Ph.D., P.E., DOE, F.SEI, F.ASCE, Professor, UT Austin
- Abiy Melaku, Ph.D., Aff.M.ASCE; Postdoctoral Scholar, NHERI SimCenter, University of California, Berkeley
- David S. Nolan, Ph.D.; Professor of Atmospheric Sciences, University of Miami
- Gonçalo Pedro, Ph.D.; Technical Director–Labs, RWDI
- Dan Rhee, Ph.D., A.M.ASCE; Research Structural Engineer, NIST
- Delong Zuo, A.M.ASCE; Professor, Texas Tech University

B.3.5. Structural Engineering Applications

Moderator: **Bradley Young**, P.E., S.E., M.ASCE; Skidmore, Owings & Merrill
Scribe: **Austin Devin**, P.E., Ph.D.; Skidmore, Owings & Merrill
Participants:

- Matiyas Bezabeh, Ph.D.; Assistant Professor of Civil Engineering, McGill University, Montreal, Canada
- Jan Dale, P.Eng., M.ASCE; Technical Director/Principal, Rowan Williams Davies & Irwin Inc.
- Roy Denoon, Ph.D., M.ASCE; Senior Principal/Vice President, CPP Wind Engineering Consultants
- Rakesh K. Kapania, Ph.D., F.AIAA, A.M.ASCE; Mitchell Professor of Aerospace and Ocean Engineering, Virginia Tech
- Emily Kim, P.E.; Structural Engineer, HDR Inc.
- Long Phan, Ph.D., P.E., M.ASCE, F.ACI; NIST
- David Phillips, Ph.D., Software Architect, Cadence Design Systems
- Sumanth Reddy
- Rob Rowsell, C.Eng, IMechE; Wirth Research Ltd
- Ting Shi, P.E., PMP; Senior Civil/Structural Engineer, Division of LNG, Office of Energy Projects, Federal Regulatory Commission
- Seymour M.J. Spence, Ph.D., M.ASCE; Associate Professor, University of Michigan
- Teng Wu, Ph.D., M.ASCE; Associate Professor, University at Buffalo

B.4. Workshop Reading Material

NIST CWE Workshop: Reading List 1/9/2023

Melissa Burton:

AWES: Quality Assurance Manual Wind Engineering Studies of Buildings (https://www.awes.org/product/quality-assurance-manual-wind-engineering-studies-of-buildings/)

Additional material:

ASCE 49: Wind Tunnel Testing for Buildings and Other Structures (https://ascelibrary.org/doi/book/10.1061/9780784412282)

Ted Stathopoulos:

Additional materials:

Geleta, T. N., and Bitsuamlak, G. (2022). Validation metrics and turbulence frequency limits for LES-based wind load evaluation for low-rise buildings. Journal of Wind Engineering and Industrial Aerodynamics, 231, 105210. https://doi.org/https://doi.org/10.1016/j.jweia.2022.105210

Ricci, M., Patruno, L., and de Miranda, S. (2017). Wind loads and structural response: Benchmarking LES on a low-rise building. Engineering Structures, 144, 26–42. - ASCE https://doi.org/10.1016/J.ENGSTRUCT.2017.04.027

Stathopoulos, T. (1997). Computational wind engineering: Past achievements and future challenges. Journal of Wind Engineering and Industrial Aerodynamics, 67–68, 509–532. https://doi.org/10.1016/S0167-6105(97)00097-4

Yan, B. W., and Li, Q. S. (2015). Inflow turbulence generation methods with large eddy simulation for wind effects on tall buildings. Computers and Fluids, 116, 158–175. https://doi.org/10.1016/J.COMPFLUID.2015.04.020

Ahsan Kareem:

Additional materials:

Ding, F., Kareem, A. and Wan, J. (2019). Aerodynamic Tailoring of Structures Using Computational Fluid Dynamics.

Kareem, A. (2020). Emerging frontiers in wind engineering: Computing, stochastics, machine learning and beyond.

Brad Young:

Additional materials:

Towards a standard CFD setup for wind load assessment of high-rise buildings: Part 1 - Benchmark of the CAARC building. Thordal, Bennetsen, Capra, Koss, Journal of Wind Engineering and Industrial Aerodynamics, Volume 205, October 2020

Towards a standard CFD setup for wind load assessment of high-rise buildings: Part 2 - Blind test of chamfered and rounded corner high-rise buildings. Thordal, Bennetsen, Capra, Kragh, Koss, Journal of Wind Engineering and Industrial Aerodynamics, Volume 205, October 2020.

Catherine Gorle:

Additional materials:

Sensitivity of LES predictions of wind loading on a high-rise building to inflow boundary condition. Lamberti, Gorle, Journal of Wind Engineering and Industrial Aerodynamics, Volume 206, September 2020

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 Goal B of NWIRP is "Improve the Understanding of Windstorm Impacts on Communities," while Objective No. 5 and Objective No. 6 for this program are "Advance understanding of windstorm effects on the building environment" and "Develop computational tools for use in wind and flood modeling on buildings and infrastructure." Also, from the 2014 NIST *Measurement Science R&D Roadmap for Windstorm and Coastal Inundation Impact Reduction* study Research Topic No. 6: "Pressure coefficient for wind load determination, the development of CFD tools was addressed."

The following language is taken directly from the NWIRP Strategic Plan document with references to the workshop Priority Research Needs added in bold and brackets to show how the Workshop Research Needs are consistent with the Program Elements of the NIST NWIRP program.

NWIRP Objective No. 5, "Advance Understanding of Windstorm Effects on the Building Environment"

> Basic and applied research to advance engineering knowledge of windstorm effects on the built environment is needed. Such research should seek to improve understanding of civil infrastructure vulnerabilities in extreme windstorm events, refine computational tools to predict performance of civil infrastructure including water and wastewater, communications, energy, and transportation systems, and advance knowledge to improve relevant codes and standards **[Priority Research Need 1].** This includes studying the effects of extreme winds, wind-borne debris, and wind-driven rain **[Priority Research Needs 3, 5, and 9],** as well as understanding the overland flow hazard, and the subsequent loads and structural responses for storm surge. For most of the United States outside of the hurricane-prone region, tornadoes and thunderstorms cause the greatest wind damage to building and power and communication infrastructure.
>
> Thunderstorms: The effects on buildings and structures of the short duration and vertical variations of wind speed and turbulence intensity in thunderstorm downburst are largely unknown. Although thunderstorms are the largest contributor to the wind speed hazards in locations outside hurricane-prone regions, the wind loading provisions given in codes are based on research for stationary boundary layer wind and their effects on buildings. It is therefore important to develop a better understanding of the relationship between transient thunderstorm downburst winds, their resulting loads, and response of structures to these loads. An improved understanding of these loads could be achieved through experimental and computational modeling (downburst simulators) and full-scale experiments **[Priority Research Needs 3, 7, and 9].**

Tornadoes: Our understanding of the mechanisms by which tornadoes impart loads on buildings and other structures is still in its infancy. For example, little is known about the role of atmospheric pressure change (APC) in tornado-induced loads, or the characteristics of the tornado turbulent winds near the ground and their effect on loads. The atmospheric pressure change load on buildings has largely been disregarded in the past by assuming building in tornadoes have been damaged to the extent that the internal pressure and external pressures due to APC balance and therefore APC can be ignored when calculating loads. This assumption has never been validated and may well be wrong. Our understanding of tornadic wind loads can be improved using field and full-scale experiments, laboratory experiments, and numerical modeling.

Wind-borne Debris and Wind-Driven Rain: Advancements needed in the understanding of wind-borne debris include the effect of the type of windstorm, the duration of the storm, and the density and sources of debris. Improved debris impact assessments **[Priority Research Need 5]** and modeling will lead to improved probabilistic models to quantify wind-borne debris impact frequencies, velocities, momenta, and energy for developing risk-consistent design/test criteria. Similarly, improved testing methods are needed to evaluate wind-driven rain at the component and assembly levels **[Priority Research Need 5]**. A better understanding of how water penetrates the building envelope and what damage it causes once inside is needed.

Improved tools for estimating wind and flood induced loads and resistances are needed to enable the prediction of wind and flood performance of structures without having to resort to physical models, either full-scale or model-scale. Computational tools are needed to automatically incorporate structure specific location data that can affect the hazard data given in maps.

…

Wind-tunnel Test Database: Engineers often use publicly available databases containing wind tunnel test data for their research. These data have been used for developing new load criteria for wind loading standards and in loss modeling tools. It is desirable that these databases be expanded to assess the effects of extreme windstorms on more building types and geometries **[Priority Research Needs 2 and 4]**. These data can improve requirements of code and standards.

Outcome: Improved understanding of the interaction between windstorm hazards (extreme winds, atmospheric pressure change, wind-borne debris, wind-driven rain, storm surge, and wind-driven waves) and building and other structures, lifelines, and infrastructure. Research conducted to improve the understanding of windstorm effects on the built environment is a long-term effort.

NWIRP Objective 6, “Develop Computational Tools for Use in Wind and Flood Modeling on Buildings and Infrastructure”

Computational Windstorm Loads: Wind and flood load criteria given in design standards have been developed using results from limited model and full scale tests. Computational methods for evaluating wind and coastal flood loads on building and infrastructure hold great promise to improve load estimates, expanding on the limited experimental data to provide better load standards compared to current engineering practice. Thes computational tolls cannot yet provide reliable estimates of aerodynamic or hydrodynamic loads suitable for design calculations, and continued research is needed so that reliable load estimates can be made. The long term goal is to advance these computational tools to the point where they can replace physical tests and even be used in a design office, replacing the approaches used today where loads are estimated using simplified graphs and equations given in load standards. Improved computational fluid dynamics (CFD) for modeling overland water currents and waves, and their interaction with the building environment, will improve the estimation of coastal flood loads on structures thereby improving load standards. A key to verification of CFD tools is comparisons to model and full scale data, with the full scale data in real-time during windstorm events **[Priority Research Needs 2, 3, 6, and 9]**.

Automated Data Extraction: Computer tolls that poll data bases, including aerial and satellite imagery, to automatically determine the surface roughness and terrain exposure in which a structure is located would improve the accuracy of the terrain category required in the wind design process. Computer tools that use digital elevation data to automatically evaluate data to automatically evaluate topographic effects on wind speeds would eliminate the need for designers to estimate speed-ups with a difficult to use and very approximate method in current standards. Terrain and speed up effects are particularly important for the design of communications and transmission towers that are often intentionally located on tops of hills.

Outcome: Tools to incorporate local data to further automate the design process, increasing efficiency and accuracy, and reducing errors. Advances in computational wind engineering to the point where it can replace model test and wind load standards. The development of tools in incorporate local data into the design process is a short-term effort. The use of computational tools in lieu of model tests or load standards is a long-term effort requiring significant research, development, and validation.

The following language is taken directly from the NIST *Measurement Science R&D Roadmap for Windstorm and Coastal Inundation Impact Reduction* document with references to the workshop Priority Research Needs added in bold and brackets to show indicating how the Workshop Research Needs are consistent with the Program Elements of the NIST program.

Item 4.2.2–1

> Wind loading simulation tools (e.g., computational fluid dynamics) need to be developed for use in the practice of wind engineering, and must be validated by other wind pressure testing or calculation methods **[Priority Research Needs 2, 6, and 8].**

Appendix D. Program Participants: Alphabetical List

Bilal Alhawamdeh, Ph.D., A.M.ASCE		Western Michigan University
Bianca Augustin	Workshop Coordinator	ASCE/SEI
David Banks, Ph.D., P.Eng., M.ASCE	President	CPP Inc.
Matiyas Bezabeh, Ph.D.	Assistant Professor of Civil Engineering	McGill University, Montreal, Canada
Girma Bitsuamlak, Ph.D., A.M.ASCE		University of Western Ontario
Melissa Burton, Ph.D., C.Eng., M.ASCE	Principal	Arup
Stefano Capra, C.Eng.; MICMechE	Head of Department Advanced CFD Simulations	Ramboll
Mattia Ciarlatani, Ph.D. Candidate		Stanford University
Jan Dale, P.Eng., M.ASCE	Technical Director/Principal	Rowan Williams Davies & Irwin Inc.
Roy Denoon, Ph.D., M.ASCE	Senior Principal/Vice President	CPP Wind Engineering Consultants
Austin Devin, P.E., Ph.D.		Skidmore, Owings & Merrill
Fei Ding	Postdoctoral Scholar	NHERI SimCenter University of California, Berkeley
Lakshmana Doddipatla, Ph.D., A.M.ASCE		FM Global
Jason Garber, M.E.Sc, P.Eng., M.ASCE	Technical Director, Principal	RWDI
Tsinuel Geleta, Ph.D. Candidate		Boundary Layer Wind Tunnel Laboratory and WindEEE Research Institute at Western University
Catherine Gorle, Aff.M.ASCE		Stanford University
Jennifer Goupil, P.E., F.SEI, F.ASCE	Managing Director, SEI, and Chief Resilience Officer	ASCE/SEI
Yanlin Guo, Ph.D.		Colorado State University
Fred Haan, Ph.D., A.M.ASCE	Professor of Engineering	Calvin University
Emily Kim, P.E.	Structural Engineer	HDR Inc.
Lance Manual	Professor	UT Austin
Claudia Marin	Professor	Howard University
Hassan Hemida, Ph.D.	Professor	University of Birmingham, UK
Yunjae Hwang, Ph.D.	Postdoctoral Research	NIST
Aleksander Jemcov, Ph.D.	Associate Research Professor	University of Notre Dame
Harry Kabodha	University Student Researcher	University of Arkansas
Rakesh K. Kapania, Ph.D., F.AIAA, A.M.ASCE	Mitchell Professor of Aerospace and Ocean Engineering	Virginia Tech
Ahsan Kareem, F.EMI, Dist.M.ASCE		University of Notre Dame
Hiroto Kataoka, Ph.D., Eng.	Senior Expert	Technology Research Institute, Obayashi Corporation

Faiaz Khaled, Ph.D.	Postdoctoral Research Associate	University of Illinois Urbana–Champaign
Marc Levitan, Ph.D., A.M.ASCE		NIST
Claudio Mannini, Ph.D.	Assistant Professor	University of Florence (Italy)
Arif Masud, Ph.D., F.EMI, M.ASCE	Professor	University of Illinois at Urbana–Champaign
Abiy Melaku, Ph.D., Aff.M.ASCE	Postdoctoral Scholar	NHERI SimCenter, University of California, Berkeley
Wesam Mohamed, M.E.Sc		University of Illinois at Urbana–Champaign
David S. Nolan, Ph.D.	Professor of Atmospheric Sciences	University of Miami
Joy Pauschke, Ph.D., P.E.	Program Director	NSF
Gonçalo Pedro, Ph.D.	Technical Director–Labs	RWDI
Huy Pham, A.M.ASCE		Virginia Tech
Long Phan, P.E., M.ASCE, F.ACI		NIST
David Phillips, Ph.D.	Software Architect	Cadence Design Systems
Adam Pintar	Statistician	NIST
Theodore Potsis, Ph.D. Candidate		Concordia University
Rubina Ramponi, Ph.D., C.Eng., MCIBSE		Arup
Sumanth Reddy		
Dan Rhee, Ph.D., A.M.ASCE	Research Structural Engineer	NIST
Milad Roohi, Ph.D., A.M.ASCE	Assistant Professor	University of Nebraska-Lincoln
Rob Rowsell, C.Eng., IMechE		Wirth Research Ltd
Don Scott, P.E., S.E., F.SEI, F.ASCE	President	Don Scott Consulting
R. Panneer Selvam, Ph.D., P.E., F.ASCE	University Professor	University of Arkansas
Xiaoyun Shao, P.E., M.ASCE	Professor in Structural Engineering	Western Michigan University, Department of Civil and Constructing Engineering
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