

NIST Grant Contractor Report
NIST GCR 26-072

Forward-Looking Codes and Standards: Future Load Effects

Workshop Report
July 29–30, 2025, Reston, VA

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Abstract

Forward Looking Codes and Standards: Future Load Effects workshop report includes recommended research needs on the following themes: changes in hazard demand relative to historical basis, changes in structural capacity due to changes in material properties, and geotechnical conditions.

Keywords

Codes and standards; Building codes; Future hazards; Load effect: Design guidelines; Design criteria; Structural capacity; Adaptation; Resilience.

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Preface

In October 2024, 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.1333ND24PNB730652 to develop workshops on *Forward-Looking Codes and Standards*. This report documents the results of the second workshop on *Forward-Looking Codes and Standards: Future Load Effects* based on contributions to the workshops by scientists, natural hazard experts, structural engineers and other design professionals, and standard and code development experts.

The following are the themes of the four workshops:

1. **Future hazards for design:** Confidence/uncertainty in hazard projections, local downscaling of global models, and conversion of hazard projections to engineering design criteria;
2. **Future load effects on the built environment:** Changes in hazard demand relative to historical basis, changes in structural capacity due to changes in material properties, and geotechnical conditions;
3. **Engineering design guidelines and criteria:** Nonstationary reliability, service life, design loads, resistance, and structural capacity degradation; and
4. **Adaptation and resilience:** Adaptive design for buildings and infrastructure systems, considering future hazards, material durability, and structural capacity degradation, and strategic planning methods for future conditions.

The impetus for the project was the observed increases in land and ocean temperature extremes; sea-level change; frequency and length of heat waves; and changes in the frequency and intensity of heavy precipitation, flash floods, severe storms, and cyclones. Because of potential changes in environmental hazards and structural capacity over time, the need to advance design practices to incorporate future hazard predictions and their uncertainties into codes and standards for buildings and infrastructure is urgent. NIST continues to conduct research and provide leadership in the advancement and knowledge of these hazards and to provide the science and engineering that supports the development of standards and guidelines that will lead to more resilient communities and economic continuity across the nation.

The workshop development process started with a review of ongoing research, guideline development efforts, and relevant case studies. An extensive workshop preparation process followed this review that convened four one-and-a-half-day workshops to obtain input from experts in these areas and resulted in report preparation and review by the Workshop Steering Committee (Obeysekera et al. 2026a, b, c, d).

The workshops identified a broad range of research and development activities required to advance codes, standards, and engineering design practice that capture the effects of future

conditions and have the goal of reducing impacts from severe environmental hazards. This report includes the discussion of current needs in design practice and specific recommendations on research needs to advance next generation building standards and codes and to achieve specific goals of adaptation and resilience.

SEI is indebted to the leadership of Jayantha “Obey” Obeysekera, Ph.D., P.E., F.EWRI, M.ASCE, who served as the Workshop Director and the Workshop Steering Committee members Meg Ackerson, P.E.; Joe Ackroyd, P.E., M.ASCE; Joseph Barsugli, Ph.D.; Kevin Borth, P.E., S.E., M.ASCE; Michel Ghosn, Ph.D., F.SEI, M.ASCE; Matt Gilbertson, P.E., S.E., M.ASCE; Elisabeth Gilmore, Ph.D.; Jack Hogan, P.E.; Sihan Li, Ph.D., P.Eng., M.ASCE; Mari Tye, Ph.D., C.Eng., M.ASCE for their contributions to putting the workshop together and developing this report.

SEI gratefully acknowledges NIST for its leadership and vision for this project. Appreciation is also extended to the many individuals who participated in the workshop. Appendix C lists the names and affiliations of all who participated in the workshop and, therefore, contributed to this report. Thank you to the ASCE staff— especially Katie Stueckle, who served as Workshop Coordinator; Jessica Jun, who served as a Workshop Conference Manager; James Pullis, who served as the Conference Center Manager; and Addie Gordon, who served as a Workshop Coordinator and drafted and edited the final report.

Jennifer Goupil, P.E., F.SEI, F.ASCE
Managing Director Structural Engineering Institute and American Society of Engineers Chief
Resilience Officer

1. Section 1: Workshop Overview

1.1. Introduction

The National Institute of Standards and Technology (NIST) has a long history of conducting research and development to identify methods and practices; to advance codes and standards; and to support the resilience of buildings, physical infrastructure, and communities.

NIST's commitment to the effects of hazards on codes and standards for the built environment, and on engineering more broadly, is reflected in its being the lead agency for the National Earthquake Hazard Reduction Program, the National Windstorm Impact Reduction Program, and its Disaster and Failure Studies Program and Community Resilience Program. Similarly, ASCE/SEI is actively committed to integrating future hazard data and future conditions into technical standards, especially within the national model design standard for structural loads in *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (ASCE/SEI 7-22, ASCE 2022). The next edition, ASCE 7-28, is currently developing a new section for future hazard design loads. To continue with these efforts, one of NIST's strategies is to further develop codes and standards to better prepare for future hazards and conditions.

The second workshop for *Future-Looking Codes and Standards: Future Load Effects*, held on July 29-30, 2025, and this resulting report, focused on the research and development efforts needed to implement future hazards and associated design criteria in codes and standards, and potential degradation of structure capacity, to inform strategic planning for future requirements in the built environment, and to understand potential changes to design requirements.

1.2. Workshop Scope and Purpose

The purpose of the workshops was to provide a science-based assessment of data and development needs to advance design practice and building standards for future natural hazards and conditions across U.S. communities.

The workshop scope covered the broad subject area of future hazards for codes and standards development, specifically the needed input from scientists, practitioners, and researchers on how to do the following:

- Prioritize research and development needs to advance design practice for future hazards and conditions (beyond the ongoing efforts of ASCE/SEI 7-28);
- Use the best available science to characterize future hazards and conditions for design practice;
- Identify a path toward improving building standards and design practice; and
- Consider resilience, adaptation, and social and economic impacts to businesses and communities.

1.3. Workshop Development Process

The development of these workshops began with the selection of the Workshop Steering Committee (WSC) for all four workshops, which includes climate scientists, structural engineers, and social scientists. They are qualified academics and practicing experts who have worked in the fields of future hazard projections, engineering design, social impacts, resilience, and adaptation. The WSC included the following experts:

- Meg Ackerson, P.E., Arup;
- Joe Ackroyd, P.E., M.ASCE, Assistant Commissioner; Technical Affairs & Code Development; New York City Department of Buildings, NYC;
- Joseph Barsugli, Ph.D., Research Scientist III, CIRES, University of Colorado Boulder, NOAA Physical Sciences Laboratory Affiliate;
- Kevin Borth, P.E., S.E., M.ASCE, Sr. Structural Project Engineer | Associate Vice President, HGA;
- Michel Ghosn, Ph.D., F.SEI, M.ASCE, Professor, the City College of New York/CUNY;
- Matt Gilbertson, P.E., S.E., M.ASCE, Sr. Technical Manager, Simpson Gumpertz & Heger;
- Elisabeth Gilmore, Ph.D., Professor, Carleton University;
- Jack Hogan, P.E., Associate Climate Risk and Resilience Engineer, Arup;
- Sihan Li, Ph.D., P.Eng., M.ASCE, Senior Specialist, Associate, RWDI; and
- Mari Tye, Ph.D., C.Eng, M.ASCE, NIST PREP Fellow, Whiting School of Engineering, Johns Hopkins University.

The WSC started meeting in February 2025 to develop the content of the workshop. The WSC selected the following topics as critical issues, and the participants were selected based upon their expertise in these areas:

- Confidence and uncertainty in hazard projections,
- Downscaling of global climate models, and
- Conversion of hazard projections to design loads and associated criteria.

To help understand the current state of future-looking codes and standards, the WSC shared reading materials to with workshop participants, which are referenced in Appendix C.

The one-and-a-half-day workshop was convened on July 29–30, 2025, to identify the highest priority needs that form the basis of this report. The WSC, industry-leading experts, academics, and representatives from key government agencies attended the workshop. Members of the public were also able to view speaker presentations on the first morning of the workshop via Zoom webinar. The workshop was held at ASCE headquarters in Reston, Virginia (Figure 1-1) and was simultaneously streamed for virtual participants (Figure 1-2). Thirty in-person and 36 virtual participants attended the workshop.



Figure 1-1. In-person participants at the NIST/SEI *Forward-Looking Codes and Standards: Future Load Effects* workshop on July 29, 2025.



Figure 1-2. Online participants at the NIST/SEI *Forward-Looking Codes and Standards: Future Load Effects* workshop on July 29, 2025.

The design of the NIST/SEI *Forward-Looking Codes and Standards* workshop enabled all in-person and online participants to contribute in multiple ways. The workshop began with subject matter expert presentations of ongoing, synergistic efforts and several state-of-the-practice presentations that were also viewed by registered public attendees.

Following the presentations, the public session concluded, and a plenary session engaged the participants in a discussion to define the state of the art and the future ideal state needed to incorporate future load effects into design standards and codes.

The participants were then divided into five breakout groups based upon four hazard types (wind, inland flood/rain, coastal flood/sea-level rise, and snow/permafrost/ice) and one that specifically focused on structural capacity. The goal of the hazard-based breakout groups was to identify what is needed to characterize future loads and load effects and the next generation of research needs. The goal of the structural capacity breakout group was to identify the most impactful future effects on structural capacity and the next generation of research needs. In these breakout groups, the participants were given three prompts to answer their group goals: (1) identify critical research needs, (2) identify topics not currently considered, and (3) prioritize the top five research needs.

Each breakout group then reported back to all the workshop participants in a general session and described its prioritized research and development needs. Following these presentations

and subsequent discussions, all the workshop participants prioritized the separate breakout group research and development needs.

1.4. Workshop Framework

The framework for Workshop 2 was developed around key questions and intended outcomes from the WSC and was organized into two main topics.

The first was to estimate load effects due to future hazards. To do so, participants were asked to consider (1) how future hazard demand changes relate to historical basis, such as parameter and coefficients (e.g., wind speed and air density), and (2) how to incorporate uncertainty—both aleatory and epistemic (e.g., modeling, analysis, projection-downscaling, pathways)—when estimating loads under future conditions.

The second topic explored how changes in assumed structural capacity, material properties, soil, performance, and so on, may change under future conditions.

These topics framed the final set of questions posed to participants, which centered on identifying the resources, research, and tools desired for design and focused on the discussion of next-generation research needs, including

- Future hazard data and models for engineering load effects and design,
- Guidelines for incorporating uncertainties for design, and
- Evolution of structural capacity as a function of future hazard conditions.

1.5. Workshop Report Organization

Following Section 1, Workshop Overview, the workshop report is organized as follows:

- Section 2 describes the current state of the art and summarizes presentations from the workshop,
- Section 3 describes the discussions on advancing the workshop goals that were held during breakout discussions,
- Section 4 describes the top recommended research needs that were identified during the breakout sessions,
- Section 5 describes the analysis of research needs that were identified during the breakout sessions,
- Section 6 lists acronyms and abbreviations, and
- Section 7 provides the references cited.

The report also includes three appendices. Appendix A Priority Research Needs includes additional details about the priority research needs identified by each breakout session during the workshop. Appendix B Workshop Materials contains the workshop agenda, copies of the presentations. Appendix C Workshop Participants lists the workshop participants in alphabetical order.

2. Section 2: Current State of the Art

2.1. Workshop Presentations

The first three speakers shared presentations on Synergistic Efforts focused on load effects to build a foundational understanding of the current field.

Alex Cannon (Appendix B.2.1.1) presented an overview of how the 2025 National Building Code of Canada (NBCC) integrates projected changes in climatic design values. His talk emphasized the use of historical data and future projections to recalibrate design parameters for wind and snow loads. He discussed the statistical modeling approaches, including the use of Gumbel and lognormal distributions, and highlighted the shift from traditional 50-year return periods to longer durations (e.g., 500-year) to better reflect future climate risks. The presentation underscored the importance of incorporating scaling factors to ensure reliability and safety in structural design under evolving environmental conditions.

Hanping Hong (Appendix B.2.1.2) detailed the methodology used to calibrate wind and snow load effects in the 2025 NBCC. He explained the reliability-based design framework, including the selection of limit state functions, target reliability indices, and probabilistic models for various loads. His analysis incorporated future effects using scaling factors and emphasized the importance of adjusting load combinations and importance factors based on building categories. Hong proposed a more uniform risk approach and updates to wind and snow load factors to enhance consistency and resilience in structural design.

Therese McAllister (Appendix B.2.1.3) presented findings from the ASCE/NIST Special Publication on the impact of future conditions on structural loads and performance. She outlined the challenges posed by nonstationary climate variables and their implications for design reliability. The presentation covered various affected load types, including temperature, wind, snow, ice, rain, and flooding. She concluded with the need for probabilistic modeling, scenario-based design approaches, and the integration of climate science into engineering standards to maintain safety and functionality over the life cycle of infrastructure systems.

Next, a panel (Appendix B.2.1.4), moderated by Abbie Liel, discussed the methodology, assumptions, and decisions behind updates to ASCE/SEI 7-28 Chapter 36. Matt Gilbertson addressed flood loads, proposing the use of future sea-level rise projections and enhanced local flood maps. Sihan Li discussed wind load modeling using downscaled data and Monte Carlo simulations, advocating for a nonstationary reliability approach. Abbie Liel presented snow load projections using generalized extreme value models and climate data. Ken Kunkel covered rain load projections using multiple downscaled datasets and extreme value statistical analysis. Ahmed Abdelaal focused on atmospheric ice loads and the need for improved spatial coverage and data access. Collectively, the panel emphasized the importance of integrating future scenarios into load calculations to ensure structural resilience.

The presentations of the remaining three speakers centered around Structural Capacity and Functional Underperformance.

Brian Pailes (Appendix B.2.1.5) explored the mechanisms and impacts of structural material degradation, particularly corrosion, on steel and reinforced concrete. He discussed various deterioration processes such as alkali-silica reaction, freeze-thaw damage, and microbial-induced corrosion. Pailes showed the need to understand deterioration rates and their effects on structural capacity, especially in changing conditions. Improved inspection techniques and the incorporation of degradation data into design practices were some strategies discussed.

Ted Zoli (Appendix B.2.1.6) shared insights from real-world infrastructure performance, focusing on bridges and other exposed systems. His presentation examined how evolving load effects, regulatory environments, and design adaptations influence structural resilience. Zoli highlighted issues such as overweight vehicles, wind behavior, and vessel impacts. He stressed the need for continual code updates, better measurement practices, and a focus on rapidly changing conditions.

David Frost (Appendix B.2.1.7) introduced the concept of “foundation-based architecture” as a paradigm shift in structural design. He discussed the hidden impacts of groundwater changes, including erosion, saltwater intrusion, and subsurface variability, which are often overlooked in conventional design processes. Frost proposed rethinking the top-down design approach to start with site-specific subsurface conditions. He illustrated how foundations can be multifunctional, adaptable, and sustainable, offering solutions to challenges posed by changing future conditions and resource limitations and calling for a more integrated and resilient approach to foundation and structural design.

2.1.1. Workshop Reading Materials for Current State of the Art

Prior to the workshop, participants received one-page pre-reading materials on ASCE/SEI 7-28 Chapter 36 hazard loads for flood, ice, rain, snow, and wind to prepare for current state-of-the-art discussions and the workshop breakout sessions. ASCE/SEI 7-28 introduces Chapter 36 Future Conditions, addressing how future climate will alter design loads for floods, ice, rain, snow, and wind. The chapter supplements existing provisions by adjusting hazards expected by late century, while maintaining current reliability standards for structural safety.

Flood loads rely on Federal Emergency Management Agency (FEMA) flood maps for present conditions but incorporate future sea-level rise projections from the National Oceanic and Atmospheric Administration (NOAA’s) 2022 Interagency Report. Local jurisdictions’ future flood maps, when available, are prioritized. A “bathtub” model currently adds projected sea-level rise to stillwater elevations, though more advanced nonlinear methods are desired. Local hydrologic and hydraulic analysis remains essential due to the site-specific nature of flooding.

Ice loads are based on freezing rain hazards, using historical station data and North American Coordinated Regional Downscaling Experiment (NA-CORDEX) (Bukovsky 2020) regional climate

models. Ice accretion is modeled with U.S. Army Corps of Engineers – Cold Regions Research and Engineering Laboratory’s (CRREL) thermodynamic model and a conservative wind-driven method. Nonstationary extreme value analysis (Generalized Pareto Distribution) estimates design ice thickness for multiple return periods. Improvements are needed in spatial coverage, observations, and public dataset access.

Rain loads adjust the 100-yr, 15-min rainfall intensity using climate model–derived adjustment factors (AFs). Observed data from NOAA Atlas-14 provide the baseline, with climate projections (statistical and dynamic downscaling) producing multiplicative AFs for future design. A nonstationary Generalized Extreme Value framework incorporates warming trends. Pending publication of NOAA Atlas-15 may streamline delivery of updated rainfall values.

Snow loads are projected using a Variable Infiltration Capacity model forced by the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project, Phase 5 (CMIP5) climate outputs. Reliability-targeted ground snow loads are recalculated with nonstationary probability distributions, allowing parameters to evolve over time. Change factors are derived across U.S. Environmental Protection Agency ecoregions and applied consistently. The approach ensures that future loads do not decrease below current levels, maintaining minimum safety margins.

Wind loads incorporate non-hurricane (synoptic and thunderstorm) and hurricane winds. Future non-hurricane winds are derived from downscaled datasets (NA-CORDEX, ECCC [Environment and Climate Change Canada]), with gust factors applied to convert mean winds to design gusts. Hurricanes are simulated using a Monte Carlo framework with climate-modified environmental inputs. A nonstationary minimax approach ensures reliability over a 50-year reference period. Limitations remain in thunderstorm modeling and full-physics hurricane projections.

Overall, ASCE/SEI 7-28 Chapter 36 represents an initial structured effort to standardize climate-adjusted design loads nationally. While methodologies are built on existing ASCE/SEI 7 frameworks, uncertainties persist due to local variability, data gaps, and evolving climate science. Future improvements will focus on refined modeling, broader observational coverage, and standardized national datasets for future flood and other hazard projections.

These overviews of hazard loads in ASCE/SEI 7-28 Chapter 36 were discussed in the workshop in a panel moderated by Abbie Liel, as described previously (Appendix B.2.1.4).

2.2. Goals for Future State

The plenary focused on loads and load effects that are developed into design standards and codes. Key themes centered on individual specific hazards and how those are translated into loads and load effects and how nonstationarity has effects on structural capacity.

As participants discussed the future of structural design, they concluded that codes and standards must evolve to reflect increasing uncertainty in hazards and load effects. Next-generation requirements could include a tiered approach to hazard classification, which may help capture varying levels of knowledge and uncertainty, especially as we consider compound events such as flood and wind interactions and cascading effects like debris-induced damage. Current design philosophies must adapt to account for time-varying capacities and loads, potentially shifting toward scenario-based or performance-based design (PBD) frameworks. The treatment of transient loads, such as short-duration rainfall or convective wind events, requires better data and modeling to inform load combinations and thresholds. Coastal and inland flood events, including distinctions between pluvial and fluvial flooding, should be addressed separately in future codes. Additionally, serviceability-level loads and long-term degradation must be considered for all infrastructure, but particularly for aging infrastructure in flood-prone areas affected by sea-level rise (SLR). Marine design standards may no longer be functional under future conditions, prompting a reevaluation of system-level modeling versus member-level approaches.

Future codes may need to be structured differently, with flexible timelines and prescriptive elements that avoid long-term rigidity. Human behavior, maladaptation, and evolving usage patterns also influence future load effects, highlighting the need for guidelines for both new and existing structures. As climate data and models improve, design targets like the 3 °C goal may shift, requiring a deeper understanding of uncertainty sources. Public-facing rating systems could help communicate structural resilience, while decision-makers must be equipped to understand and weigh required versus optional criteria. Finally, the education of future engineers must evolve to prepare them for designing in a world of moving targets, where data, models, and hazards are constantly changing.

The workshop participants envision a future design ecosystem where nonstationary load effects and capacity are considered together. This vision includes the following:

- Load effects that incorporate nonstationary and compounding or cascading effects and long-term degradation;
- Design approaches that include time-varying loads and capacity and shift toward structural performance objectives and design acceptance criteria;
- Engineers and design professionals who are equipped with knowledge of how to evaluate structural performance based upon the most critical loads and load effects and expected capacity for the design; and
- Project teams who will have access to guidelines that define the anticipated loads and load effects, including cascading and compounding effects, to be evaluated for expected capacities of infrastructure components and systems for both new and existing projects.

3. Section 3: Discussion of Advancing Future Load Effects

This section includes summaries of the discussions that occurred in the breakout groups. The participants in the breakout groups discussed several prompts before agreeing on the research needs, which are summarized in Section 4.

3.1. Breakout 1. Wind

Breakout group 1 focused on the challenges and future needs for building codes and design standards that pertain to wind. To provide context, wind types were listed in terms of those causing the most damage to the built environment: tropical cyclones, severe convective storms (excluding tornadoes), extratropical storms, tornadoes, and orographic winds (special regions).

In terms of data and models, the biggest gap is the current ability to characterize severe convective storms. Extratropical storms are the most frequent but are less likely to affect design wind levels; they are likely the design basis for west coast winds. Tropical cyclones, severe convective storms, and extratropical storms are combined for design wind speed maps. The following research needs were identified during the discussion.

Higher-resolution temporal and spatial data are needed to improve modeling for future severe convective storms. For example, convective storms need a minimal spatial resolution of 1 km and temporal data at 5 min intervals. However, methods for future events need to consider other scales, such as those used for historical data (4 km and 5 min). New methods might benefit from the use of machine learning (ML) or other artificial intelligence (AI) methods. Such methods need to limit the use of ML or AI to interpolation, not extrapolation. If a method interpolates with smoothing algorithms, it needs a correction factor that considers the dynamic characteristics of wind events. One example of a dynamic process is the ability to resolve a thunderstorm/tornado apex in high-resolution models. Other issues that need to be addressed include if the gust factor in use is now appropriate for thunderstorms and how we better connect coarse regional climate models with extreme tails of distributions.

Uncertainty in future wind events and associated wind speeds needs to be quantified through multiple simulations and datasets for global climate models and regional models. Historical records and measurements document that average global temperatures have been increasing since the start of the industrial age, between 1850 and 1900. Part of the uncertainty studies should be the question of when the temperature effects on future hazards, such as wind speed, become significant relative to the baseline data. Sensitivity studies can help determine when significant increases in future hazards become relevant for the built environment. Such timelines may vary by region, but a consistent approach will benefit from standardization.

To advance thunderstorm models, improved observational data are needed. Wind data from Automated Surface Observing Systems (ASOS) instruments are sparse and have insufficient spatial and temporal details to discern thunderstorm winds. The need for better observational data includes network equipment that would not lose power or stop recording data during peak

wind events. The quality control process by NOAA for ASOS data is another source of data loss, as the process sometimes loses peaks that are real measurements and keeps recorded peaks that are not; NOAA does not keep raw data for review or comparison. This also occurs for peaks in tornado data.

Design assumptions for wind loads need to be reviewed. For instance, a 3 s gust wind speed for thunderstorms does not produce the same wind effect as a hurricane. Wind tunnels use boundary conditions to model extratropical events; however, thunderstorms have other conditions (such as strong shear flows) that are not simulated. Vertical profiles, durations of events, and scales of turbulence length differ among wind types. Other sources of thunderstorm data may be available that are not in public space that could be added to current datasets.

Research needs for tornadoes include spatial and temporal resolution issues across affected areas, wind field structure changes due to atmospheric warming, whether the frequency of future tornado events is higher, and whether a surrogate or proxy model could be used to study tornado event characteristics and future changes. The cause of the observed trend of increased tornado events in the Southeast is not clear; while the central plains still have several tornado events. Dynamic downscaling models show a further increase in future tornado events for the Southeast. A longer-term trend may exist for tornado events that the current datasets, which are from the 1990s to the present, cannot be used to evaluate. Research may need to focus more on regional changes than on frequency/intensity changes.

Significant wind event types that fall between downbursts and tornadoes need to be defined. One approach would be to study thunderstorm generation mechanisms and characteristics (particularly time components, including duration of events). For instance, a derecho will have a longer time frame than a downburst. Downbursts are small contributors to extreme wind events. This research should be guided by identifying which wind events are most relevant for design.

A review to determine whether current codes and standards adequately address wind loads is needed. This may include defining required data quality, model capabilities, design assumptions, uncertainties, and so on, that lead to minimum loads and load combinations.

Currently, design wind speeds are based on a stationary process. How well this assumption of stationarity applies to future thunderstorms and other wind events is unclear. Evaluation of methods and technology to reduce uncertainty in future wind events is needed. For example, the turbulence of wind flow varies among events, which can lead to greater uncertainty for thunderstorm events than that currently assumed in reliability analyses.

The duration of wind events and the upwind exposure affect wind speeds and structural performance; upwind exposure categories can change over the life of a structure. Design wind speed maps assume a 1 h duration for all wind events at a given location; this assumption should be reexamined. Similarly, damage is associated with wind events that do not reach

design-level wind speeds. Damage to walls is primarily due to debris, whereas roof uplift is a structural load path failure (a need exists to see if recent code updates provide adequate resistance). In general, for wind speeds less than design levels, the structural system (e.g., the main wind force resisting system or MWFRS) performs well, but the building envelope (i.e., the components and cladding or C&C) is damaged, often due to design/construction quality or debris impact. Tornado events are the exception to this observation. Building envelope ensembles are not evaluated as a system, unlike MWFRS. Furthermore, to advance structural performance and community resilience, social consequences to building and infrastructure failures need to be addressed in future design solutions.

The following topics are not currently considered and were identified for wind events and their impact on the built environment:

- An improved understanding of tiered confidence levels by climate scientists is needed to develop design criteria for future hazards. Characterizing the basis of low confidence criteria may include the source of data, sources of uncertainty, site factors, and the physics of wind events.
- When the sample size is small, downscaled models may have a single realization, which is inadequate for future event characterization. A wider ensemble of datasets is needed to inform future hazard characterization, including sensitivity to resolution and so on.
- Structural design does not currently address wind-driven rain, which is a significant factor in property damage in hurricanes and can occur during other wind events (an atmospheric river, for example). The ASTM International standard tests for wind-driven rain use 15% of wind load with simulated rain for physical laboratory testing; this has proved to be inadequate to prevent this type of water intrusion.
- Serviceability/functionality issues related to building use may need to be adjusted for future hazard events.
- Wind-driven hail damages building envelopes, which may lead to rain intrusion.
- Wildfire-driven winds can create vortexes outside the fire perimeter that lead to unanticipated damage to buildings.
- Tornado events and resulting debris fields have significant impacts. Tornadoes create more debris than hurricanes. Tornado provisions have adopted hurricane debris criteria for now, but further studies comparing hurricane and tornado debris fields as a function of wind speed are needed. Debris impact affects design criteria for windows and C&C.
- Field studies need to consider design versus construction quality to assess structural capacity and performance.

3.2. Breakout 2. Inland Flood/Rain

Breakout group 2 focused on challenges and future needs in evolving flood-related building codes and design standards. Participants discussed technical, policy, and data-driven issues, particularly regarding how future climate scenarios intersect with the built environment and the need to rethink flood hazard data/mapping and design approaches.

Noncoastal flood hazard areas present a unique challenge compared with other natural hazards we design buildings to resist. Noncoastal flood risk is highly localized and sensitive and can vary widely from watershed to watershed.

Participants noted significant gaps in flood risk data for public infrastructure and suggested a more holistic view of new and existing construction. A common topic throughout the discussion was the inadequacy of current FEMA flood maps for engineering purposes, especially when considering flood events beyond the historic 100-year flood. These maps are intended for insurance, not engineering design, and lack the granularity necessary to assess localized flood risk, especially in areas affected by short-duration stormwater flooding or complex compound flood scenarios (e.g., storm surge plus heavy rainfall). Current practice for considering future flood hazards often involves extrapolating future conditions from present-day analyses using conservative scaling factors. However, this method lacks regional specificity and produces oversimplified risk estimates. Localized flood maps that reflect the distinct characteristics of individual watersheds and better align with future precipitation estimates are needed.

The most recent editions of ASCE standards (ASCE/SEI 7-22 Supplement 2 and ASCE/SEI 24-24) require designing most buildings for the 500-year flood event, while critical buildings are designed for 750- or 1,000-year flood events. These data are often unavailable, using FEMA maps or otherwise, and most projects lack the resources to conduct site-specific hydrologic and hydraulic (H&H) studies. There is a consensus that building designers cannot be expected to conduct detailed watershed modeling, especially for smaller or resource-constrained projects. Under ASCE/SEI 24-24, scaling factors are applied to account for these more extreme events. Methods and tools are needed that can help practitioners assess risk more precisely without deep H&H expertise, especially given the wide variation in floodplain behavior under changing conditions.

Another layer of complexity relates to the interaction between existing infrastructure and observed behavior, such as riverine flooding, which is often underrepresented in flood analyses and maps. Debris blockages and damming effects can drastically alter flood elevations and extents. For example, hydrodynamic flood loads change significantly when water is temporarily slowed by debris and then released suddenly.

Regarding stormwater/urban flood hazards, participants noted the problem of outdated or insufficient stormwater infrastructure data, particularly in dense urban areas that experience frequent stormwater flooding, such as New York City. Participants emphasized the inadequacy of current design precipitation values for stormwater systems. Field experiences in Texas and North Carolina showed actual flooding exceeded expected impacts due to unmapped or poorly understood local features like stream crossings and embankments. Public infrastructure is inconsistently documented, which hinders effective risk assessments.

Several participants advocated for a shift from prescriptive codes to PBD, which has become common in other hazard areas like seismic and wind design. However, the data needed to support PBD for flood-resistant design are still lacking.

While the group generally agreed that the process of converting hazard data into structural loads is well understood, the challenge lies in defining and quantifying the hazard itself. Participants stressed the uncertainty in climate model projections and the implications for future rainfall intensity and frequency. The unknowns associated with the built environment and land development may carry more uncertainty than future precipitation.

Participants strongly agreed that research should support both new and existing structures because their implications and solutions may differ. While load characterization may be similar, the response and mitigation strategies would vary significantly.

The group discussed the current movement to integrate ASCE/SEI 24-24 and ASCE/SEI 7-22 Supplement 2 into the International Building Code, especially for residential applications. One major obstacle is the public's assumption that if a site is permitted for construction, it must be safe, which complicates the adoption of more stringent codes.

Participants discussed how to enhance consideration of more resilient flood design in residential settings, particularly with the adoption of forward-looking flood-resistant design in the International Residential Code. Better appraisal models that reflect reduced flood risk for elevated or flood-resilient buildings could improve incentives. The group contrasted the public's growing awareness of wildfire risk with the slower recognition of flood risk in property value and development decisions. Participants agreed on the need for more public education, social science research, and integration of economic incentives to align resilience with market behavior.

In addition to the top five priorities described in Section 4, the group identified the following topics that may necessitate research to enhance noncoastal flood mitigation:

- Short-duration flash flooding: Noncoastal flood events driven by intense, localized storms (e.g., 15 min, high-intensity rainfall event) are underrepresented in current maps. Mapping efforts must better reflect the flood extents and the rapid rate of such flood events.
- Site-specific vulnerability: Risk assessments must account for vulnerabilities not only in buildings but also in supporting infrastructure systems, such as utilities, roadways, and bridges that contribute to broader community resilience.
- Performance-based versus prescriptive design: Future standards may need to shift toward performance-based approaches that tailor solutions to specific flood characteristics and acceptable risk levels, moving beyond prescriptive code requirements.
- Riverine versus coastal versus compound flood hazards: Transition zones where riverine and coastal flooding intersect require unique consideration. These flooding areas remain among the least understood and most complex to model accurately. In addition, future conditions may cause a shift in controlling flood events in these areas.
- Debris loads and damming effects: Flood models must include physical factors like debris-induced damming, which can dramatically change hydraulics and increase localized flood loads.

- Climate uncertainty and regionalization: A significant challenge is determining which climate models best represent future precipitation and how uncertainty propagates through to flow predictions. Regionalization of these projections is essential to produce reliable design guidelines.
- Glacial lake outburst floods (GLOFs): Extreme events such as GLOFs provide valuable case studies to improve understanding of rapid-onset flood mechanisms.
- Design-focused flood maps: Insurance-focused flood maps are often not the best tool for informing structural design. Design-specific flood maps that incorporate deeper technical parameters (e.g., velocity, debris impact, load duration) are needed.

3.3. Breakout 3. Coastal Flood/Sea-Level Rise

The coastal flood/sea-level rise breakout session identified critical research needs for addressing flood loads and coastal design in the context of future climate. A key issue is the limitation that current tools were not developed for future climate impacts and lack consistency across locations. A mismatch exists between wind load discussions incorporating hurricane models, which consider future climate, and flood models that do not, leading to inaccurate predictions of storm surge and rainfall. Participants highlighted the need for national mapping, accounting for nonstationarity with sea ice melting in sea-level rise estimates and integrating storm surge and sea-level rise to identify extreme flood events (e.g., 100-, 500-, and 1,000-year floods). The discussion also emphasized the lack of standards in the coastal field compared with other areas; the difficulty for clients to fund site-specific modeling; and the need for methodologies to plan under uncertainty, such as risk-based approaches in nonstationary settings and dynamic adaptation pathways. Participants underscored the importance of training more coastal engineering experts to address the growing complexities in this field and providing materials and tools that can support engineers who lack coastal expertise but work in the coastal zone.

Further research needs include moving beyond depth to analyze velocity and wave action impacts on coastal structures, addressing the lack of velocity data for dynamic flood loads, and focusing more on extremes rather than averages. Social science research is needed on how to present extremes, averages, and probabilities, as is model development to integrate wind, precipitation, sea level, and storm surge for compound flooding. The group also discussed the efficiency of nature-based solutions in reducing wave loads and their potential inclusion in future codes and manuals. Other topics include the interactions between adaptation strategies and hazards, incorporating structural capacity and groundwater into codes, and a system-level approach to resilience for critical infrastructure. The group also highlighted the need to consider both existing and new structures and how to modify existing infrastructure for changing human activity and technology alongside environmental conditions. Integrated models that encompass precipitation, wind, sea-level rise, and bathymetry are also a critical need.

3.4. Breakout 4. Snow/Permafrost/Ice

The six breakout participants discussed research to inform codes and standards with respect to snow and ice loads. Participants drew on their direct experience with code updates including ASCE/SEI 7-28 Chapter 36 (Future Conditions) and the National Building Code of Canada (NBC 2025), both of which include future hazard effects. For this summary, the research needs that were discussed for snow and ice have been grouped by hazard.

The discussions of snow loads dealt with characterizing ground snow loads, translating ground loads to roof loads, and finally developing more detail about the interaction of these loads with the structures and other design criteria. Current standards and codes are based on the annual maximum ground snow load as measured by the weight of snow water equivalent (SWE). While U.S. snow data tend to measure SWE directly (where measurements are taken including the effect of rainwater on the snowpack), Canadian data are typically only for snow depth and must be converted based on assumptions of bulk density. Research into possible regional changes in snow density and frequency of rain-on-snow events with respect to future conditions was suggested.

Participants noted that annual maximum SWE does not account for the intermittency of ground snow loads in locations where snowstorms are rare and melting between storms is considerable. Therefore, more data on duration of ground and roof snow loads would be particularly useful when considering load combinations. For example, a peak snow load that lasts five days before melting would be associated with a lower risk of combining with a seismic event than one that lasts a month or more.

More consideration of how to design for nonstationary hazards would be particularly important for snow loads that are either decreasing or nonmonotonic with increases before decreasing. The implications of designing for lifetime versus maximal annual risk should be examined in more detail. In the broader discussion, the possibility was raised of increases in extreme snow due to increased moisture in the atmosphere, even in regions where snow occurrence is decreasing overall. Participants expressed concern that current analysis methods of ground snow loads might not capture the possibility of larger maximal snow roof loads (even if less frequent). Thus, how to better characterize the changing probability distributions and the implications for risk could be a topic for research.

Participants paid considerable attention to the translation from ground snow loads to roof snow loads. Even if ground snow load decreases, roof loads may increase because of the effect of warming temperatures on the redistribution of snow. For example, in regions that transition from very cold winters, wind scour of snow on roofs might become less effective. Alternatively, a warming climate might lead to the possibility of melt and refreeze, leading to ice layers that can reduce accumulation. Accounting for this possibility, the NBCC moved from uniform load factors and drift provisions to incorporate wind factors (as does ASCE/SEI 7-22) and added a winter temperature variable in the ground-to-roof load factor. However, more research into temperature and other climatic effects on ground-to-snow translation of loads was seen as

needed, including understanding regional variations in the processes involved.

Discussions also addressed the load effects on and interactions with structures. Thermal effects on roof loading were discussed, noting that energy codes specify higher R-values that could lead to greater snow retention, either for new construction or for retrofits. Because a thermal factor is included in the standards for snow loads (though not for ice loads), this is more of a design decision. Some newer roofing materials have considerably lower friction, including some plastics/polymer materials. More research is needed on how new building materials affect loads through shedding of snow and redistribution of snow on the roof through sliding, potentially concentrating loads.

More broadly, participants discussed the balance of safety (e.g., protecting people from sliding snow and ice from roofs) with the potential for increased snow retention, for example, by barriers that retain snow. Many jurisdictions require that snow and ice falling hazards be mitigated, but no guidelines exist on how to incorporate that into design. The development of guidelines in the standards on how to design for public safety from falling snow and ice was a suggested topic for research.

The broader discussion raised the possibility of extending codes to cover tied structural systems. Design codes assume that the maximum load occurs at the same point in time everywhere on the structure, but on larger systems drifting snow loads may occur at different locations at different times, which might lead to overdesign with current codes. While currently dealt with by using bespoke structural modeling for each project, research into how to include this into codes, along with duration of load effects, is needed. The participants also expressed concern about overdesign for rare large events where the most extreme risks could be mitigated through active monitoring and management of roof snow loads. However, current codes do not allow for active melting of snow to reduce design loads because of the possibility of those systems failing during power outages precisely when they are needed most.

The discussion then moved to ice. The potential for ice accretion on structures is determined by the presence, intensity, and duration of freezing rain, which is then used as input to an ice accretion model to estimate ice thickness on a cylindrical object. The design ice loads are then determined through extreme value analysis. As with snow, the discussion can be broken down into needs for better characterization of the environmental hazard and better understanding of how to translate this hazard to structural loads. The primary challenge associated with determining design loads for a changing climate is the shift from observation to model-based determination of freezing rain conditions. However, considerable challenges also exist in developing estimates from the current observational record at locations between observation sites.

Participants discussed the problems with the current observational record for determining the present-day hazard and for use in model validation extensively. The data, ideally hourly or a finer temporal resolution, come from automated weather stations, mostly at airports. The data are spatially sparse, and the historical record needed to determine extremes has gaps. The

sparsity issue is particularly acute in Alaska. The relevant meteorological variable is the amount of precipitation falling as freezing rain. This quantity is typically calculated from measurements of the precipitation rate when the ice is detected by the ice sensor at the observation station, if included in that instrument package. In many weather stations, the presence of ice is noted, but the thickness is not measured. Newer sensors measure ice thickness, but the accuracy or relevance of these ice thickness measurements for structures is questionable and the cost is about \$10,000 per unit. Several innovative research ideas were suggested to increase the quality and quantity of observations of both freezing rain and ice accretion. These include development of low(er)-cost sensors to measure freezing rain and ice accretion thickness and leveraging of newer technology infrastructure for gathering data, including along smart roads. The participants explored possible economic incentives for increasing the observational coverage and noted that economically motivated sectors could participate in public-private monitoring partnerships. A potential synergy with aviation safety research (including some research at the National Center for Atmospheric Research on cloud icing) and the electric transmission industry and the possibility of using nontraditional data, such as from the insurance industry, were noted. Finally, the possibility of using citizen science was put forth, if adequately quality controlled.

ASCE/SEI 7-28 is moving toward using model-based estimates of freezing rain to fill in the gaps in observational records (through weather reanalysis products such as using fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis tool (ERA-5) (Herbach 2020)) and to use in climate models to project to the future. Current climate models, and even weather models, have trouble directly simulating freezing rain, largely because of horizontal and vertical resolution and the temporal increments for recording and saving data. Instead, empirically based algorithms (for example, the Bourgouin algorithm) are used to deduce the likelihood of freezing rain from temperature and humidity output at several vertical model levels in the atmosphere. However, these algorithms are wanting: a 46% hit rate for correct deduction of freezing rain is typical. While several models are being compared for the current ASCE/SEI 7-28 updates, research to improve the detection algorithms for precipitation type, perhaps using advanced ML techniques, is desired. Improved observations would be needed for calibration and validation of these models. Also suggested was that the simulation of freezing rain be investigated with convection-permitting climate models (those with finer than 4 km horizontal resolution and more vertical levels in the atmosphere). The primary goal of this would be to study model processes to improve the translation from climate model scales to local scales and constrain the epistemic uncertainties in climate that are unlikely to be adequately sampled by the limited quantity of higher-resolution models. Therefore, research is needed to leverage reanalysis and climate model data to better characterize freezing rain and ice loads where observations are lacking, including between observation stations in the present and in all locations in the future.

The ice accretion model that is used was developed for a cylindrical object at right angles to the wind and was developed to simulate ice accretion on transmission lines. Research into the accretion of ice on other surfaces is a priority. Flat surfaces, particularly solar panels, are also a priority as the installation of solar panels proliferates, even in cold climates. Solar panels are

not currently considered in codes, however, and developing guidelines for a “flat” icing factor would be helpful.

In considering broader topics regarding frozen precipitation, research into the problem of in-cloud (rime) icing was mentioned. This is a particular concern for tall structures, including transmission towers, wind turbines, cable-stayed bridges, and tall buildings. As noted previously, a potential synergy exists with aviation icing research. The breakout group also briefly discussed the specific problem of icing on bridges, noting that ice loads are small compared with other loads, but that ice shedding is a large safety concern. These concerns do not directly affect existing codes and standards to the knowledge of the participants. The design of other mitigation strategies, such as surface-applied heat technology or other means of controlling ice shedding, is unregulated. Hail is not currently considered in the codes but was mentioned as being particularly significant for insured losses. The relevance to structural loads arises because hail can compromise the building envelope leading to later structural damage. Research would include better characterization of the current hail hazard and better understanding of future hazards. Finally, the impact of snow and ice on communities, particularly on community lifelines and horizontal infrastructure, and economic livelihoods, was discussed, and the group proposed further research into the effect of snow and ice loads and hazards on community resilience.

Section 4 presents the group’s top five priority research needs. The group also provided additional research needs typology based on their conversation. Research needs are categorized according to the typology introduced in the first workshop report.

1. *Uncertainty and Nonstationary Reliability*: Characterization of design load risks when snow load increases with warmer temperatures before it decreases. Incorporation of temperature effects when translating ground snow to roof snow loads.
2. *Hazard Data*:
 - Characterize duration of ground snow loads in addition to annual maximum,
 - Characterize the changing probability distribution of extreme ground snow loads,
 - Improve freezing rain and ice thickness measurements, and
 - Provide more comprehensive hail hazard data in the present and projections into the future.
3. *Design*:
 - Design for snow loads on tied structures;
 - Standard for active monitoring and management of snow loads;
 - Guidelines for managing snow and ice on structures for public safety (falling/sliding snow and ice), including effect on snow loads; and
 - Investigation of effect of new roofing (and building envelope) materials on snow and ice accumulation, ablation, redistribution, and so on.
4. *Methods/Models*:

- Ice accretion on flat and other noncylindrical surfaces;
 - Improved precipitation type algorithms, perhaps AI/ML, to determine freezing rain intensity and duration from climate model and reanalysis model data;
 - Analysis of convective-permitting climate models for better process understanding; and
 - Modeling of snow load distribution (on large structures) due to various effects.
5. *Communication/Knowledge*: Understanding of risk of snow and ice on community lifelines, including horizontal infrastructure, and economic impacts on communities.

3.5. Breakout 5. Structural Capacity

The most common materials used in the construction of buildings and other structures consist of reinforced concrete; steel; wood; masonry; and for some applications glass, aluminum, and fiber-reinforced plastics. Current structural design codes and standards implicitly account for the long-term behavior of these materials by applying appropriate load and resistance factors to ensure that structural components made from these materials achieve reliability levels consistent with those of structures that have demonstrated adequate performance over their service lives. However, evidence suggests that the aging and deterioration of structural materials is accelerating under the effects of changing environmental and human-made stressors. This implies that currently used design specifications may no longer adequately reflect future structural safety levels and that using historic trends to calibrate code-specified load and resistance factors may lead to building structures that may have shorter service lives than anticipated. Civil and structural engineers and material scientists have been investigating deterioration mechanisms of structural materials to identify the most important stressors, develop models to project future reductions in the load-carrying capacity of typical structural materials, and investigate approaches to shield them from damaging elements and improve their performance over time. Summarizing the discussion of breakout group 5 of the second workshop, this report seeks to identify issues related to the effects of the environment on the structural capacity of buildings and civil infrastructure systems; identify topics that are not currently considered in structural design codes and standards; and prioritize research needs, taking into consideration future changes in pertinent loads and hazards.

The primary causes of structural material aging include environmental exposure, chemical reactions, and mechanical stresses. The effects of various climate hazards and their interaction with other stressors on accelerating material deterioration mechanisms have been the subject of research for many years. This section provides a short listing of the main climatic hazards that influence structural material deterioration.

Reinforced Concrete: Chloride penetration primarily causes corrosion of reinforcing steel in concrete members. Chlorides from sea salt and deicing salts may be deposited on concrete surfaces and with time penetrate the concrete through existing cracks and diffusion processes. Corrosion is initiated when the chlorides reach the passive layer that normally protects the steel from rusting. Chlorides break the passive layer, initiating an electrochemical interaction among iron atoms from the steel, oxygen, and water to produce rust, which has a larger volume

than steel, leading to concrete cracking and spalling. Concrete members in regions exhibiting increased precipitation, higher frequencies of snow and freezing rain with associated increases in the spread of deicing salts, and members exposed to changes in wind intensities and directions that carry ocean and deicing salts farther afield, may be subject to higher corrosion rates than previously anticipated. Similarly, the intrusion of salts into groundwater as sea levels change contributes to increased deterioration of concrete foundations. Furthermore, changes in temperature and humidity could facilitate the diffusion of chlorides into concrete layers, accelerating the initiation of the corrosion process. Increasing carbon dioxide (CO₂) concentrations in the atmosphere react with the alkaline cement paste, lowering its pH and increasing the risk of reinforcing steel corrosion in a process known as carbonation. Changes in the frequency of freeze-thaw cycles lead to increased cracking and spalling of concrete due to the expansion and contraction of water within concrete pores. Increases in ambient humidity, moisture, and temperature can cause concrete to shrink and creep, leading to cracking and large deformations. Higher rates and intensities of precipitation carrying abrasive substances and chemicals can lead to erosion, scaling, or spalling of concrete surfaces.

Structural Steel: As is the case with steel rebars in concrete, electrochemical reactions among steel; oxygen; increasing humidity and moisture levels; and higher levels of chloride ions from wind-carried saltwater, deicing salts, and the intrusion of salts into groundwater lead to the formation of rust and loss of material, reducing the load-carrying capacity and stiffness of structural steel and steel foundations. Increasing frequencies and intensities of windstorms and associated vibrations can lead to sudden and unexpected fatigue failures of steel members, while increasing humidity and moisture may accelerate corrosion that would not only compromise the strength and stiffness of structural steel but also reduce its resistance to cyclic fatigue. Higher temperature differentials can lead to increased deformation levels and higher stresses in steel members.

Wood: Increasing moisture levels create an environment conducive to biological attack and mechanical damage. Moisture can lead to warping and splitting of structural wood and the corrosion of metal fasteners. High temperatures contribute to creep under permanent loads. Moisture and high temperatures create a favorable environment for the wood's infestation with bacteria, fungi, termites, and other insects. These break down the wood's cellular structure, leading to its weakening and eventual failure. Changes in cloud patterns and associated increases in ultraviolet (UV) radiation, rain, and temperature fluctuations lead to cracking, checking, and erosion of wood.

Masonry: Rain, snow, rising dampness, and freeze-thaw cycles lead to erosion, weakening, and cracking of mortar joints. Salt from deicing agents and airborne sea salts can chemically react with masonry materials, degrading their load-carrying capacity. Mold, mildew, and other biological organisms thrive in damp conditions, potentially causing structural damage and weakening the material.

Glass: If they do not directly break glass surfaces on impact, hail and wind-borne debris can still create surface flaws and microcracks, reducing glass strength. Low temperatures and freeze-

thaw cycles can accelerate the growth of existing microcracks under sustained tensile stress, a phenomenon known as stress corrosion, significantly reducing the glass strength and potentially leading to failure. Repeated application of stress from winds and other hazards, even below the material's yield strength, can cause the glass to fail due to fatigue, especially in humid environments.

Aluminum: Aluminum is prone to fatigue failure under repeated loading and unloading cycles. Thus, flexible aluminum components exposed to repeated wind-related stress cycles are prone to higher risks of failure. Higher temperatures increase the tendency of aluminum components to deform under the influence of permanent loads. High temperatures can also accelerate microstructural changes, potentially increasing fatigue failures.

Fiber-Reinforced Plastics (FRPs): Moisture can penetrate the FRP matrix, causing swelling and plasticization and ultimately leading to degradation. This process can also create microcracks and delamination within the composite, further reducing its strength. High temperatures can lead to degradation of the matrix while fluctuations in temperature can induce thermal stresses, contributing to microcracking and delamination. Freeze-thaw cycles can lead to debonding and reduced load transfer between the fiber and the matrix. Changes in cloud cover increases exposure to UV radiation, reducing the ultimate tensile strength and modulus of FRP components.

Protective Systems: Structural steel is normally protected against corrosion by protective coating systems such as paint, while concrete and wood are protected using various types of sealants. Changes in temperature, moisture, or substrate conditions can lead to loss of adhesion between the sealant or coating and component surfaces. Exposure to UV radiation can cause polymers in sealants and coatings to degrade, leading to cracking, chalking, and loss of adhesion, exposing the material to all degradation mechanisms.

Climate hazards in combination with other natural or manmade loads may indirectly undermine structural capacity. For example, the scouring of soil around foundations due to flooding events reduces the ability of structures and infrastructure systems to resist all types of applied loads even when the structural materials themselves are not affected by the flood.

Modeling, prediction, and validation was the next point in the breakout group conversation. Assessing the safety of structures over their expected service lives requires accurate models that engineers can employ during the design phase to predict future conditions of the structure and subsequently decide on proper and timely repairs and rehabilitation strategies. Researchers are investigating various approaches to establish such models and verify their validity. These models can be classified as either high fidelity or predictive, both of which should be validated to ensure their reliability. The most useful models must be easily implementable in engineering practice and should be sufficiently flexible to incorporate data collected in the field and be updated based on information gathered from in situ inspections.

High-fidelity models, also known as constitutive models, are empirical-theoretical models that incorporate fundamental physics, chemistry, and mechanics concepts to predict the long-term behavior of structural materials and estimate their effective service lives. Such models link transport and diffusion processes that follow the movement of substances like moisture, chlorides, and other chemicals considering the permeability of the substrates and the presence of pressure gradients. High-fidelity models would also account for chemical reactions, such as those that create rust, that alter the properties of structural materials and reflect the mechanical and chemical interaction between different constituents, such as those that bond reinforcing steel bars to concrete, to estimate the overall strength and stiffness of the altered materials. The most advanced models incorporate multiscale representation of heterogeneous materials starting at the micro level up to the macro scale and employ numerical approaches such as finite element methods to simulate structural behavior and account for the interaction among different constitutive materials of various geometric shapes and boundary conditions. High-fidelity models provide a deep understanding of the complex interaction between climatic hazards and basic constituents, which facilitates a long-term projection of the behavior of structural materials. They also would help in investigating options for improving the performance of materials by identifying the influence of various potential additives and protective systems.

Predictive models are primarily based on available information from past data and historic performance of structural materials using various analytical and statistical techniques. The goal of predictive models is to forecast future behavior even if the underlying fundamental principles are not fully understood. Predictive models are usually easier to implement in routine practice than high-fidelity models. However, they are limited by the scarcity of historic data, which are difficult to collect because of changes introduced by manufacturers in material formation procedures over the years and changes in the underlying physical and climate conditions over the long service lives of structures.

Both high-fidelity and predictive deterioration models must be validated using experimental laboratory and field data. Monitoring real-time deterioration mechanisms requires long periods of observation, which has led many researchers to apply accelerated testing procedures. Also, lab experiments are usually conducted in carefully controlled environments, such as controlled temperature settings in humidity chambers and controlled infusion of chemicals and other substances. Despite their convenience, scaling accelerated testing results to real time and reconciling the differences between controlled lab conditions and the variabilities in field conditions, which are impossible to control and difficult to monitor over long periods of time, present a real challenge for researchers and engineers.

The most useful models can be adjusted to incorporate information about the structural materials from inspection data, actual field conditions, and monitored variations in climate conditions to compare the predicted degradation of the materials with estimates of component strength and stiffness estimated based on in situ data.

Structural material degradation simulators for concrete, structural steel, and other structural materials should be made available through open-source, web-based platforms that are easily accessible by practicing engineers. These models should be established and continually updated by appropriate government agencies (e.g., National Labs) or professional societies (e.g., ASCE) to provide long-term estimates of material behavior over its life cycle. The models should allow for entering site-specific information on physical and environmental conditions to estimate the reduction in the load-carrying capacity of structural components under various loading conditions. The platforms should also provide information on the model's underlying assumptions, sources of uncertainty, and reliability of predictions.

Current structural standards are developed based on estimates of the initial load-carrying capacity of structural components along with projections of the maximum expected loads within a preset service reference period. Models for estimating future reductions in the strength of components, in combination with models for estimating changes in future loads and hazards, should provide the ingredients for developing improved risk-informed, reliability-based structural design codes and standards. The calibration of design codes requires the evaluation of the aleatory uncertainties associated with estimating the various parameters and the epistemic uncertainties that reflect the limitations in the ability of the models to accurately predict the behavior of structural materials over time.

The degradation of structural resistance in combination with potential increases in many climate hazards confirms the nonstationary, time-dependent nature of the reliability of structural systems. This phenomenon amplifies the complexity of structural reliability calculations. It also raises questions regarding how to adjust current design codes and standards to account for the time-dependent behavior of a structure when its construction must meet strict criteria that ensure its overall safety up to the ill-defined end of service time.

One issue that arises when dealing with nonstationary loads and structural material strengths relates to the definition of the design reference period. While the current 50-year reference service life adopted in ASCE/SEI 7-22 does not necessarily reflect the actual service lives of many buildings and other structures, it has long been accepted as an adequate planning horizon for code calibration purposes when addressing stationary loads and resistances. Because deterioration mechanisms vary widely based on local conditions, material-processing methods, construction practices, and exposure to hazards, and because of differences in the acceleration of deterioration processes of various materials over time, review of possible alternatives to the current preset reference design service period has been requested. Furthermore, the overwhelming uncertainties in projecting future changes in nonstationary material resistances and loads over long periods of time hamper any possible revisions.

Estimating the reduction in structural material strengths involves determining a large number of variables that are associated with significant statistical variations. Furthermore, even under controlled conditions, existing material degradation models involve high levels of epistemic uncertainties due to their inherent limitations. Also, strong evidence suggests that the environmental factors (e.g., temperature, moisture, airborne substances) that have a large

impact on structural degradation are changing over time. Projecting future changes in these parameters involves another set of large epistemic uncertainties. Therefore, the time-variant strength and stiffness of structural components can only be assessed in a probabilistic sense.

The probability models that are used to calibrate structural design loads and standards must account for the uncertainties in the resistance and load parameters. In traditional reliability analyses, common practice has been to assume that resistance and loads are independent, fully uncorrelated random variables. However, the discussion in this report reveals that structural deterioration mechanisms are highly related to the intensity and frequency of many climate hazards that also drive the environmental loads applied to the structure. Advanced new-generation structural design standards must be calibrated to account for such correlations, which may indicate that future structures may exhibit lower safety levels than previously assumed.

Frequently, nonstructural systems (e.g., building envelopes or protective systems such as paint) serve as shields to the structure from the elements and tend to reduce their degradation. However, the deterioration of such nonstructural systems would not only reduce the efficacy of the shield but may often hide signs of structural component deterioration leading to potential failures.

Structural design primarily focuses on reducing the risk of failures under the effect of extreme events. Often, a material is subjected to repetitive, low-intensity loads that cause microscopic material defects or slip processes that introduce microcracks. Under stress concentrations, these eventually coalesce into macrocracks that may subsequently rapidly propagate, potentially leading to structural failure in a process known as cyclic material fatigue. Degradation river scour under repeated low-level floods is another type of damage that often remains unnoticed until the failure of structural foundations.

Current standards account for the effects of compounding hazards using load combination factors and, as mentioned earlier, ignore the correlation between the effect of a hazard on the loads and their effect on material degradation. Furthermore, load combinations factors are usually determined following Turkstra's rule, which assumes that high-level hazards have low probability of occurring simultaneously and that even if they do occur their intensity levels are statistically independent. However, these assumptions are not always valid, and in many situations the levels of intensity of different loads are highly correlated, such as the combination of high levels of precipitation, storm surges, and wind intensities that cause low-cycle fatigue failures during hurricanes. Compounding effects do not necessarily occur from a single major event. For example, in the context of material degradation, corroded materials are known to exhibit lower resistance to cyclic loading in a phenomenon known as corrosion fatigue. Freeze-thaw cycles may cause crack expansion in concrete members, but these cracks may also expand due to all types of other loadings. Most codes and standards tend to ignore such combinations of effects and focus on the degradation of materials assuming that the effects are independent.

Structural design codes and standards do not account for the degradation of structural members in a direct, explicit manner. One approach to include degradation in the design-check equations is to calibrate strength reduction factors that would be added to current resistance factors. These reduction factors would be calibrated using structural reliability principles and would ideally account for all the issues mentioned in this subsection of the report. The resistance reduction factors would account for the changing capacity over the service life of the structure and consider the correlations between material strength and load combinations.

This breakout group also addressed various areas of field testing, monitoring, and inspection. Many existing traditional structural inspection methods are geared toward identifying signs of deterioration. Existing methods may be human-driven approaches, such as visually observation of rust-related discoloring or hands inspection of fatigue or other types of cracks, or approaches that utilize mechanical and electronic devices, such as hammering to identify areas of compromised concrete or measuring corrosion rates in reinforcing steel. Other measurement devices such as magnetic resonance can help identify the concrete internal structure and proportions of various constituents. These methods may effectively recognize the presence of deterioration or the composition of the material but require subjective assessments in combination with analytical techniques to obtain estimates of reductions in member stiffness and strength. Structural health-monitoring instruments, including accelerometers and radar that measure the response of a structure to ambient loads or applied loads, have been used in combination with structural optimization techniques to infer the stiffness and other properties of structural components and by correlation the strength and load-carrying capacity of structural members. However, most existing approaches are associated with a relatively large range of errors, and a continuous need exists to improve existing technologies to develop rapid, reliable, cost-effective test methods that provide consistent in situ evaluations of the strength and stiffness of deteriorating components.

Current design codes and standards are developed to ensure that many structure types and geometries meet risk-informed target reliability levels that are based on a priori assumptions on future member behavior and loading conditions. At regular periods of time after construction, it is possible to assemble specific information on hazard data, recognize signs of member deterioration, and observe and measure the response of a structure to random human-engineered and environmental loads and field testing.

The design codes are also based on the assumption that some reasonable level of over-conservatism would not lead to excessive increases in construction cost. However, rehabilitating an existing deteriorated structure to meet the same criteria set for a new structure usually involves prohibitive costs, which is often not justified because the information that can be assembled in the field about the structural behavior of the system; the deterioration of the members; and the types, frequencies, and intensities of loads will considerably reduce both the aleatory and epistemic uncertainties that are usually utilized to develop the general design criteria.

Except for the case of highway bridges, currently no guidelines exist on how to apply information on an existing building or other structural type after construction. The guidelines should provide protocols for performing inspections, evaluating existing capacity of components, and predicting performance accounting for future reductions in capacity and changes in loading under climate impacts. The guidelines for the assessment of existing structures should clearly define the metrics, sampling strategies, and the scope of behavior-informed testing, and incorporate these into a reliability-based procedure that accounts for the aleatory and epistemic uncertainties and the possibility of measurement errors to estimate the future performance of the structure and estimate its safe remaining life.

The Federal Highway Administration mandates that bridges undergo rigorous inspections on a biennial basis and that bridges be classified based on well-established condition-rating and load-rating procedures conducted by certified inspectors and engineers that meet strict risk assessment criteria. Various jurisdictions and authorities should establish similar requirements and schedules for monitoring, inspecting, and assessing the safety of all types of structures.

Component-level and system-level assessments were the next major topic of conversation.

The structural design process is based on an analysis of the load path to compare the effects of the applied loads to each member's capacity. It usually assumes that all structural members remain in their original, pristine condition and maintain their original linear, elastic behavior throughout the loading process. Structural deterioration often initiates at a concentrated point within a structural element before it spreads to affect a single component or member and possibly multiple members of a structural system. Even concentrated local deterioration may alter the overall behavior of a structural member, degrading its stiffness and strength. Modeling the effects of localized deterioration on member behavior is even more challenging than modeling classical member plastification and nonlinear behavior because it depends on the specific random damage location and the extent of damage within the member.

Traditional structural analysis processes ignore changes in the load path within a structural system whether the change is due to the nonlinear behavior of nondeteriorated members or due to member stiffness and strength degradation that result from deterioration mechanisms. Furthermore, in nonredundant structural systems, a single member's deterioration may initiate a cascading effect that would jeopardize the structural system's robustness and lead to a catastrophic collapse. Therefore, specialized organizations should aim to develop protocols for performing advanced analysis processes that will lead to accurate modeling of the behavior of structural members exposed to different types of deterioration mechanisms and for using member behavior models to assess the performance and safety of the entire structural system. The analysis should not only concentrate on strength and the possibility of failure but be sufficiently flexible to consider structure-specific performance criteria.

Because of the large uncertainties in estimating deterioration rates and future conditions of structural members under changing environmental and loading conditions, the breakout group recommends that the design of structures whose members are susceptible to levels of

degradation be designed to be inspectable so that critical members can be easily accessed for visual or other types of inspection. Also, the structure should be designed and constructed to permit the reinforcement, repair, or replacement of deteriorated members, or the upgrading of members that evidence suggests are being exposed to higher levels of deteriorating agents or to changes in physical conditions and climate stressors.

4. Section 4: Recommendation of Research Needs

In their discussions, each breakout group identified the top five priority items and/or research needs to characterize future loads and load effects on their specific hazard (groups 1-4) or on structural capacity (group 5).

4.1. Breakout 1. Wind

As part of its research needs analysis and prioritization of future loads and load effects for wind hazards, breakout group 1 first categorized wind types that produce damage in order of hazard significance: tropical cyclones, severe convective storms (excluding tornado), extratropical storms, tornadoes, and orographic winds (special regions). The following topics were identified as top priority for research:

- Develop multiple high-resolution (km-scale) simulations for historical and future severe convective storms, bounded by observations, are needed to reduce or better quantify uncertainty.
- Collect observational data with a higher quality and resolution to ensure extreme events for wind types are adequately captured and to improve future hazard models and projections. Data sets should use existing, new, and emerging data sources, including wind measurement stations, satellite data, and NOAA's Next Generation Weather Radar (NEXRAD).
- Assess wind load design assumptions for the range of wind types to determine adequacy for historical and future wind loads. This includes the applicability of the 3 s gust wind speed for severe convective storms and the choice of the appropriate reference period for reliability analyses.
- Develop methods for improved tornado wind modeling and enhance understanding of changes in regionalization. This includes characterizing changes to frequency and intensity due to warming and observed trends of increased tornado events east of the central plains.
- Develop methods and design criteria to capture effects associated with damage due to wind-driven rain, to ensure continued functionality.

4.2. Breakout 2. Inland Flood/Rain

Breakout group 2 focused its future loads and load effects research and priority needs on inland flood and rain hazards. The group identified key research priorities to improve noncoastal flood resilience through better data, modeling, design, and interdisciplinary approaches. The central focus is transitioning from reactive, flood-resilient design based on past observations to more proactive, forward-looking strategies anticipating future flood conditions and land development:

- Leverage existing data for near-term predictions: In the short term, the engineering community must develop more methods to use existing flood data from FEMA or other sources to estimate future flood conditions, particularly where new models or downscaled climate projections may not yet be available. These methods should consider local watershed characteristics to account for the variable behavior of noncoastal flood hazards.

- **Develop noncoastal flood characterization:** Flood hazard studies must go beyond inundation maps to capture characteristics that are critical to flood-resistant design and planning, such as floodwater velocity, rate of rise, and flood duration. These parameters are crucial for evaluating potential damage and designing flood-resistant structures.
- **Account for the influence of future development:** Modeling must incorporate future development patterns, including changes in land use and stream migration, to ensure that future infrastructure decisions are considered in assessing local flood hazards. This includes both physical development and environmental changes that alter flood behavior, such as stream migration.
- **Automate flood mapping:** The process of developing flood hazard studies and maps must become more efficient to keep flood risk data up-to-date and more comprehensive. Automation, including the use of machine learning and artificial intelligence, can reduce the duration of map update cycles and expand map coverage, especially in underserved areas of the country.
- **Encourage design for adaptation:** In some instances, resilient design emphasizes adaptation to noncoastal flooding, rather than seeking to resist or eliminate the hazards. Multidisciplinary approaches are needed to develop strategies that consider long-term mitigation and the evolving nature of risk.

4.3. Breakout 3. Coastal Flood/Sea-Level Rise

The focus of breakout group 3 was on future loads and load effects related to coastal flood and sea-level rise hazards. The following are needs identified by the group:

- Consistent flood hazard maps (e.g., depth, velocity, wave height, extent) at the national level that consider various flood drivers (e.g., SLR, storm surge, precipitation, wave action, groundwater rise, erosion, subsidence, coastline change) to provide up-to-date, scientifically credible, fit-for-purpose, and regularly updated data for localized design.
- Techniques for dealing with nonstationarity and uncertainty of hazards (e.g., SLR, storm surge, precipitation); for example, under a specified warming level (e.g., 3 °C) and the timeline to reach that level, design life of the structures, and impact to reliability considerations in design.
- Incorporation of decision analytic frameworks into design and guidelines on how to select an approach in design, such as dynamic adaptive pathways, benefit-cost assessments, risk-based designs, design for functional recovery, and design for serviceability performance during frequent hazards.
- Research into nature-based solutions (e.g., ecotone levee, oyster reefs) to understand their performance, capacity, and impact on hazard reduction and development of appropriate and viable design criteria. As a priority, we need Tribal partners to incorporate their knowledge of nature-based solutions into design.
- A new design philosophy that incorporates a systems approach to account for the spatial distribution of infrastructure, environment, and people exposed to coastal hazards, including changing societal preferences for coastal access (e.g., availability, public access, habitat restoration) and their impacts on design (e.g., larger ships wave

wake effect, functional changes on hazard levels). We need to identify and include key partners in civil society, community organizations, government agencies, and industry to co-develop code philosophy as part of the code development process.

4.4. Breakout 4. Snow/Permafrost/Ice

Breakout group 4 primarily identified upcoming research needs related to snow, permafrost, and ice. After discussion and grouping of certain topics, the top five research needs for snow and ice load effects were developed through consensus among the participants. These were not ranked individually:

- Research is needed to relate ground snow to roof and drifting loads and to understand the processes that are involved and how climate effects can be incorporated. The goal is to better understand regional differences in snow movement and accumulation both on the ground and on large structures (such as arenas), and how this will change in the future.
- Engineering research is needed to understand building interactions arising from newer roofing materials (e.g., snow sliding, redistributing) and how management of the risks of falling snow and ice affects snow loads. Guidelines on dealing with these public safety concerns would be welcome.
- Research is needed to leverage reanalysis and climate model data to better characterize freezing rain and ice loads where observations are lacking, including between observation stations in the present and for the future in all locations. This research includes developing more reliable observations of freezing rain and ice accretion thickness at more locations, validation of reanalysis products (such as ERA-5), and better detection algorithms to translate climate model output to local ice. Options include
 - Developing low-cost sensors and leveraging other sensor networks such as smart roads and other new technology infrastructure;
 - Combining hindcasts from weather models and nontraditional data such as insurance claims to enhance the observational record;
 - Quantifying ice accretion and load on different (noncylindrical) surfaces, for example solar panels; and
 - Investigating convection-permitting model simulations for better process understanding of future conditions.
- Investigation of frozen precipitation loads that are not currently included in the standards, including hail and rime icing, is needed. For example, hail can lead to degradation of the structure once the envelope is compromised. Rime icing is a concern for tall structures, including power transmission towers, wind turbines, and tall buildings. Potential synergy exists with aviation research on in-cloud icing.
- Research is needed into load distribution effects that are not currently treated, including snow redistribution that causes beam deflection beams and leads to secondary ponding and concentration of loads, or from human intervention (e.g., people clearing snow from parking garages).

4.5. Breakout 5. Structural Capacity

Breakout group 5 was tasked with identifying the most impactful future effects on structural capacity and the next generation of research needs. The discussion presented in the previous sections led to the identification of the following top research topics:

- Develop models for various deterioration mechanisms for structural materials that account for the effects of different environmental stressors (temperature, humidity, CO₂, chloride, saltwater) and their combination with mechanical stressors. These models should be implemented in open-source tools and presented so as to facilitate their adoption in engineering practice. The models should be able to provide engineers with information on changes in the stiffness and strength of structural materials.
- Validate deterioration models using advanced numerical tools and real-time and accelerated laboratory and field testing.
- Build reliability models that account for aleatory uncertainties in deterioration agents and parameters and the epistemic uncertainties associated with the methods used to assess the degradation in structural capacity and apply those to calibrate load combination factors and generate data-driven, site-specific capacity reduction factors that can be added to the resistance side of load and resistance factor design (LRFD) type design-check equations.
- Improve understanding of the effects of localized deterioration and its impact on component and system performance and develop criteria for assessing the redundancy and robustness of structural systems whose members are prone to different types of deterioration mechanisms.
- Provide guidelines for monitoring and inspection requirements for evaluating the capacity of structural members and systems and their future performance under future climate impacts.

5. Section 5: Analysis of Research Needs

Following the breakout sessions, the workshop participants reconvened and reviewed the recommended research needs from each breakout session. Along with the review, the participants engaged in robust discussions about the identified research needs, noting some duplication. As the workshops progressed, the WSC noticed the emergence of several themes that were aligned with, but not quite identical to, the focus of the specific workshop. Consequently, the WSC reviewed the prioritized research needs and indexed each according to the themes identified below.

5.1. Prioritized Research Needs Indexed to Themes

A summary discussion of results is useful for understanding the scope and complexity of the workshop topic. In general, the workshops were designed to build upon each other and progress the participants' thinking and understanding of the research needs. While each workshop focused on a specific aspect of overall need, each workshop yielded meaningful discussions in several areas. In review of the results, six themes emerged and the research priorities identified were aligned with the themes to consistently organize all topics across all of the workshops. The following briefly describes these themes.

1. *Future Hazard Data and Information.* Development of **up-to-date, scientifically credible and fit-for-purpose, future-ready hazard data frameworks** that are scientifically robust, transparent, and directly usable in engineering and planning decisions. Identifies future hazard datasets and associated information, including projections and their uncertainties, that are needed for future engineering design criteria.
2. *Future Load Effects and Infrastructure Conditions.* Advancement of **load characterization under future conditions, infrastructure performance modeling, and structural capacity assessments** that explicitly account for future climate, nonstationarity, and evolving built-environment conditions. The aim is to enable reliable, transparent, and forward-looking load and infrastructure condition assessments that support resilience modeling, code development, and risk-informed engineering decisions under future conditions.
3. *Design Guidelines, Criteria, and Tools.* Modernization of **design guidelines, criteria, and engineering tools** to explicitly address nonstationary hazards, future climate conditions, and time-dependent infrastructure performance. Translates evolving climate science and infrastructure performance knowledge into practical, transparent, and flexible design guidelines that support resilient infrastructure under future conditions.
4. *Resilience and Adaptation.* Advancing **resilience- and adaptation-focused engineering frameworks** that move beyond prescriptive design toward performance-based, risk-informed, and decision science–based approaches suited for future conditions. The aim is to enable transparent, scalable, and socially informed adaptation strategies that support long-

term infrastructure performance and community resilience under evolving climate and risk conditions.

5. *Planning and Design Frameworks*. Evolution of engineering practice toward **risk-informed, adaptive, and life-cycle-based decision frameworks** capable of addressing nonstationary hazards and long-term climate uncertainty. Includes research needs to align engineering design, planning, and code development with long-lived infrastructure performance, community resilience outcomes, and evolving societal risk preferences under future conditions.
6. *Codes and Standards*. **Modernization of codes, standards, and design philosophies** to reflect system-level risk, nonstationary hazards, and long-term infrastructure performance under future climate conditions. Enables adaptive, evidence-based codes and standards that support resilient infrastructure, informed decision-making, and timely adoption of best available knowledge.

The final outcome is the list of research needs indexed according to the six themes identified by the WSC (Table 5-1). Note that the list of research needs are those prioritized by the workshop participants, but the list is not in priority order. Additional details from each breakout group, along with preliminary indexing, are provided in Appendix A.

Table 5-1. Priority Research Needs Identified by the Workshop Participants Indexed across Six Themes *

Research Need	Future Hazard Data and Information	Future Load Effects and Infrastructure Conditions	Design Guidelines, Criteria, and Tools	Resilience and Adaptation	Planning and Design Frameworks	Codes and Standards
Assess wind load design assumptions for the range of wind types to determine adequacy for historical and future wind loads.	2	2	1			
Multiple high-resolution (km-scale) simulations for historical and future severe convective storms, bounded by observations, are needed to reduce or	1	2				

better quantify uncertainty.						
Observational data with a higher quality and resolution to ensure extreme events for wind types are adequately captured and to improve future hazard models and projections. Data sets should use existing, new, and emerging data sources, including wind measurement stations, satellite data, and NEXRAD.	1		2			
Develop methods and design criteria to capture effects associated with damage due to wind-driven rain to ensure continued functionality.		1	2			
Develop methods for improved tornado wind modeling and enhance understanding of changes in regionalization. This includes characterizing changes to frequency and intensity due to warming and observed trends of increased tornado events east of the central plains.	1	2	2			

As a near-term approach until standardized, universal future conditions flood hazard data products are developed, we need to develop a method(s) to adjust or augment currently available flood hazard data from present-day flood maps and studies to estimate future conditions. This method(s) may consist of multiple scaling factors to account for different future effects.		1	2			
Develop multidisciplinary design and mitigation approaches that accommodate flooding rather than simply resist floods or elevate above the flood, such as floating structures, low water-crossing bridges, etc.		2	1			
We must improve our current definitions (boundary conditions) and models of various flood characteristics and better understand their associated uncertainties.	2	2	1			

Develop method(s) to account for future development and other non-climate-related future conditions that may impact noncoastal flooding, such as worsening runoff characteristics, including potential drought conditions. This will improve the reliability of future climate models to reflect the built environment.		1	2			
Institute measures to automate flood mapping and improve the efficiency of flood map development, such as AI or ML to develop models and maps. Human effort should focus on oversight and field verification of existing conditions. In addition, we must improve understanding of hydrological models that translate precipitation into flood characteristics.		2	1			
Consistent flood hazard maps (e.g., depth, velocity, wave height, extent) at the national level that consider various flood drivers (e.g., SLR, storm surge, precipitation, wave action, groundwater		1	2			

rise, erosion, subsidence, coastal change) to provide up-to-date, scientifically credible, fit-for-purpose, and regularly updated data sources for localized design.						
Develop techniques for dealing with the nonstationarity and uncertainty of hazards (e.g., SLR, storm surge, precipitation). For example, under a specified warming level, such as 3 °C and the timeline to reach that level, design life of the structures, and impact to reliability considerations in design.			1		2	
Develop a new design philosophy that incorporates a systems approach to account for the spatial distribution of infrastructure, environment, and people exposed to coastal hazards, including changing societal preferences for coastal use and their impacts on design. Identify key partners in civil society, communities of practice, government agencies, and industry to co-			1		2	2

develop code philosophy as part of the code development process.						
Incorporate decision analytic frameworks into design and provide guidelines on how to select an approach in design, such as dynamic pathways, benefit-cost assessments, risk-based design, design for functional recovery, and design for serviceability or performance during frequent floods.				1	2	
Improve our understanding of nature-based solutions (e.g., ecotone levee, oyster reeds) to understand their performance, capacity, and impact on hazard reduction and to develop and validate design criteria. As an industry, work with Tribal partners and incorporate their knowledge of nature-based solutions into design.		2		1		
Research is needed to relate ground snow to roof and drifting loads, the processes that are involved, and how		1	2			

climate effects can be incorporated. The goal is to better understand regional differences in how snow moves and accumulates, and how this will change in the future.						
Research is needed to leverage reanalysis and climate model data to better characterize freezing rain and ice loads where observations are lacking, including in the future. This includes more reliable observations of freezing rain and ice accretion thickness at more locations, validation of reanalysis products, and better methods to translate climate model output to local ice.		1	2			
Investigate ice loads that are not covered now, including hail and its effects on buildings and rime icing and its effects on power transmission.	2	1				
Research is needed into load distribution effects that are not currently treated, including deflection (beams) leading to secondary ponding concentration of loads or from human intervention.		1	2			

Engineering research is needed to understand building interactions arising from newer roofing materials (e.g., snow sliding) and how management of the risks of falling snow and ice affect loads.		1	2			
Develop models for various deterioration mechanisms accounting for different environmental stressors (temperature, humidity, CO2, chloride, saltwater, etc.) and implement them in open-source tools for practice.		1	2			
Build reliability models accounting for uncertainties in capacity degradation and apply those to calibrate load combination factors and generate data-driven, site-specific capacity reduction factors.		2	1			
Provide guidelines for monitoring and inspection requirements for evaluating capacity and future performance under climate impacts.			1		2	2
Validate deterioration models using advanced numerical tools and real-time and		1	2			

accelerated laboratory and field testing.						
Improve understanding of localized deterioration and its impact on component and system performance.		1	2			

*Table Key:

- 1 = Primary research need
- 2 = Secondary research need
- 3 = Related research need

5.2. Discussion of Results

The outcomes of Workshop 2 on future load effects and infrastructure conditions reveal a strong and consistent message: advancing resilience under future climate conditions will require coordinated progress across hazard data, load characterization, infrastructure performance, design practice, planning frameworks, and codes and standards. While each theme represents a distinct dimension of the challenge, the highest-priority research topics emphasize integration, linking future hazard information to structural loads, structural response, and ultimately to engineering and planning decisions for the built environment that must perform reliably over long time horizons.

5.2.1. Future Hazard Data and Information

Emphasizing the outcomes of the first workshop on future hazards, the second workshop focused on establishing up-to-date, scientifically credible, fit-for-purpose future hazard datasets for engineering use. Workshop participants emphasized the need to move beyond fragmented or purely scientific climate products toward developing frameworks for hazard datasets that are transparent, reproducible, and directly applicable to engineering design and risk assessment. High-priority research topics include improving the quality and spatial resolution of observational (historical) datasets; high-resolution (km-scale) simulations of future extreme events; and better characterization of future hazards such as extreme winds, snow and rain, flooding, and compound events that drive infrastructure risk.

A recurring theme is the importance of clearly quantifying and communicating uncertainty. Rather than treating uncertainty as an afterthought, future hazard datasets must include uncertainty information in a meaningful way that engineers and planners can use. Priority

research, therefore, emphasizes standardized methods, clear documentation of assumptions, and consistency across regions for each hazard type. Other research topics focus on refinement of existing datasets and improved linkage between historical observations and future projections, which are valuable but secondary to the need for future-ready hazard frameworks.

5.2.2. Future Load Effects and Infrastructure Conditions

The future load effects and infrastructure conditions theme identified several consequential and technically demanding areas of research. Priority topics address future hazard characterization for engineers to determine loads and load effects and to understand the evolving condition and capacity of an engineered system. Participants identified a critical gap between climate science and future hazard models due to significant uncertainty and nonstationarity and the consequence of these factors on engineering load models and structural performance assessments. For instance, participants recognized that high-resolution simulations for historical and future storms, bounded by historical observations, are needed for assessing uncertainties in future hazards and loads.

Priority research calls for the development of load characterization methods that explicitly account for nonstationarity, changing hazard characteristics, and evolving infrastructure conditions, particularly degradation mechanisms. This includes advancing approaches to translate future wind, flood, wave, surge, precipitation, temperature, and compound hazards into time-dependent structural and geotechnical loads and degradation effects. Importantly, these methods must move beyond static design assumptions to reflect how loads may intensify, shift in frequency, or interact over the service life of infrastructure.

High-priority topics for infrastructure capacity changes over time emphasize improved representation of aging, degradation, maintenance practices, and material performance under climate stressors such as corrosion, fatigue, thermal effects, and moisture intrusion. Participants stressed that not only increasing demands but also declining capacity drive future risk of damage or failure, and that both processes must be represented. Research is also needed to better capture system interactions and cascading effects, recognizing that infrastructure failures often arise from interconnected system responses or compounding loads or load effects rather than isolated components or hazards.

Other topics in this theme focus on incremental refinement to existing load models and performance tools. While useful, these efforts were viewed as insufficient without more fundamental advances that enable transparent, scenario-based assessments of future load effects and infrastructure conditions.

5.2.3. Design Guidelines, Criteria, and Tools

Priority research in design guidelines, criteria, and tools focuses on translating advances in hazard models and structural loads, effects, and conditions into practical guidelines for engineering applications. Participants highlighted the growing disconnect between rapidly evolving climate science and the design tools and criteria used in everyday engineering practice. High-priority topics, therefore, emphasize the modernization of design guidelines to explicitly address nonstationary hazards, future climate conditions, and time-dependent infrastructure performance.

This includes developing flexible criteria that can accommodate multiple future scenarios, improving transparency in how environmental hazard information is incorporated into design decisions, and enhancing tools that allow practitioners to apply future-condition data consistently. Secondary priorities include updating existing guidelines and refining tools once future-oriented design criteria are more firmly established.

5.2.4. Resilience and Adaptation

Within the resilience and adaptation theme, high-priority research emphasizes a shift toward performance-based, risk-informed, and decision-science-based approaches. Participants underscored the need for engineering frameworks that explicitly address uncertainty, support adaptive decision-making, and link technical performance metrics to broader resilience outcomes for infrastructure systems and communities at large.

High-priority topics include developing methods to evaluate adaptation strategies over time, supporting transparent trade-off analyses, and integrating social and economic considerations into engineering decision-making. Other topics focus on refining existing resilience metrics and adaptation frameworks, which are important yet depend on advancing developments in hazard, load, and performance modeling.

5.2.5. Planning and Design Frameworks

Priority research under the theme of planning and design frameworks centers on evolving engineering practice toward life-cycle, systems-based decision frameworks that can accommodate long-lived infrastructure and deep climate uncertainty. High-priority topics emphasize aligning planning, design, and investment decisions with future performance objectives; risk tolerance; and adaptive pathways for design, construction, and maintenance.

Participants highlighted the need for frameworks that support sequencing of actions over time, coordination across sectors, and integration of engineering decisions with broader planning and governance processes. Secondary priorities include harmonizing existing planning tools and

improving coordination between planning and design once future-oriented frameworks are in place.

5.2.6. Codes and Standards

Finally, the codes and standards theme highlights the need to modernize regulatory and standards frameworks to reflect system-level risk, nonstationary hazards, and long-term infrastructure performance under future climate conditions. Priority research focuses on developing adaptive, evidence-based approaches for codes and standards and applications that maintain credibility while allowing timely incorporation of emerging technologies.

High-priority research topics include mechanisms for integrating interim guidelines, addressing future loads and performance explicitly, and shifting from purely prescriptive requirements toward risk-informed principles. Other topics include incremental updates and improved dissemination of existing standards, which depend on advances across the other themes.

5.3. Summary

In summary, the workshop priorities point to a clear research trajectory: future resilience depends on strengthening the full chain of hazard characterization; loads; infrastructure performance; design practice; and ultimately codes, standards, and planning decisions. Priority research consistently emphasizes integration, developing future-ready hazard data that can be credibly translated into time-varying loads; evaluated against evolving infrastructure conditions and capacity; and embedded within performance-based, risk-informed decision frameworks. Advancing any single theme in isolation will be insufficient; progress in design guidelines, resilience strategies, and codes and standards is fundamentally constrained by the ability to represent future hazards, loads, and infrastructure performance in a transparent and decision-relevant manner. Collectively, these priorities underscore the need for coordinated, interdisciplinary research that not only advances scientific understanding but also ensures that new knowledge is usable; adaptable; and timely for the engineers, planners, and decision-makers responsible for long-lived infrastructure under an uncertain and changing climate.

6. Section 6: Acronyms and Abbreviations

AF	Adjustment Factor
AI	Artificial Intelligence
ASCE	American Society of Civil Engineers
C&C	Components and Cladding
CO ₂	Carbon Dioxide
FEMA	Federal Emergency Management Agency
FRP	Fiber-Reinforced Plastic
GLOF	Glacial Lake Outburst Floods
H&H	Hydrologic and Hydraulic
ML	Machine Learning
MWFRS	Main Wind Force Resisting Structure
NBCC	National Building Code of Canada
NEXRAD	Next Generation Weather Radar (NOAA)
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
PBD	Performance-Based Design
SEI	Structural Engineering Institute
SWE	Snow Water Equivalent
UV	Ultraviolet
WSC	Workshop Steering Committee

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Appendix A. Discussion of Priority Research Needs

Tables A-1 through A-5 summarize the breakout session research needs. After the breakout session reporters presented and described their sessions' research needs, the full group of participants rated each research recommendation from all breakout sessions.

Table A-1. Breakout Group 1: Wind: Research Needs, as Rated by the Workshop Participants

Priority need	% of total ranking
Assess wind load design assumptions for the range of wind types to determine adequacy for historical and future wind loads.	31%
Multiple high-resolution (km-scale) simulations for historical and future severe convective storms, bounded by observations, are needed to reduce or better quantify uncertainty.	26%
Observational data with a higher quality and resolution to ensure extreme events for wind types are adequately captured and to improve future hazard models and projections. Data sets should use existing, new, and emerging data sources, including wind measurement stations, satellite data, and NEXRAD.	21%
Develop methods and design criteria to capture effects associated with damage due to wind-driven rain, to ensure continued functionality.	13%
Develop methods for improved tornado wind modeling and enhance understanding of changes in regionalization. This includes characterizing changes to frequency and intensity due to warming and observed trends of increased tornado events east of the central plains.	9%

Table A-2. Breakout Group 2: Inland Flood/Rain: Research Needs, as Rated by the Workshop Participants

Priority need	% of total ranking
As a near-term approach until standardized, universal future conditions flood hazard data products are developed, we need to develop a method(s) to adjust or augment currently available flood hazard data from present-day flood maps and studies to estimate future conditions. This method(s) may consist of multiple scaling factors to account for different future effects.	25%
Develop multidisciplinary design and mitigation approaches that accommodate flooding rather than simply resist floods or elevate above the flood, such as floating structures, low water-crossing bridges, etc.	25%
We must improve our current definitions (boundary conditions) and models of various flood characteristics and better understand their associated uncertainties.	20%
Develop method(s) to account for future development and other non-climate-related future conditions that may impact noncoastal flooding, such as worsening runoff characteristics, including potential drought conditions. This will improve the reliability of future climate models to reflect the built environment.	15%
Institute measures to automate flood mapping and improve the efficiency of flood map development, such as AI or ML to develop models and maps. Human effort should focus on oversight and field verification of existing conditions. In addition, we must improve understanding of hydrological models that translate precipitation into flood characteristics.	15%

Table A-3. Breakout Group 3: Coastal Flood/Sea-Level Rise: Research Needs, as Rated by the Workshop Participants

Priority need	% of total ranking
Develop consistent flood hazard maps (e.g., depth, velocity, wave height, extent) at the national level that consider various flood drivers (e.g., SLR, storm surge, precipitation, wave action, groundwater rise, erosion, subsidence, coastal change) to provide up-to-date, scientifically credible, fit-for-purpose, and regularly updated data sources for localized design.	32%
Develop techniques for dealing with the nonstationarity and uncertainty of hazards (e.g., SLR, storm surge, precipitation). For example, under a specified warming level, such as 3 °C and the timeline to reach that level, design life of the structures, and impact to reliability considerations in design.	30%
Develop a new design philosophy that incorporates a systems approach to account for the spatial distribution of infrastructure, environment, and people exposed to coastal hazards, including changing societal preferences for coastal use and their impacts on design. Identify key partners in civil society, communities of practice, government agencies, and industry to co-develop code philosophy as part of the code development process.	19%
Incorporate decision analytic frameworks into design and provide guidelines on how to select an approach in design, such as dynamic pathways, benefit-cost assessments, risk-based design, design for functional recovery, and design for serviceability or performance during frequent floods.	11%
Improve understanding of nature-based solutions (e.g., ecotone levee, oyster reeds) to understand their performance, capacity, and impact on hazard reduction and to develop and validate design criteria. As an industry, work with Tribal partners and incorporate their knowledge of nature-based solutions into design.	8%

Table A-4. Breakout Group 4: Snow/Permafrost/Ice: Research Needs, as Rated by the Workshop Participants

Priority need	% of total ranking
Research is needed to relate ground snow to roof and drifting loads, the processes that are involved, and how climate effects can be incorporated. The goal is to better understand regional differences in how snow moves and accumulates, and how this will change in the future.	39%
Research is needed to leverage reanalysis and climate model data to better characterize freezing rain and ice loads where observations are lacking, including in the future. This includes more reliable observations of freezing rain and ice accretion thickness at more locations, validation of reanalysis products, and better methods to translate climate model output to local ice.	30%
Investigation of ice loads that are not covered now, including hail and its effects on buildings and rime icing and its effects on power transmission.	16%
Research is needed into load distribution effects that are not currently treated, including deflection (beams) leading to secondary ponding concentration of loads or from human intervention.	8%

Engineering research is needed to understand building interactions arising from newer roofing materials (e.g., snow sliding), and how management of the risks of falling snow and ice affects loads.	7%
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Table A-5. Breakout Group 5: Structural Capacity: Research Needs, as Rated by the Workshop Participants

Priority need	% of total ranking
Develop models for various deterioration mechanisms accounting for different environmental stressors (temperature, humidity, CO ₂ , chloride, saltwater, etc.) and implement them in open-source tools for practice.	42%
Build reliability models accounting for uncertainties in capacity degradation and apply those to calibrate load combination factors and generate data-driven, site-specific capacity reduction factors.	23%
Provide guidelines for monitoring and inspection requirements for evaluating capacity and future performance under climate impacts.	13%
Validate deterioration models using advanced numerical tools and real-time and accelerated laboratory and field testing.	12%
Improve understanding of localized deterioration and its impact on component and system performance.	10%

Appendix B. Workshop Materials

B.1. Workshop Agenda



SEI NIST Forward-Looking Codes and Standards: Future Load Effects Workshop

DATE: July 29–30, 2025

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

VIRTUAL: Zoom and Teams links sent separately

Workshop Agenda

Workshop Director: Jayantha “Obey” Obeysekera, Ph.D., Research Professor,
Director of Sea Level Solutions Center, Institute of Environment at FIU

WORKSHOP MATERIALS: [Link to Digital Materials Package](#) (password: futureloads)

Day 1: July 29, 9:00am–5:00pm ET

8:00am–9:00am: NETWORKING CONTINENTAL BREAKFAST PROVIDED

GENERAL SESSION

9:00am–9:30am: Welcome

- Welcome, Purpose, and Workshop Agenda and Goals
 - Welcome and Opening Remarks—Jayantha “Obey” Obeysekera, Ph.D., P.E., Research Professor, Director of Sea Level Solutions Center, Institute of Environment at FIU
 - Purpose—Therese McAllister, Ph.D., P.E., F.SEI, Dist.M.ASCE, Deputy Chief, Materials and Structural Systems Division, NIST
 - Workshop Agenda and Goal—Jennifer Goupil, P.E., F.SEI, F.ASCE, Managing Director SEI, Chief Resilience Officer ASCE
- Introductions—All Participants

9:30am–10:45am: Synergistic Efforts: Load Effects

Presentations on current, ongoing synergistic work: this workshop will leverage and build on complementary efforts.

- **2025 Building Code of Canada: Projected Changes in Climatic Design Values;**
Alex Cannon; ECCC Canada [15 min]
- **2025 Building Code of Canada: How and Which Load Effects Were Addressed;**
Hanping Hong; Western University [15 min]
- **Analysis of Climatic Loads: ASCE Special Publication 2024;**
Therese McAllister; NIST [10 min]

- **Load Effects under Consideration by ASCE/SEI 7-28 Chapter 36: Methodology, Assumptions, and Decisions** [25 min]
 - Moderator: Abbie Liel, University of Colorado
 - Matt Gilbertson, SGH: Flood
 - Sihan Li, RWDI: Wind
 - Abbie Liel, University of Colorado: Snow
 - Ken Kunkel, NOAA/NCSU: Rain
 - Ahmed Abdelaal, SUNY Polytechnic Institute: Ice
- **Q&A Discussion**; Moderator: Jayantha Obeysekera [10 min]

10:45pm–11:00am: PICTURE + COFFEE BREAK

11:00am–12:00pm: Synergistic Efforts: Structural Capacity and Functional Underperformance

- **Structural Degradation**; Brian Pailles, SGH [15 min]
- **Lessons Learned from Bridges and Other Exposed Infrastructure**; Ted Zoli, HNTB [15 min]
- **Hidden Effects of Groundwater Changes on Erosion, Saltwater Intrusion, and More**; David Frost, Georgia Tech [15 min]
- **Q&A Discussion**; Moderator: Jayantha Obeysekera [10 min]

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

12:30pm–1:30pm: Plenary Discussion

Session to define the goals for future state, followed by instructions for the breakout sessions.

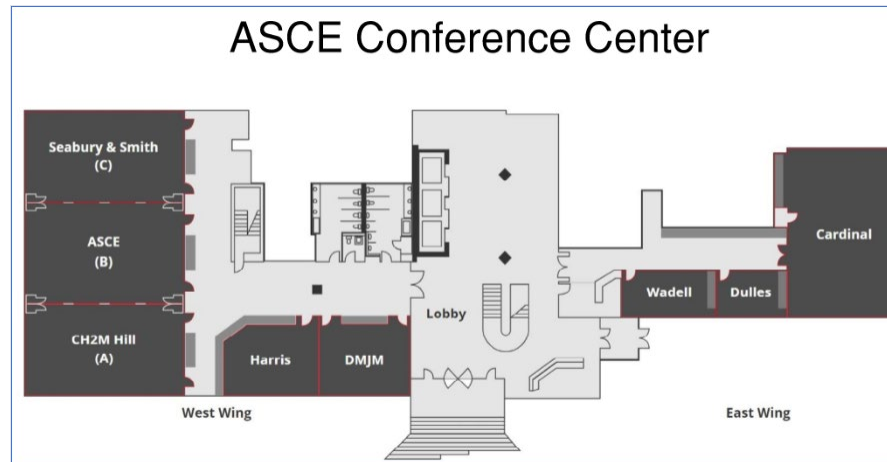
- **Next-Generation Goals for Load Effects**; ALL [45 min]
Moderators: Jayantha Obeysekera, Therese McAllister
Discussion to prepare for breakouts.
- **Charging Breakouts**; Jennifer Goupil [15 min]
Instructions on how the breakouts will work.

GOAL: What do you wish you had? What is needed to characterize future loads and load effects? What are the most impactful future effects on structural capacity? What are the next-generation research needs?

PROMPTS:

1. *Identify critical research needs.*
2. *Identify topics not currently considered.*
3. *Prioritize top 5 research needs. (Each written as a sentence.)*

1:30pm–1:45pm: Move to assigned breakout rooms (see following plan)



1:45pm–3:15pm: Concurrent Breakout Sessions

3:15pm–3:30pm: *COFFEE BREAK*

3:30pm–4:45pm: Concurrent Breakout Sessions (*cont.*)

4:45pm–5:00pm: Reconvene

- Summary and Adjourn Day 1

Day 2: July 30; 8:00am–12:00pm ET

7:30am–8:00am: NETWORKING CONTINENTAL BREAKFAST PROVIDED

8:00am–8:15am: Welcome

- Purpose and Goals of Day 2

8:15am–10:30am: Report Out

- Breakout Session Report Out: [15 min EACH = 10 min + 5 min Q&A]

15-minute COFFEE BREAK (9:30am)

- Moderated Discussion of Breakout Reports [45 min]
Moderator: Jayantha Obeysekera

10:30am–11:45am: Prioritization

- Prioritization of Research Needs: Survey [15 min]
- Discussion of Survey Results [60 min]

11:45am–12:00pm: Conclusion

- Summary and Adjourn Day 2

12:30pm–3:30pm: Workshop Steering Committee Meeting

B.2. Workshop Presentations

B.2.1. Day 1: Overview Presentations

FUTURE LOAD EFFECTS

*The workshop presentations and discussion do not necessarily reflect
the views or policies of NIST or the United States Government.*

July 29-30, 2025

SEI/NIST Forward Looking Codes and Standards Workshop #2



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FORWARD-LOOKING CODES AND STANDARDS: WELCOME

Jayantha 'Obey' Obeysekera, Ph.D., P.E.
Research Professor & Director, Sea Level Solutions Center,
Institute of Environment at Florida International University
Project Director, SEI/NIST Workshops



WELCOME & OVERVIEW

- Already observing increasing land and ocean temperature, more frequent and prolonged heat waves, increased frequency and intensity of heavy precipitation, severe storms and cyclones, and increased droughts in some areas.
- There is an urgent need to advance design practices to incorporate future hazard projections into codes and standards of buildings and infrastructure.
- The Structural Engineering Institute (SEI) of the American Society of Civil Engineers (ASCE) has contracted with the National Institute of Standards and Technology (NIST) to develop and execute a series of **four workshops** on Forward-Looking Codes and Standards.



OVERARCHING GOAL: RESEARCH ROADMAP INFORMED BY WORKSHOPS

- Address future hazards, conditions, impacts for design:
 - Temperatures (atmospheric, sea surface)
 - Precipitation (rain, snow, ice, hail)
 - Flood (sea level; coastal/inland flooding)
 - Wind (convective storms, hurricanes)
 - Earthquake (landslides, liquefaction, drought)
 - Wildland-urban interface (WUI) fires
 - Material/Structural degradation (e.g., concrete, steel corrosion)
- Identify and prioritize *next generation* gaps and research needs for implementing future hazards and associated design criteria in codes and standards.
- Inform strategic planning for future requirements in the built environment, and potential changes to design parameters (e.g., nonstationary reliability, service life, design loads).



WORKSHOP STEERING COMMITTEE

- PROJECT DIRECTOR: **Obey Jayantha**, Ph.D., Research Professor, Director of Sea Level Solutions Center, FIU
- **Meg Ackerson**, P.E., Arup (Co-participant with Jack Hogan)
- **Joe Ackroyd**, Assistant Commissioner; Technical Affairs & Code Development; New York City Department of Buildings, NYC
- **Joseph Barsugli**, Ph.D., Research Scientist III, CIRES, University of Colorado Boulder, NOAA Physical Sciences Laboratory Affiliate
- **Kevin Borth**, P.E., S.E., Sr. Structural Project Engineer | Associate Vice President, HGA
- **Keith Dixon**, Ph.D., Deputy Division Head of the GFDL Marine Ecosystems & Downscaling Division, NOAA Geophysical Fluid Dynamics Laboratory
- **Michel Ghosn**, Ph.D., Professor, The City College of New York / CUNY
- **Matt Gilbertson**, Sr. Technical Manager, Simpson Gumpertz Heger
- **Elisabeth Gilmore**, Professor, Carleton University
- **Jack Hogan**, P.E., Associate Climate Risk and Resilience Engineer, Arup
- **Sihan Li**, Ph.D., P.Eng., Senior Specialist, Associate, RWDI
- **Amanda McCarty**, Director, NOAA Climate Ready Nation
- **Mari Tye**, Ph.D., Project Scientist II, Climate and Global Dynamics Laboratory (CGD), National Center for Atmospheric Research (NCAR)



WORKSHOP STEERING COMMITTEE (CONT.)

NIST

Materials and Structural Systems Division, Engineering Laboratory

- **Terri McAllister**, Ph.D., P.E., MSSD Deputy Chief, Research Structural Engineer for Community Resilience Group
- **Marc Levitan**, Ph.D., Research Structural Engineer, Structures Group
- **Siamak Sattar**, Ph.D., Earthquake Engineering Group Leader, Research Structural Engineer
- **Jennifer Helgeson**, Ph.D., Acting Group Leader and Program Manager, Community Resilience Program
- **Scott Jones**, Ph.D., Research Material Scientist, Infrastructure Materials Group

ASCE/SEI

- **Jennifer Goupil**, P.E., ASCE Chief Resilience Officer and Managing Director, Structural Engineering Institute of ASCE
- **Katie Stueckle**, Structural Engineering Institute of ASCE



WORKSHOPS THEMES

ASCE/NIST will host 4 workshops in 2025 for advancing building and infrastructure codes and standards. Cross-cutting topics will include future hazards, design impacts, and social and economic consequences:

1. **JUNE 4-5: Future hazards for design** - confidence/uncertainty in hazard projections, downscaling of global models, converting hazard projections to design criteria
2. **JULY 29-30: Future load effects on the built environment** - (a) load effects for future hazards, (b) changes in load effects relative to historical basis, (c) changes in structural performance, material properties, soils, ...
3. **TBD: Engineering design guidance and criteria** - non-stationary reliability, service life, design loads, resistance, deterioration
4. **OCT. 28-29: Adaptation and resilience** - buildings and infrastructure system assessment, material durability, mitigation, retrofit,...



FORWARD-LOOKING CODES AND STANDARDS: PURPOSE AND SCOPE

Terri McAllister, Ph.D., P.E., F.SEI., Dist.M.ASCE,
MSSD Deputy Chief, Research Structural Engineer for
Community Resilience Group; NIST



PURPOSE AND SCOPE

- **Purpose:** to provide a **science-based assessment of data and development needs** to advance **design practice and building standards** for future natural hazards and conditions across US communities.
- **Scope:** Input from scientists, practitioners, and researchers is needed on how to:
 - Prioritize what is needed to achieve **the next generation of future hazards and conditions for design** (beyond ASCE 7-28)
 - Identify a path forward to improve building standards and design practice.
 - Consider resilience, adaptation, and social and economic impacts to businesses and communities.



STANDARD DEVELOPMENT ORGANIZATIONS

- **National Building Code of Canada (NBCC) 2025**

The 2025 version addresses Future Conditions

- **ASCE 7-28: Standard for Minimum Design Loads for Buildings and Other Structures**

The 2028 version will have a new section on Future Conditions

- **Other SDOs**

ASTM, American Concrete Institute, American Institute of Steel Construction, NDS for Wood Construction, etc.

- **NIST/NOAA Grants to support ASCE 7-28**

Hazards and Conditions

- Nonstationary reliability methods
- Wind, snow, rain, atmospheric ice hazards and loads

Structural Capacity and Performance

- Corrosion in reinforced concrete
- Ground failure and impacts on structures
- Adaptive design and assessment of reinforced concrete structures



COMMUNITY AND BUSINESS RESILIENCE

- Develop performance goals that include functional recovery
- Assess current and future exposure and interdependencies
- Identify primary risks and hazards
- Evaluate potential solutions for new and existing infrastructure
- Prioritize investments
 - Infrastructure vulnerabilities
 - Social and community consequences



Shopping Center
Marianna, FL

Tyndall AFB, FL

Hurricane
Michael
2018



<https://www.airandspaceforces.com/daily-report/>

SYNERGISTIC EFFORTS

NIST Climate Science and Building Codes Workshop -- Jan 2021

- *Future hazard needs of building regulatory community*

SEI Climate impacts workshops -- March, May, Oct 2022

NIST-ASCE-NOAA Community Resilience Workshops -- Nov 2023 to Jan 2024

- *Leading practices for future hazards in community resilience planning*

ASCE 7-28 Future Conditions Subcommittee
-- 2022 to 2027

ASCE-NOAA Task Force Summit -- Feb 2023

- *Temperature, Rainfall Workshop*---Sep 2022
- *Extreme Wind, Coastal Hazards Workshop*---Oct 2022

ASCE-NOAA Summer Workshop: Building the Resiliency Business Case -- Jun 2025

ASCE Committee on Adaptation to a Changing Climate

ASCE/SEI Special Report -- 2024

- *Effects of Climate Change on Life-Cycle Performance of Structures and Infrastructure Systems*



WORKSHOP #2 GOALS FOR LOAD EFFECTS

Current State of the Art

Canadian Approach in NBCC 2025

- Climatic Design Values and Load Effects

ASCE/SEI Special Publication

- Analysis of Climatic Loads

ASCE 7-28 Future Hazards & Load Effects

- Flood, wind, snow, rain, atmospheric ice

Structural Capacity & Underperformance

- Structural degradation, bridges, groundwater effects

Next Generation Goals

What do you wish you had?

What is needed to characterize future loads and load effects?

What are the most impactful future effects on structural capacity?

What are the next generation research needs?

- Data, Methods, Models, ...

FORWARD-LOOKING CODES AND STANDARDS: AGENDA AND GOAL

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

ASCE Chief Resilience Officer and Managing Director, Structural
Engineering Institute of ASCE



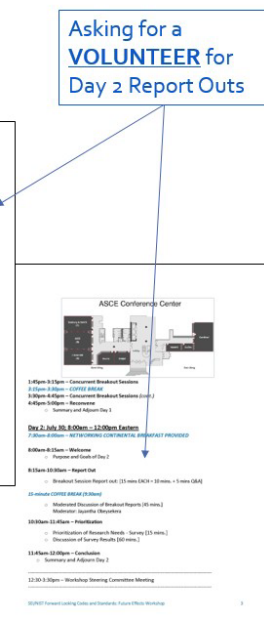
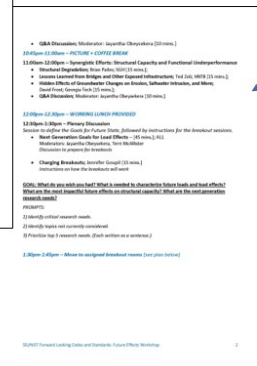
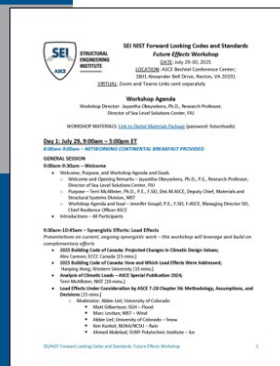
AGENDA

Fully Hybrid = PLEASE
STATE YOUR NAME WHEN
YOU ARE SPEAKING!

Digital Package

(password: futureloads)

- AGENDA
- Participant List
- Slide Decks



SELF INTRODUCTION

Name, Organization



ON SITE PARTICIPANTS

Terri	McAllister	NIST
Jayantha	Obeysekera	FIU
Jennifer	Goupil	ASCE/SEI
Katie	Stueckle	ASCE/SEI
Michel	Ghosn	CUNY
Kevin	Borth	HGA
Meg	Ackerson	Arup
Matt	Gilbertson	Simpson Gumpertz Heger
Elisabeth	Gilmore	Carleton University
Joseph	Barsugli	Univ CO Boulder, NOAA Affiliate
Sihan	Li	RWDI
Siamak	Sattar	NIST
Jennifer	Helgeson	NIST
Scott	Jones	NIST
John	Allen	Central Michigan University
Chris	Clavin	NIST
Jan	Dale	RWDI
Naresh	Devineni	The City College of New York / City University

VIRTUAL PARTICIPANTS

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Amanda	McCarty	NOAA
Marc	Leviton	NIST
Ahmed	Abdelaal	SUNY Poly
Andrew	Newman	UCAR
Ahmed	Attar	NRC Canada
Michele	Barbato	University of California

Graziano	Fiorillo	University of Manitoba
Maria	Garlock	Princeton University
Mohammad	Houshmand	NIST
Ning	Lin	Princeton University
Aron	Newman	NIST
Tayo	Opabola	UC Berkeley
Adam	Reeder	CDM Smith
Erin	Rooney	HDR Inc
Gus	Sirakis	NYC Department of Buildings
Ken	Snyder	NIST
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Abbie	Liel	University of Colorado Boulder
Han-Ping	Hong	University of Western Ontario
Roy	Lobo	HCAI
Zoubir	Lounis	NRC Canada
Jessica	Mandrick	GMS
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Dan	Walker	University of Maryland
Xuebin	Zhang	Pacific Climate Impacts Consortium
Erik	Zuker	HNTB
Daniela	Zuloaga	Arup
Mark	Stewart	Australia/Corrosion in Fasteners
David	Roegner	University of Illinois Urbana-Champaign

SYNERGISTIC EFFORTS: LOAD EFFECTS

9:30 am – 10:45 am

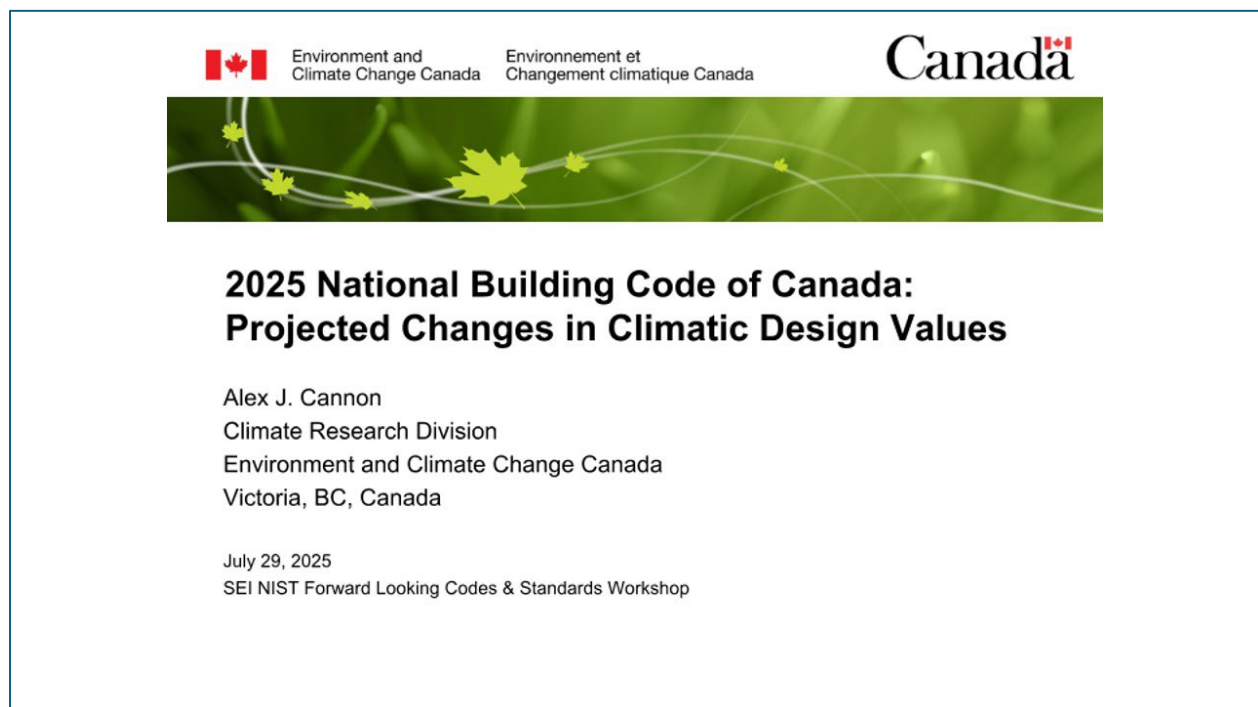
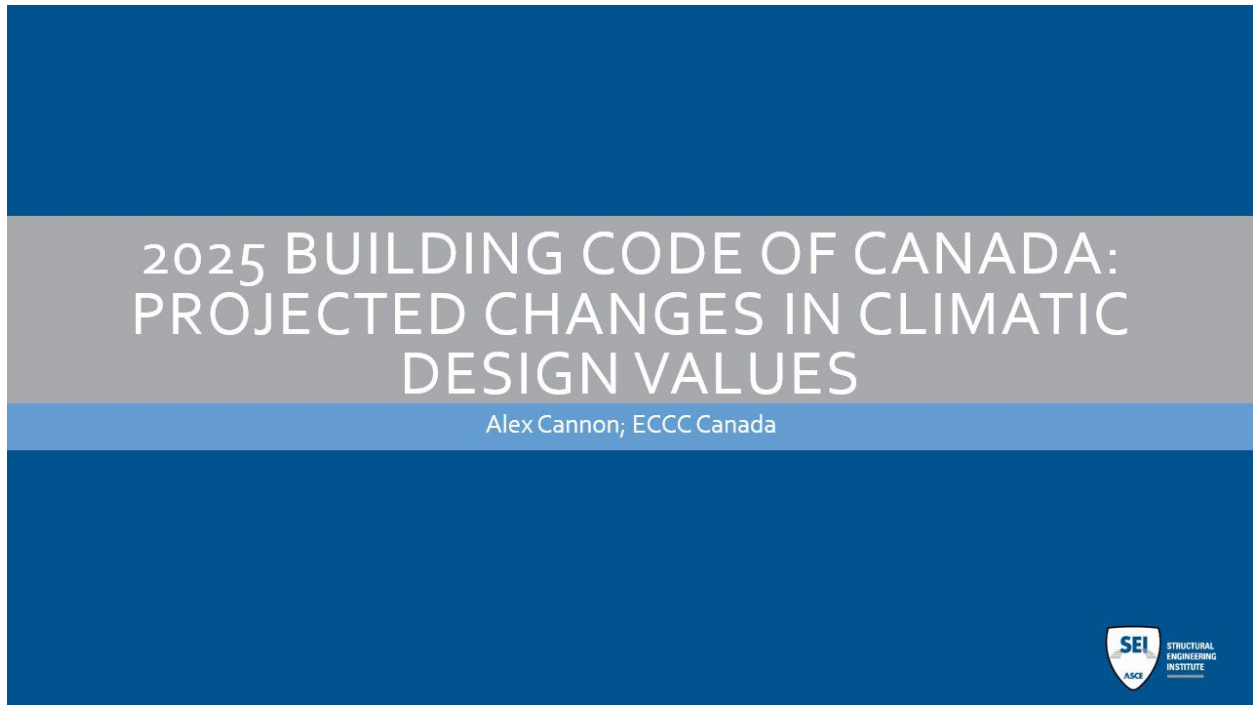


PRESENTATIONS

- **2025 Building Code of Canada: Projected Changes in Climatic Design Values;** Alex Cannon; ECCC Canada [15 mins.]
- **2025 Building Code of Canada: How and Which Load Effects Were Addressed;** Hanping Hong; Western University [15 mins.]
- **Analysis of Climatic Loads – ASCE Special Publication 2024;** Terri McAllister; NIST [10 mins.]
- **Load Effects Under Consideration by ASCE 7-28 Chapter 36: Methodology, Assumptions, and Decisions [25 mins.]**
 - Moderator: Abbie Liel; University of Colorado
 - Matt Gilbertson; SGH – Flood
 - Sihan Li; RWDI – Wind
 - Abbie Liel; University of Colorado – Snow
 - Ken Kunkel; NOAA/NCSU – Rain
 - Ahmed Abdelaal; SUNY Polytechnic Institute – Ice
- **Q&A Discussion;** Moderator: Jayantha Obeysekera [10 mins.]



B.2.1.1. Load Effects: 2025 Building Code of Canada: Projected Changes in Climatic Design Values; Alex Cannon



Future Climatic Design Data for 2025 Update

- 3-year project to assess the impact of climate change on climatic design values for Climate Resilient Buildings and Core Public Infrastructure (2018-2020)
 - 2017 MOU with National Research Council of Canada
 - Guided by Task Group on Climatic Data and Loads
 - Collaboration with Pacific Climate Impacts Consortium
- The final report extended the scientific assessment in Canada's Changing Climate Report (CCCR) – Canada's National Climate Assessment – to cover climatic variables in:
 - National Building Code of Canada and Canadian Highway Bridge Design Code

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CLIMATE-RESILIENT BUILDINGS & CORE PUBLIC INFRASTRUCTURE

An Assessment of the Impact of Climate Change on Design Data in Canada

Authors: Alex J. Cannon, Dae Il Jeong, Xuebin Zhang, and Francis W. Zwiers
Contributors: Charles L. Curry, Guilong Li, Hui Wan, Chao Li, Vivek K. Arora,
Trevor Q. Murdock, Stephen R. Sobie, and Bárbara Tencer
Review Editor: Francis W. Zwiers
External Review: National Research Council Task Group on Climatic Data and Loads

Bilingual publication on the [Canadian Climate Scenarios and Data](#) website in PDF and HTML format

<http://climate-scenarios.canada.ca/>

Table C-2
Climatic Design Data for Selected Locations in Canada

Phenology and Location	Elev. m	Design Temperature			Design Wind Speed m/s	15 min T _{max} °C	15 min T _{min} °C	Ann. Rain mm	Moist. Index	Ann. Tot. Rain mm	Daily Rain fall max. mm Per 1% S	Snow Load N/m ²	Hourly Wind Profile		
		15 min T _{max} °C	15 min T _{min} °C	15 min T _{avg} °C									1:10	1:50	
		15 min T _{max} °C	15 min T _{min} °C	15 min T _{avg} °C									1:10	1:50	
British Columbia															
1000-Mile House	1065	-30	-22	26	17	5033	10	48	300	0.44	435	6.6	0.3	0.37	0.35
Abbotsford	70	-4	-16	26	20	2683	12	112	1525	1.50	1650	10.0	0.3	0.34	0.44
Agassiz	15	-9	-31	31	21	2155	8	128	1665	1.71	1710	2.4	0.7	0.36	0.47

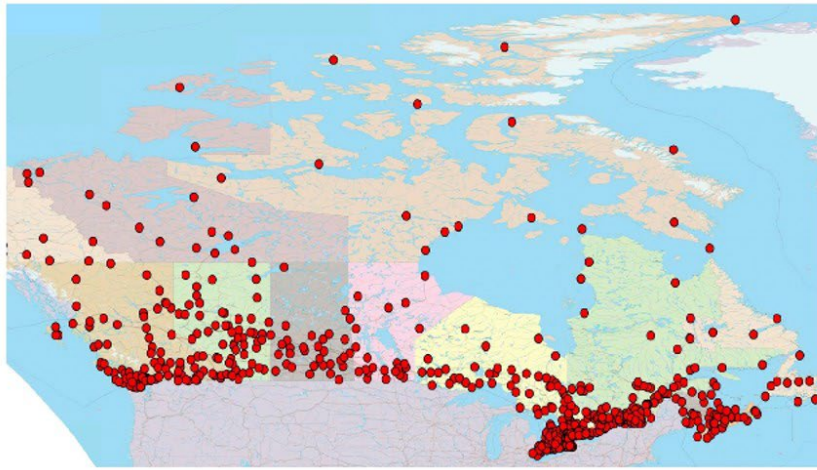
plus additional temperature variables and CHBDC variables:

- ☐ annual maximum ice accretion on exposed surfaces
- ☐ permafrost region

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Sites in Table C-2



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Structure of Assessment

- ☐ Climatic design variables grouped into three tiers according to confidence in future projections for large regions of Canada
 - based on judgements about the body of available evidence
 - ☐ published literature both in Canada and abroad
 - ☐ evidence from targeted research based on Canadian climate model simulations (50 member CanESM2-CanRCM4 Large Ensemble at 50 km grid spacing)
 - ☐ lower spatial resolution to enable estimation of signal-to-noise ratio of regional change

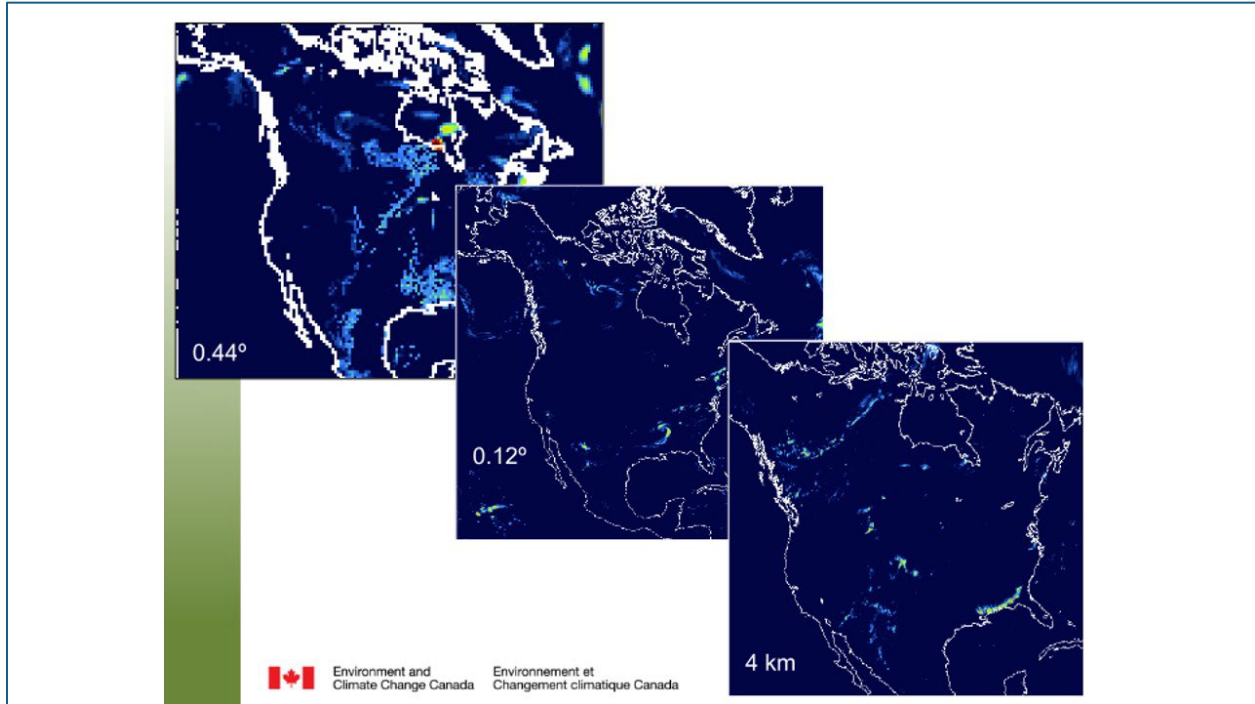
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A Tiered Approach (Tier 1)

- Tier 1 variables are those for which there is generally *high* or *very high* confidence in the future projections for a given level of global warming. This level of confidence is afforded by in-depth understanding of the processes involved, as well as an abundant and a strong body of evidence (including evidence for other parts of the world) that deals with the causes of observed changes.
- This implies relatively high confidence in projected change factors for these variables, which suggests that specific values of these change factors could be considered when designing new infrastructure if justified from an engineering perspective and if suitable approaches exist to consider remaining uncertainties, including uncertainty in the amount of warming that might occur by the end of the service life of the structure that is being designed.
 - heating degree days
 - hourly design temperatures
 - (January 2.5% dry bulb, January 1% dry bulb, July 2.5% dry bulb, and July 2.5% wet bulb)
 - maximum and minimum mean daily air temperatures

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A Tiered Approach (Tier 2)

- Tier 2 variables are those for which there is generally *medium* confidence in the future projections for a given level of global warming. In most instances, an assessment of *medium confidence* means there is some understanding of the processes that lead to future change. This might be supplemented by a body of evidence linking the causes of observed changes at large scales, but generally, such evidence would be much less extensive, with available studies showing a lower degree of consistency, than for Tier 1 variables.
- In contrast to situations when climate scientists have *high* or *very high confidence*, climate scientists are generally not able to estimate the likelihood of a projected change when they determine that they have *medium confidence* in future projections. Change factors for these variables are therefore more suitable for cost/benefit analyses or for a risk analysis, as well as for the exploration of uncertainty associated with design.
 - annual total precipitation and annual total rainfall
 - annual maximum 1-day rain (50-yr return period)
 - annual maximum 15-min rainfall (10-yr return period)

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A Tiered Approach (Tier 3)

- Tier 3 variables are those for which there is *low* or *very low* confidence in the future projections for a given level of global warming. *Low* or *very low confidence* is given to projections for variables that have not been widely studied in the published literature or for which the processes involved are poorly understood. In some instances, very low confidence is given to projections for variables that are diagnosed indirectly, for example, using empirical relationships because process understanding is limited.
- While change factors are projected, they are likely best suited to exploring the potential impacts of climate change on structural reliability in different warming and load combination scenarios.
 - annual mean relative humidity
 - annual maximum hourly wind pressures (10, 25, 50, and 100-yr return periods)
 - annual maximum driving rain wind pressures (5-yr return period)
 - annual maximum snow load (50-yr return period)
 - annual maximum ice accretion on exposed surfaces (20-yr return period)
 - permafrost region

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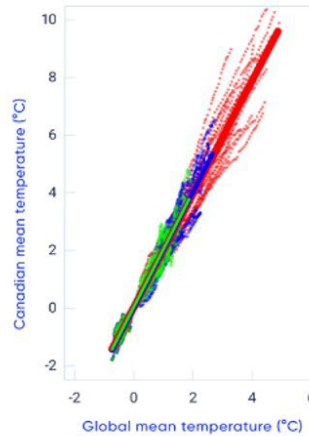
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Link Regional Projections to Global Warming Levels

- Provide information on the regional expression of specified global warming for each climatic design variable
- On the climate modelling side, no need to stratify by emissions scenario when estimating climatic design variables
- Useful to separate epistemic (*scenario and climate model; global*) and aleatoric (*internal climate variability; regional*) uncertainties
- More future proof (CMIP6 is complete and CMIP7 is underway)
- Which global warming level (GWL) at what time horizon?



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Table 2.1: The year at which the indicated global mean warming ΔT relative to 1986-2016 reference period is irrevocably exceeded by the CMIP5 (single ensemble member per model) multi-model mean for RCP8.5, RCP6.0, RCP4.5, and RCP2.6 emissions scenarios. Model results are obtained from the KNMI Climate Explorer. Years are rounded to nearest year. A dash (“—”) indicates that a sustained level warming at the level specified by the corresponding ΔT does not occur before 2100 for the emissions scenario indicated. Results from different emissions scenarios are averaged together if the years when a given level of warming is reached are within 6 years of each other for the different emissions scenarios.

ΔT	RCP 8.5	RCP 6.0	RCP 4.5	RCP 2.6
+0.5°C			2023	
+1.0°C	2035		2046	—
+1.5°C	2047		2070	—
+2.0°C	2059	2087	—	—
+2.5°C	2069	—	—	—
+3.0°C	2080	—	—	—
+3.5°C	2090	—	—	—

Note that global warming in this report is referenced relative to a recent 31-year period, 1986-2016, rather than an earlier period such as 1850-1900 as used by the Intergovernmental Panel on Climate Change (IPCC), or “pre-industrial”, typically taken to be 1750, as referenced in the UN Framework Convention on Climate Change. Offsets can be used to link warming levels that are expressed relative to different base periods. **About +0.8°C of global warming has occurred between the IPCC and CRBCPI baselines.**

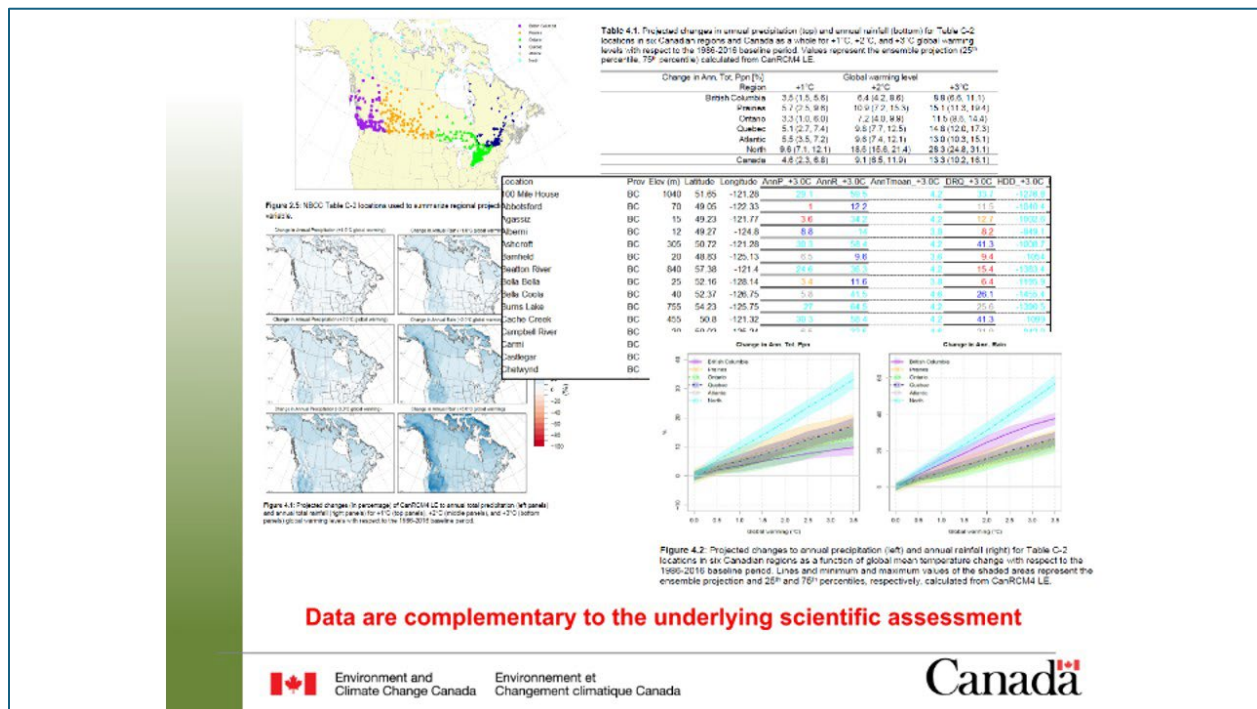
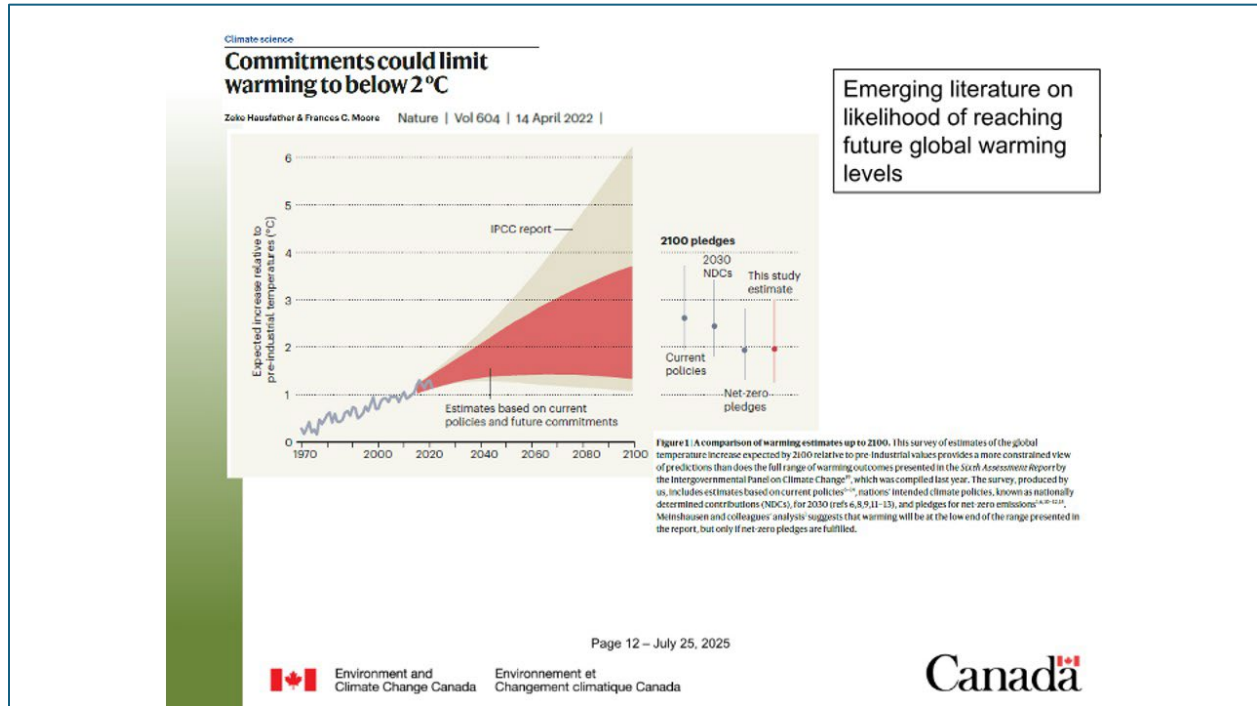
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Take Home Messages Leading up To 2025

- ☐ Canadian climate has changed, and change will continue
- ☐ Changes are evident across different variables including extremes
- ☐ Climate projections are subject to uncertainty from various sources; part of the uncertainty is irreducible
- ☐ Future changes are closely linked to the level of global warming
- ☐ Simple number-crunching is unlikely to produce reliable information, instead critical assessment of scientific understanding of physical processes and model limitations is required
- ☐ ECCC is committed to supporting Canada's infrastructure adaptation, but proper use of climate information requires close involvement of knowledge producers and users

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Looking Forward

- ☐ 2030 harmonized code cycle – follow the same basic framework but informed by new model simulations and updated understanding
- ☐ Emerging availability of CMIP6/7 GCM simulations, CORDEX CMIP6 RCM simulations, and convection-permitting model simulations for (most of) Canada
 - ☐ 25 / 12 / 4 km grid spacing (~2 to 10x increased resolution) ◇ better representation of extreme precipitation and wind extremes
 - ☐ Canadian RCM large ensemble w/ run-time bias adjustment
 - ☐ Multi-RCM ensemble ◇ better assessment of uncertainty
 - ☐ Process/model understanding still holds the key towards more robust projections of rainfall, freezing rain, wind pressures, and snow
- ☐ Observationally-constrained estimates of when global warming levels are expected to be reached under different emission scenarios; emerging literature on likelihood of future warming

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Questions? Comments

- Alex Cannon (alex.cannon@ec.gc.ca)

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B.2.1.2. Load Effects: 2025 Building Code of Canada: How and Which Load Effects Were Addressed; Hanping Hong

2025 BUILDING CODE OF CANADA: HOW AND WHICH LOAD EFFECTS WERE ADDRESSED

Hanping Hong; Western University





Calibration of the design wind load and snow load by considering the historical climate statistics and future climate effects

Hanping Hong

Department of Civil and Environmental Engineering
University of Western Ontario

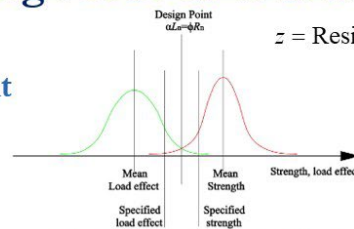
Website: https://www.eng.uwo.ca/civil/faculty/hong_h/index.html

Key points for design code calibration

NBCC objective: To limit the probability that a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to structural failure.

The algorithms and methods to evaluate the structural reliability index or failure probability are simple:
The key to a good reliability- based code calibration is:

1. Identification of limit state function
2. The selection of justifiable target reliability index
3. Selection of assignment of probabilistic models of random variables



$$z = \text{Resistance} - \text{Load effect} = R - L$$

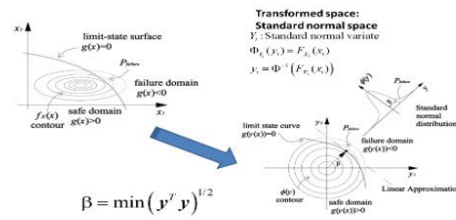
$$P_f = \Phi(-\beta)$$

Reliability index β

$$\beta = \frac{m_z}{\sigma_z} = \frac{m_R - m_L}{\sqrt{\sigma_R^2 + \sigma_L^2}}$$

Factored Design load $\leq$ Factored Design Resistance

First-order Reliability Method (FORM)



It is also known β_{RF} reliability index

$$g = R_{mem} - (L_D + L_L + L_W + L_S + L_E)$$

Limit states and target reliability index

- Limit state design format (**under-constrained problem**)

Design requirement $\phi_R R_n \geq \alpha_L L_n$ $\sum \alpha_{G_i} G_i + \alpha_{Q_j} Q_j + \sum_{j \neq k} \alpha_{C_{jk}} Q_k$

Target reliability index **CSA S-408** (Correlation aspect in converting target for different duration)

$P_{f50} \neq 1 - (1 - P_{fA})^{50}$ Because time-invariant resistance and loads and time-varying loads

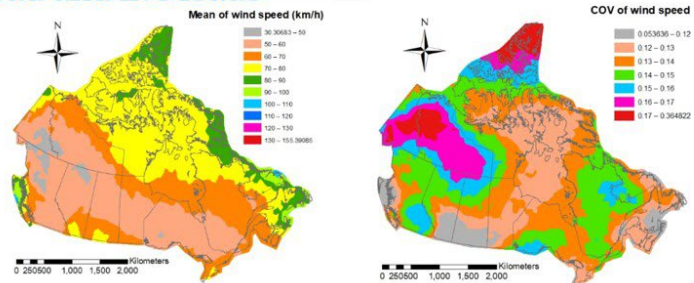
Category	Safety Class					
	Gradual			Sudden		
	1 yr	30 yr	50 yr	1 yr	30 yr	50 yr
Not serious	3.53, 2.08E-4	2.50, 6.21E-3	2.31, 1.03E-2	3.92, 4.50E-5	3.00, 1.35E-3	2.84, 2.25E-3
Serious (normal building)	4.32, 7.76E-6	3.50, 2.33E-4	3.36, 3.88E-4	4.74, 1.06E-6	4.00, 3.17E-5	3.88, 5.28E-5
Very serious	4.74, 1.06E-6	4.00, 3.17E-5	3.88, 5.28E-5	5.18, 1.13E-7	4.50, 3.40E-6	4.39, 5.66E-6

Load models: wind, snow dead and live loads

Historical climate

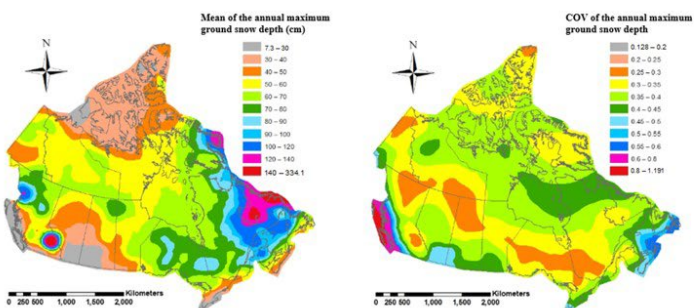
Annual maximum wind statistics

Historical climate data from ECCC for many years and for many stations are used. Annual maximum wind speed is modeled as a Gumbel distributed random variable.



Annual maximum snow depth

Gumbel distribution is used for Canadian code making, although results indicate that the lognormal distribution is preferred for majority of locations



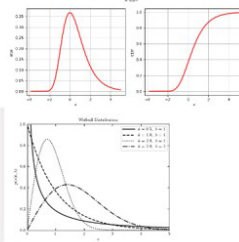
$$F_{SA}(s_A) = p_0 + (1 - p_0)F_S(s_A)$$

Hong, H. P., Tang, Q., Yang, S. C., Cui, X. Z., Cannon, A. J., Lounis, Z., & Irwin, P. (2021). Calibration of the design wind load and snow load considering the historical climate statistics and climate change effects. *Structural Safety*, 93, 102135.

Statistics and distribution models

Statistics considered for the calibration (N, LN, G, and W denote the normal, lognormal, Gumbel, and Weibull distributions).

Parameter	Mean	COV	Dist. type	Note
Normalized resistance, X_R	1.17	0.108	LN	This is typical for structural steel.
Normalized dead load, X_D	1.05	0.1	N	
Transformation factor for wind load, Z_W	0.68	0.22	LN	
Annual maximum wind speed, V_{AH}		0.05 to 0.2	G	The statistics are spatially varying with a typical COV of 0.138 for synoptic winds. The considered COV range is based on Hong et al. (2014).
“Point-in-time” wind speed (pulse of 3 hours)			W	The parameters of the distribution are to be calculated based on the annual maximum distribution (Jordaan 2005).
Transformation factor for live load, Z_L	1.0	0.206	N	
50-year extreme live load, X_L	0.9	0.170	G	
“Point-in-time” live load represented by the pulse of a duration of 6 month	0.273	0.674	W	
Transformation factor for snow load, Z_S	0.6	0.42	LN	
Annual maximum snow depth, X_S		0.2 to 0.8	G	It is considered that the bias (i.e., mean of 50 years to 50-yr return period) equals 1.1. for the COV range Hong and Ye (2014b)
“Point-in-time” snow load represented by the pulses of a duration of 14 days within 3 months (i.e., about 6 pulses).			W	The parameters of the distribution can be calculated based on the annual maximum distribution (Jordaan 2005).
Snowpack bulk density normalized with respect to its mean value	1.0	0.17	N	



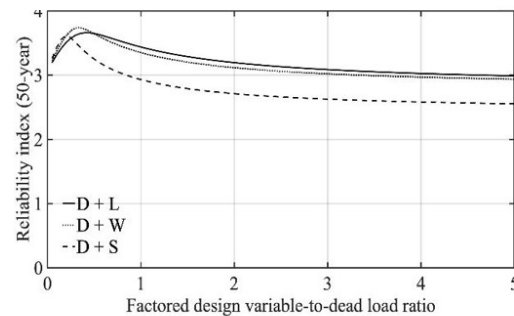
Load combinations (the 2015 edition of NBCC)

Table 1. Load combinations for ultimate limit state involving the wind load and snow load according to the 2015 edition of NBCC (D_n , L_n , W_n , and S_n are the nominal dead, live wind and snow loads).

Load combination according to NBCC	Load combination	
	Principal Loads	Companion loads
2	$1.25D_n + 1.5L_n$	$1.0S_n$ or $0.4W_n$
3	$1.25D_n + 1.5S_n$	$1.0L_n$ or $0.4W_n$
4	$1.25D_n + 1.4W_n$	$0.5L_n$ or $0.5S_n$

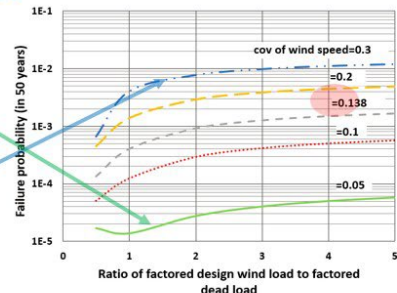
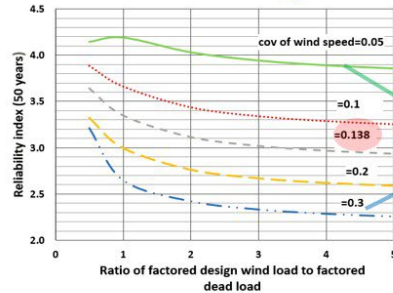
For structural steel and typical COV values of L, W, and S.

For example, for COV of annual maximum wind speed of 0.138

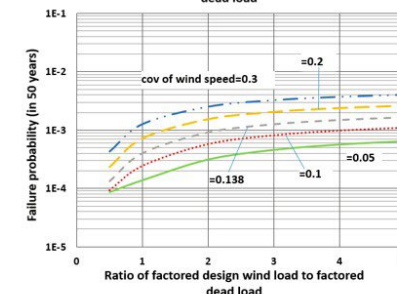
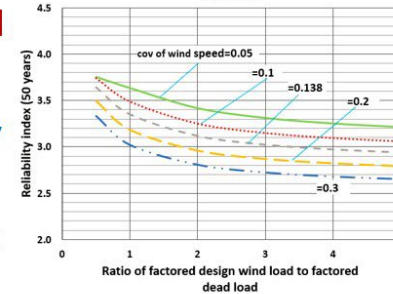


Moving from: using a load factor of **1.4** and **50-year** return period value
to using a load factor of **1.0** and **500-year** return period value for wind load.

[1.5, 50]



[1.0, 500]



Achieved enhanced
reliability consistency

Hong, H. P., Ye, W., & Li, S. H. (2016). Sample size effect on the reliability and calibration of design wind load. Structure and Infrastructure Engineering, 12(6), 752-764.

Suggested changes to wind load for NBCC

Suggested factors and v_{AH-T} for evaluating the wind velocity pressure (note that $I_W = 0.8, 1.0, 1.15$, and 1.25 for V_{AH-500} is the same as in the current NBCC).

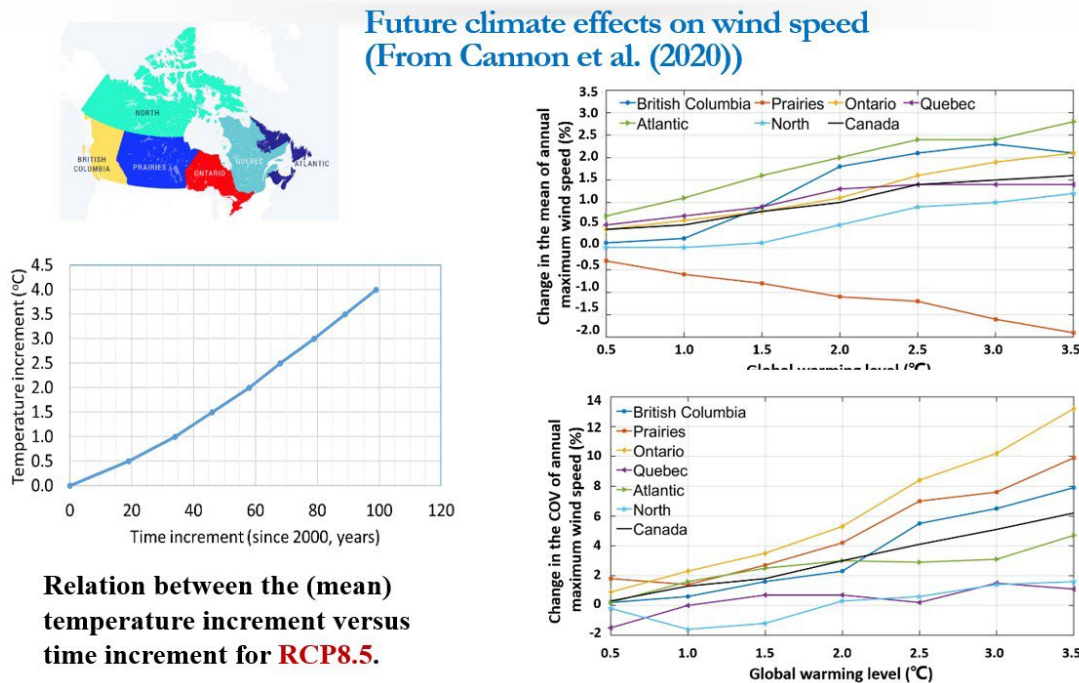
	Low importance category	Normal importance category	High importance category	Post-disaster importance category
Ultimate	$(v_{AH-500}$ and $I_W = 0.8)$ or $(v_{AH-100}$ and $I_W = 1.0)$	$(v_{AH-500}$ and $I_W = 1.0)$	$(v_{AH-500}$ and $I_W = 1.15)$ or $(v_{AH-1500}$ and $I_W = 1.0)$	$(v_{AH-500}$ and $I_W = 1.25)$ or $(v_{AH-3000}$ and $I_W = 1.0)$
Serviceability	v_{AH-10}			
Load combination with dead, live and wind loads	For principal load: Design wind load = $I_W \times$ Specified wind load; For wind acted as companion load: $\alpha_{CW} \times I_W \times$ Specified wind load, where $\alpha_{CW} = 0.3$			

Suggested changes (snow load) for NBCC

Suggested factors and s_{A-T} for evaluating the ground snow pressure (note that $I_W = 0.8, 1.0, 1.15$, and 1.25 for V_{AH-500} is the same as in the current NBCC).

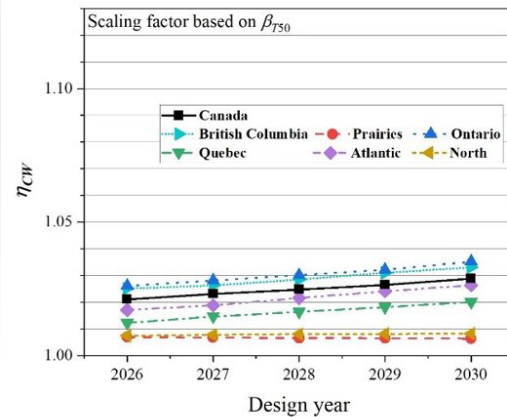
	Low importance category	Normal importance category	High importance category	Post-disaster importance category
Ultimate	$(s_{A-1225} \text{ and } I_S = 0.8)$ or $(s_{A-200} \text{ and } I_S = 1.0)$	$(s_{A-1225} \text{ and } I_S = 1.0)$	$(s_{A-1225} \text{ and } I_S = 1.15)$ or $(s_{A-5000} \text{ and } I_S = 1.0)$	$(s_{A-1225} \text{ and } I_S = 1.25)$ or $(s_{A-12000} \text{ and } I_S = 1.0)$
Serviceability	Using the snow load corresponding to s_{A-10} and a load factor of 1.2; or use the load corresponds to s_{A-30}			
Load combination with dead, Live and snow loads	For principal load: Design snow load = $I_S \times \text{Specified snow load}$; For snow acted as companion load: $\alpha_{CS} \times I_S \times \text{Specified snow load}$, where $\alpha_{CS} = 0.3$ (is consistent with 2010 edition NBCC, or alternatively use 0.5 consistent with 2015 edition of NBCC). The companion load factor for live load + snow loads, $\alpha_{CL} = 0.5$.			

$T = 1225 \text{ years (i.e., 4\% in 50 years); } P_{AE} = 0.816 \times 10^{-3};$

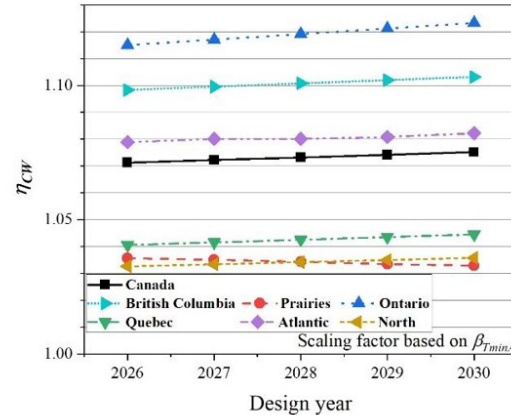


Evaluation of scaling factor for wind load by considering future climate effects $1.25D_n + \eta_{cw} W_D$ (Calibrate η_{cw} for future climate condition)

Target reliability Index for 50-year service life β_{T50} :
The calibration ensured that the calculated 50-year reliability index, incorporating future climate effects, is equal to β_{T50} on average.



Target annual reliability index β_{TminA} :
The calibration ensured that the minimum of the calculated annual reliability index for each of the 50 years of service life, incorporating future climate effects, is equal to β_{TminA} on average.



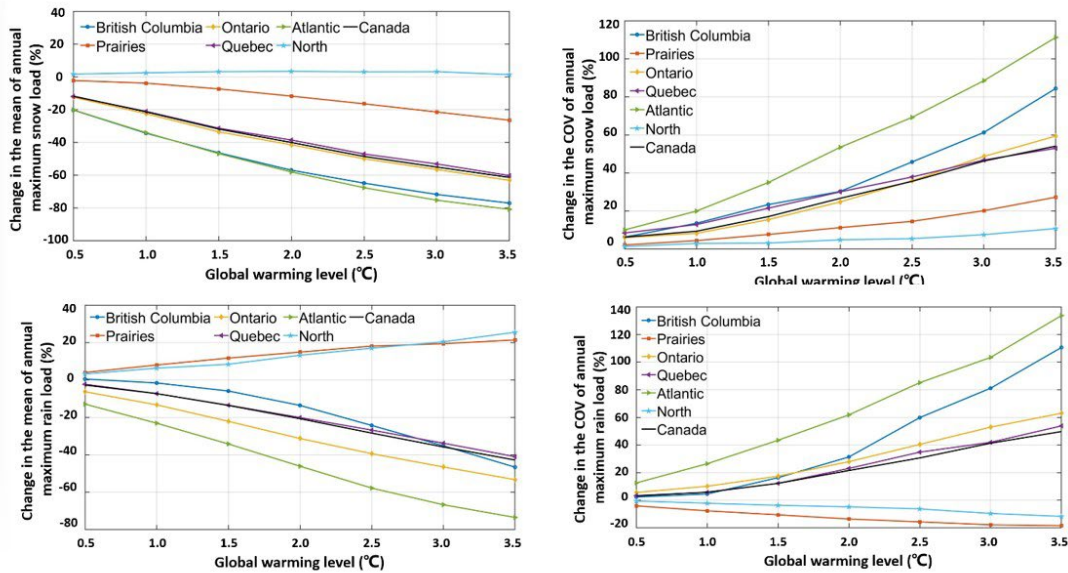
Suggested changes to wind load for NBCC

Limit State	Principal load	Factored load combination
Ultimate	Dead + Live	Preferred: $1.25D_n + 1.5L_n + (0.3\eta_{cw}W_n \text{ or } 0.3\eta_{cs}S_n)$, Alternative: $1.25D_n + 1.5L_n + (0.3\eta_{cw}W_n \text{ or } 0.5\eta_{cs}S_n)$,
	Dead + Wind	$1.25D_n + \eta_{cw}W_n + 0.5L_n$
	Option 1: Using the same return period for nominal wind load or nominal snow load, and the importance factors as those given in 2015 edition NBCC W_n is to be specified based on a return period of 500 years. Using (climate change scaling factor) η_{cw} value of 1.07 as a conservative measure to take into account the climate change effect	
Serviceability	Using 10-year return period value of wind load for serviceability checking.	

Although the use of a scaling factor of 1.07 for future climate is suggested, code writers may prefer 1.05 or 1.10.

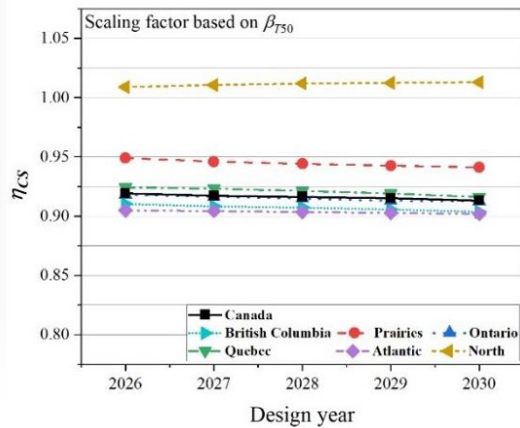
Note that: $T = 475$ years (i.e., 10% in 50 years); $P_{AE} = 2.1 \times 10^{-3}$

Future climate effect on snow load (From Cannon et al. (2020))

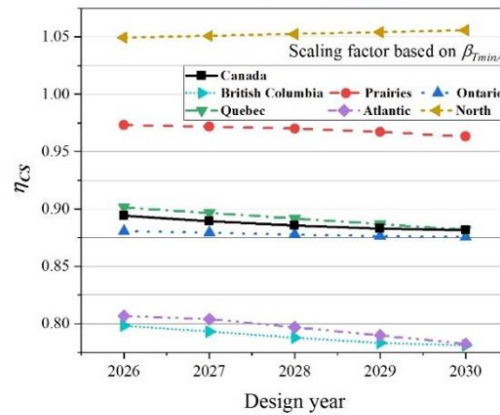


Evaluation of scaling factor for snow load considering future climate effects

Target reliability Index for 50-year service life β_{T50} :
The calibration ensured that the calculated 50-year reliability index, incorporating future climate effects, is equal to β_{T50} on average.



Target annual reliability index β_{TminA} :
The calibration ensured that the minimum of the calculated annual reliability index for each of the 50 years of service life, incorporating future climate effects, is equal to β_{TminA} on average.



Suggested changes to snow load for NBCC

Limit State	Principal load	Factored load combination
Ultimate	Dead + Live	Preferred: $1.25D_n + 1.5L_n + (0.3\eta_{cw}W_n \text{ or } 0.3\eta_{cs}S_n)$, Alternative: $1.25D_n + 1.5L_n + (0.3\eta_{cw}W_n \text{ or } 0.5\eta_{cs}S_n)$,
	Dead + Snow	$1.25D_n + \eta_{cs}S_n + 0.5L_n$
Option 1: Using the same return period for nominal wind load or nominal snow load, and the importance factors as those given in 2015 edition NBCC S_n is to be specified based on a return period of 1225 years for snow depth. I_W and I_S of 0.8, 1.15, and 1.25 are to be used for buildings classified as the low, high, and post-disaster importance categories, respectively. η_{cs} equal to 1.0 except for North $\eta_{cs} = 1.05$, as a conservative measure to take into account the climate change effect		
Serviceability	Using 10-year return period value of snow load and a factor 1.2 for serviceability checking (or 30-year return period value of snow load and a factor 1.0 for serviceability checking, which is preferred).	

- A much more uniform risk of failure is achieved by setting load factors to 1.0 and providing reference values at ultimate levels directly, such as 1/500 for wind and 1/1225 snow.
- We retain the importance factors to facilitate the use of the code.

Conclusions

Suggested changes to wind and snow loads for NBCC.

The tornado wind hazard should be further investigated and considered.

Limit State	Principal load	Factored load combination
Ultimate	Dead + Live	Preferred: $1.25D_n + 1.5L_n + (0.3\eta_{cw}W_n \text{ or } 0.3\eta_{cs}S_n)$, Alternative: $1.25D_n + 1.5L_n + (0.3\eta_{cw}W_n \text{ or } 0.5\eta_{cs}S_n)$,
	Dead + Wind	$1.25D_n + \eta_{cw}W_n + 0.5L_n$
	Dead + Snow	$1.25D_n + \eta_{cs}S_n + 0.5L_n$
	Preferred W_n is to be specified based on a return period of 500 years. S_n is to be specified based on a return period of 1225 years; I_W and I_S of 0.8, 1.15, and 1.25 are to be used for buildings classified as the low, high, and post-disaster importance categories, respectively. Using a single η_{cw} value of 1.07 otherwise using the values shown in Figure 2.29; and η_{cs} equal to 1.0 except for North $\eta_{cs} = 1.05$. Alternatively to use the importance factors (i.e., use $I_W = 1$ and $I_S = 1$), • W_n calculated for the return period $T = 100, 1500$, and 3000 years may be considered for the buildings classified as the low, normal, high, and post-disaster importance categories, respectively; • S_n calculated for the return period $T = 200, 5000$, and 12000 years may be considered for the buildings classified as the low, normal, high, and post-disaster importance categories, respectively.	
Serviceability	Using 10-year return period value of wind load for serviceability checking.	
	Using 10-year return period value of snow load and a factor 1.2 for serviceability checking (or 30-year return period value of snow load and a factor 1.0 for serviceability checking).	

Acknowledgments

Most of the results presented are those co-authored with former, current graduate students and collaborators, including Cannon, A. J., Cui, X. Z., Irwin, P., Jarrett, P. , Lounis, Z., Tang, Q., & Yang, S. C.

We gratefully acknowledge the financial support received from NRC/RWDI & ECCC.

Thank you!

B.2.1.3. Load Effects: Analysis of Climatic Loads – ASCE Special Publication 2024; Therese McAllister

ANALYSIS OF CLIMATIC LOADS – ASCE SPECIAL PUBLICATION 2024

Terri McAllister; NIST



SEI/ASCE SPECIAL PROJECT REPORT (ASCE 2024)

Therese McAllister, PhD, PE, F.SEI, Dist.M.ASCE
National Institute of Standards and Technology

Bruce R. Ellingwood, PhD, PE, NAE, F.SEI, Dist.M.ASCE
Department of Civil and Environmental Engineering, Colorado State University

ASCE-NIST Forward Looking Codes and Standards Workshop #2:
Future Load Effects on the Built Environment
July 29-30, 2025



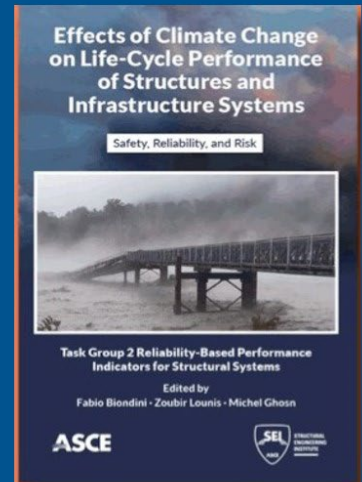
EFFECT OF CLIMATE CHANGE ON LIFE-CYCLE PERFORMANCE, SAFETY, RELIABILITY AND RISK OF STRUCTURES AND INFRASTRUCTURE SYSTEMS

- *Edited by:* Fabio Biondini, Zoubir Lounis, Michel Ghosn
- **WG2: IMPACT OF CLIMATE CHANGE ON INFRASTRUCTURE PERFORMANCE**
- Bruce R. Ellingwood, *Colorado State University, Fort Collins, CO, USA*
- Paolo Bocchini, *Lehigh University, Bethlehem, PA, USA*
- Aly Mousaad Aly, *Louisiana State University, Baton Rouge, LA, USA*
- Mitsuyoshi Akiyama, *Waseda University, Tokyo, Japan*
- Michele Barbato, *University of California Davis, Davis, CA, USA*
- Luca Capacci, *Politecnico di Milano, Milan, Italy*
- Sofia Diniz, *University of Minas Gerais, Belo Horizonte, Brazil*
- Hanping Hong, *Western University, London, Ontario, Canada*
- Yue Li, *Case Western Reserve University, Cleveland, OH, USA*
- Ning Lin, *Princeton University, Princeton, NJ, USA*
- Therese McAllister, *National Institute of Standards and Technology, Gaithersburg, MD, USA*
- Georgios Tsampras, *University of California San Diego, San Diego, CA, USA*
- George Tsiatas, *University of Rhode Island, Kingston, RI, USA*
- Farshid Vahedifard, *Tufts University, Medford, MA, USA*
- John W. van de Lindt, *Colorado State University, Fort Collins, CO, USA*



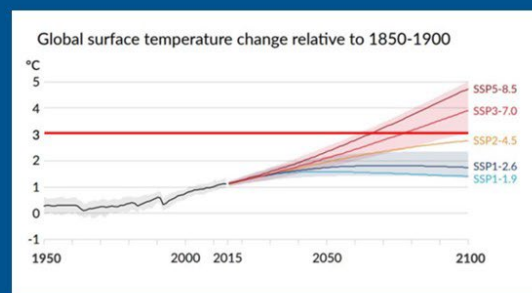
SPECIAL PROJECT OBJECTIVES

- Identify probabilistic characteristics of hazards that are susceptible to climate effects;
- Investigate non-stationarity in climate variables and its implications on climatic loads, load combinations and structural reliability levels;
- Identify and assess the impact of changes in climate related loads on the performance of structures and resilience of communities;
- Recommend processes to implement the best climate science in structural engineering without disrupting structural professional practices



CHALLENGES TO STRUCTURAL DESIGN

- Non-stationarity in future hazard event occurrences and intensities .
- Increases in projected uncertainties, especially after 2060.
- Specification of design-basis events (without return periods):
 - Uniform hazard vs uniform reliability
 - Cumulative probability of exceedance
 - Scenarios – semi-probabilistic
- Selection of service periods and target reliabilities
- Demonstrating compliance with performance objectives and reliability targets (ASCE 7-22)



STRUCTURAL LOADS IMPACTED BY FUTURE HAZARDS

- Temperature effects
- Riverine and coastal floods
- Wind pressures
- Snow loads on roofs
- Ice accretion on towers and conductors
- Rain load on roofs
- Load combinations and structural reliability



TEMPERATURE EFFECTS

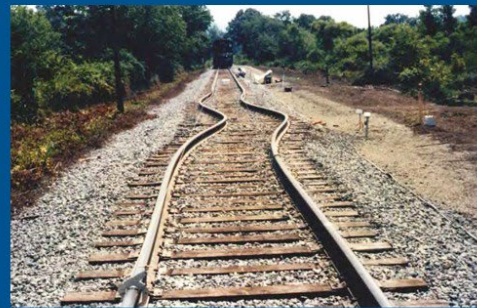
- Temperature effects in steel and concrete tall buildings and long-span bridges can result in significant thermal strain, ϵ_{th} , in restrained members.
- If a system is fully restrained, the axial force (P_{th}) developed in a member with axial rigidity (EA) may approach that of the dead and live loads

$$\epsilon_{th} = \alpha \Delta T$$

- α = coefficient of thermal expansion
- ΔT = increment in temperature

$$P_{th} = EA (\alpha \Delta T)$$

- The thermal effects in a statically indeterminate structural system depend foremost on the stiffness properties (e.g., EA or flexural rigidity EI)



Buckled railway tracks due to thermal expansion on an exceptionally hot day.
Source: US DOT



RIVERINE FLOOD LOAD EFFECTS

- Future riverine flood loads, p , include increased discharge (flow) rates that affect hydrostatic and hydrodynamic loads and foundation scour.
- The effects of riverine floods on structures are related to: (1) flood depth, z , (2) flood velocity, U , (3) structural exposure, and (4) type and depth of their foundations.

$$p = \rho g z + 0.5 \alpha \rho U^2$$

- Two approaches:
 - (1) perform a study of historical changes of river flow and floods and statistically project future floods
 - (2) model changes in primary climate parameters (e.g., temperature and precipitation) to project their influence

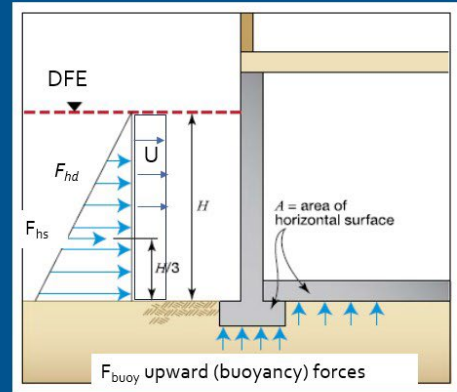


Figure 3-4: Free-body diagram of a submerged simple structures (Source: FEMA 2001)



COASTAL SLR FLOOD LOAD EFFECTS

- 2022 Global and Regional SLR Scenarios for the US, NOAA (multi agency report)
- SLR models are based on physics and empirical studies.
- Global uncertainties are increased with local estimates. Sources include the thermal expansion of oceans and currents, glaciers, ice sheets, and landmass rebound.
- Effects of Tide, Storm Surge, and Tsunami with SLR
 - Local analyses of tides with MSL variability due to SLR
 - Storm surge models (ADCIRC, SWAN, SLOSH); storm surge intensities are more sensitive to SLR in near-shore regions
 - Rigorous tsunami propagation simulations are required because SLR will decrease the effects of local bathymetry and modify the roughness coefficient, two important tsunami factors.

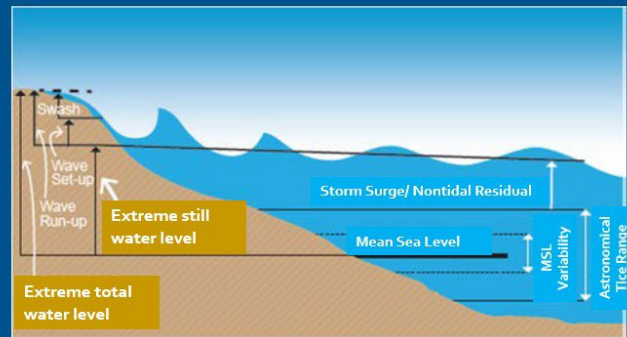


Figure 3-8: Components of the extreme total water and extreme still water measurements.



STRUCTURAL
ENGINEERING
INSTITUTE

WIND LOAD EFFECTS

Wind pressure: $W = C_W V^2$

- V = wind speed measured at 10 m elevation in open terrain (climate-dependent)
- $C_W = K_z K_d G C_p$ = exposure, directionality and aerodynamic coefficients (climate-independent)

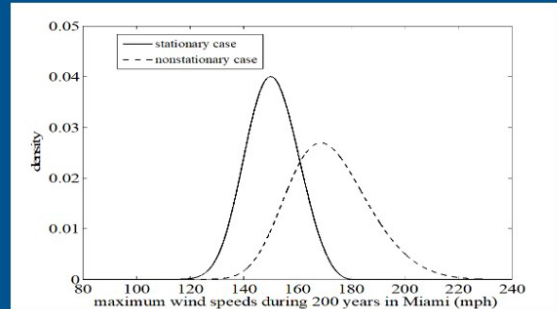
Hurricane simulations: By 2060, the design wind speeds are expected to increase on average between 14% and 26%, with a corresponding increase in design loads between 30% and 59%.

Convective wind and tornado studies: Inconclusive studies or lack of consensus

Methods for structures:

Low-regret, adaptive strategies -- Observational Method
Provide design guidance and standards

$$W_{\text{non-sta}}/W_{\text{sta}} = (168/150)^2 = 1.25$$



Lee, J.Y. & Ellingwood, B.R. (2017). *Rel. Engrg. & System Safety* 159:100-107



SNOW LOAD EFFECTS

- Important in regions experiencing long winter seasons and heavy snowfalls.
- A roof snow load (p_r) depends on ground snow (p_g) and rain-on-snow accumulation as well as melting, evaporation, and wind-induced snowdrift.
- Extreme snow statistics are site dependent; therefore, regional GEV distributions were used to develop ground snow maps in ASCE 7-22.
- Future snow loads vary by region: some regions will stay the same or decrease, and others will increase.

$$p_r = 0.7 C_s C_e C_t p_g$$



Source: Engineering Express



ATMOSPHERIC ICE LOAD EFFECTS

- Ice accretion is a hazard for transportation, aviation, structures, and infrastructure systems.
- Types of atmospheric ice:
 - Glaze ice – freezing rain – *considered for structures*
 - Rime ice – in-cloud icing
- Ice increases the structural gravity load, changes the dynamic characteristics, alters the aerodynamics, and affects structural response.
- Wind-on-ice loads are addressed in standards.
- Climate studies projected increases for Canadian prairies and northern regions and decreases elsewhere.

Extreme ice loads can collapse tower line systems and lattice structures.

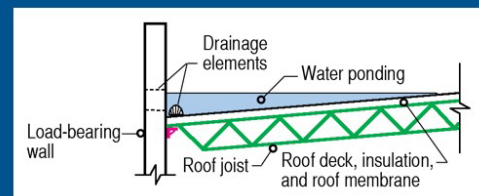


<https://www.inmr.com/impact-mitigation-icing-power-network-equipment/>



RAIN LOAD EFFECTS

- Rain loads are an important consideration for designing large flat roof structures.
- Without proper drainage, water accumulates on the roof and causes increasing deflections – or “ponding” – which can lead to a sudden failure of the roof structure.
- Current rain loads are based on:
 - 60-min duration/100-year return period rainfall event for the design of the primary drainage system
 - 15-min duration/100-year return period rainfall event for the secondary drainage system (assuming no primary drainage)
- Future rainfall intensity, duration, and frequency (IDF) will change but the fundamental design process is not expected to change.



<https://iibec.org/asce-7-standard-low-slope-roof/>



ASCE 7-22 HAZARDS AND RELIABILITY

Uniform Risk for Target Reliability

- Dead and Live (1982)
- Wind (updated 2016)
- Snow (updated 2022)
- Tornado (new 2022)
- Flood, Supplement #2 (2022)

Conditional Reliability

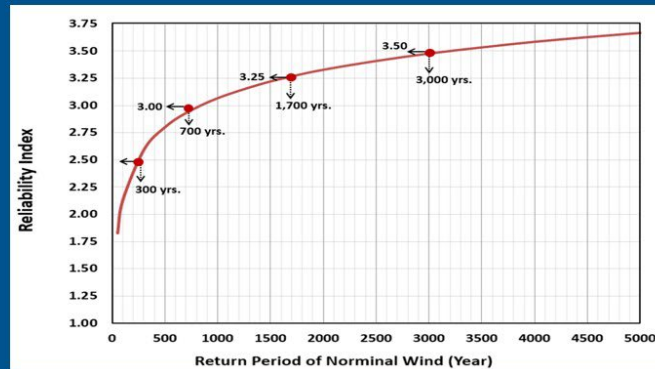
- Seismic (MCE_R) – (updated 2010)
- Extraordinary Events – fire, blast (updated 2010)
- Tsunami (new 2016)

Uniform Hazard

- Flood, Ch 5 (2022)
- Ice (500 yr MRI) - (updated 2016)

Other Basis

- Rain – 15-min and 60-min duration events



Wind MRI vs Reliability Index
(McAllister, Wang, and Ellingwood 2018)



LOAD COMBINATIONS

- With the exception of permanent (dead) loads, most loads vary stochastically in time.
- If the loads are ~statistically independent, the maximum **combined loads** during the reference service period (50 years in ASCE 7-22) occur when:
 - One load reaches its **maximum value** (*principal action*)
 - Other loads are at **arbitrary-point-in-time values** (*companion actions*).
- There is no evidence after four decades that the target reliabilities in Table 1.3-1 are inadequate.
 - Therefore, the nominal loads and strengths for future hazards will be selected for the same target reliabilities and reference service period.
- Current design values were determined assuming a constant design strength and stationary annual extreme loads.
 - The manner that design loads are specified may have to be modified to achieve these reliability targets.

ASCE 7 Table 1.3-1 Target Reliabilities

Limit state	Risk category I (storage)	Risk category II (normal)	Risk category III (assembly)	Risk category IV (hospitals)
Benign	$1.25 \times 10^{-4}/\text{yr}$ $\beta = 2.5$	$3.0 \times 10^{-5}/\text{yr}$ $\beta = 3.0$	$1.25 \times 10^{-5}/\text{yr}$ $\beta = 3.25$	$5.0 \times 10^{-6}/\text{yr}$ $\beta = 3.5$
Sudden or severe	$3.0 \times 10^{-5}/\text{yr}$ $\beta = 3.0$	$5.0 \times 10^{-6}/\text{yr}$ $\beta = 3.5$	$2.0 \times 10^{-6}/\text{yr}$ $\beta = 3.75$	$7.0 \times 10^{-7}/\text{yr}$ $\beta = 4.0$
Sudden and severe	$5.0 \times 10^{-6}/\text{yr}$ $\beta = 3.5$	$7.0 \times 10^{-7}/\text{yr}$ $\beta = 4.0$	$2.5 \times 10^{-7}/\text{yr}$ $\beta = 4.25$	$1.0 \times 10^{-7}/\text{yr}$ $\beta = 4.5$



PROBABILITY-BASED LIMIT STATES DESIGN (LRFD FOR ASCE 7-22)

Required strength (U_d) < Design strength (R_d)

$$U_d = \sum \gamma_i Q_{ni} \leq \phi R_n = R_d$$

Required strength, U_d	Principal Load	Companion Loads
2a $1.2 D + 1.6 L + (0.5 L_r \text{ or } 0.3 S \text{ or } 0.5 R)$	L	D, L_r, S, R
3a $D + (1.6 L_r \text{ or } 1.0 S \text{ or } 1.6 R) + (L + 0.5 W)$	L_r, S, R	D, L, W
4a $1.2 D + (1.0 W \text{ or } W_T) + L + (0.5 L_r \text{ or } 0.3 S \text{ or } 0.5 R)$	$W \text{ or } W_T$	D, L, L_r, S, R
4b $1.2 D + 0.5 W + 1.0 F_a + L + (0.5 L_r \text{ or } 0.3 S \text{ or } 0.5 R)$	F_a	D, W, L, L_r, S, R

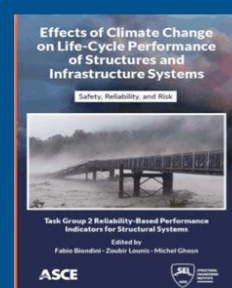
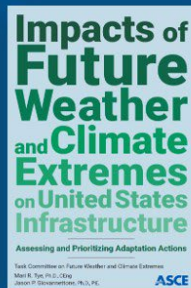
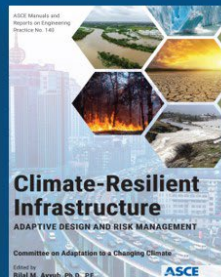
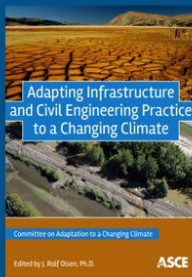
Design strength, R_d (AISC, ACI, etc)

$$R_d = 0.9 R_n \text{ (flexure)}$$



Resource documents

- Concurrent efforts in ASCE and NRC-Canada
- Chapter 3 in the SEI Special Project Report focuses on design codes and standards for buildings and other structures and infrastructure systems.



THANK YOU



**B.2.1.4. Load Effects: Load Effects Under Consideration by ASCE 7-28 Chapter 36:
Methodology, Assumptions, and Decisions; Panel Moderated by Abbie Liel**

LOAD EFFECTS UNDER CONSIDERATION BY ASCE 7-28 CH 36



LOAD EFFECTS UNDER CONSIDERATION BY ASCE 7-28 CHAPTER 36: METHODOLOGY, ASSUMPTIONS, AND DECISIONS

ASCE 7-28 Future Condition Subcommittee



AGENDA

Overview: Abbie Liel; University of Colorado

- Matt Gilbertson; SGH – Flood
- Sihan Li; RWDI – Wind
- Abbie Liel; University of Colorado – Snow
- Ken Kunkel; NOAA/NCSU – Rain
- Ahmed Abdelaal; SUNY Polytechnic Institute – Ice



LOAD EFFECTS UNDER CONSIDERATION BY ASCE 7-28 CHAPTER 36

WORK IN PROGRESS!

- Preliminary decisions
 - 3 deg C Global Warming Level
 - Consistency with ASCE 7 reliability and “base load” chapters
 - Selection of load effects that are changing in significant ways + for which we have confidence in their trends
- Key considerations
 - What has been done by other (e.g., Canada)
 - What climate projections are available + which are fit for purpose for each load effect
 - Variation in how loads in ASCE 7 have been developed
- Major activity has been translation and interpretation of the climate projections for engineering application

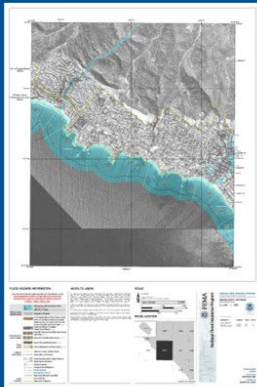


MATT GILBERTSON; SGH – FLOOD



WHAT'S CURRENTLY IN ASCE 7 FOR FLOOD LOADS?

Basis of Flood Hazard Information: (generally) FEMA Maps and Studies



MRI-based Flood Elevations based on Risk Category

Risk Category	MRI
I	100-yr
II	500-yr
III	750-yr
IV	1,000-yr

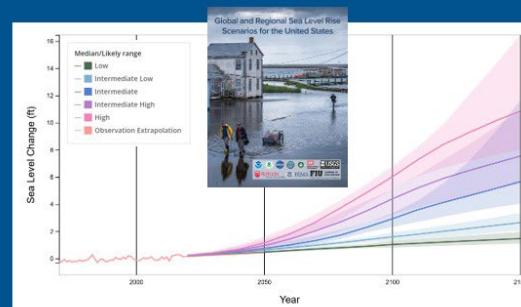
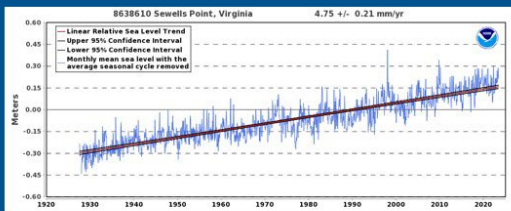
Several Categories of Flood Loads (all generally derived from the Flood Elevation)

- Hydrostatic
- Hydrodynamic
- Debris Impact
- Waves (coastal only)



WHAT'S PROPOSED FOR CHAPTER 36?

Replace historic sea level change (currently in ASCE 7) with future projections:



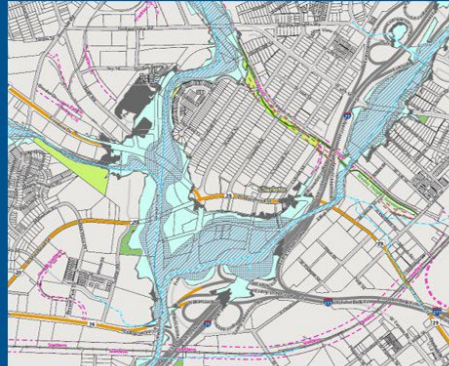
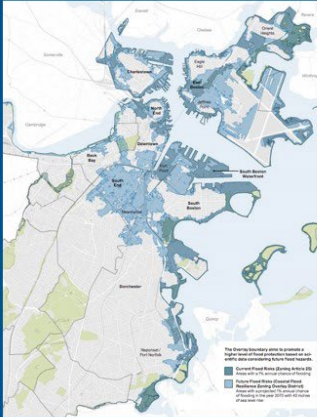
Flood elevation increases → Flood loads increase

Important note: ASCE 7 is a loads standard; it does not (directly) dictate building elevations, siting, floodproofing, or other mitigation requirements.



WHAT'S PROPOSED FOR CHAPTER 36?

Provisions to incorporate locally adopted enhanced flood regulations or future conditions flood maps:

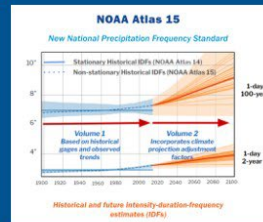


WHAT'S PROPOSED FOR THE COMMENTARY (AND POTENTIALLY FOR FUTURE CYCLES)?

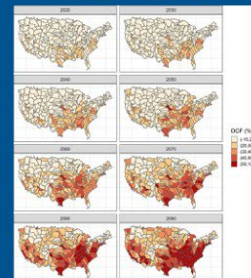
Potential sources for future flood hazard data



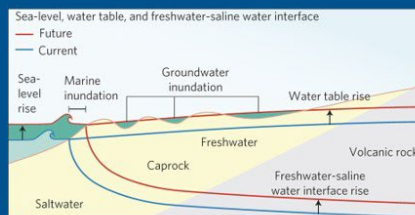
Consideration for future precipitation for site-specific studies



Methods for estimating future flooding in non-coastal areas



Groundwater rise



SIHAN LI; RWDI – WIND



HAZARD DATA SOURCES

- The current ASCE 7 basic wind speed maps incorporate separate analyses of three different storm types: tropical cyclones (e.g., hurricanes), synoptic winds, and thunderstorms (tornadoes are treated separately in Chapter 32).
- Non-hurricane wind speeds
 - Current: Based on extreme value analysis of observed peak gust data from anemometer stations across the U.S, which is quality controlled and standardized to equivalent 3-s peak gust values at 10 m height over flat, open terrain.
 - Future: Drawn from the North American component of the Coordinated Regional Downscaling Experiment (NACORDEX) and Environment and Climate Change Canada (ECCC).
- Hurricane wind speeds
 - Current: Developed using a Monte Carlo hurricane simulation model seeded with historical environmental data.
 - Future: Simulated using environmental data from the National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM), specifically, sea surface temperature, tropopause temperature, meridional winds, and zonal winds.



MODELS/METHODS FOR FUTURE DESIGN VALUES

- Future non-hurricane wind speeds
 - Provided as hourly mean wind speeds.
 - Gust factors provided in Chapter 26 were used to convert hourly mean wind speeds to 3-s gust wind speeds.
 - 3-s gust wind speeds were used to derive change factors for future basic wind speed.
- Future hurricane wind speeds
 - Developed using Monte Carlo simulation model for hurricane wind speeds in ASCE 7-22.
 - The hurricane track methodology, which uses historical hurricanes and environmental reanalysis data, reproduces their frequency and geometric characteristics as well as the variation of storm size and intensity.
 - The same simulation framework for ASCE 7-22 is used with environmental data sourced from climate model output representative of the desired future climate state.
- Future non-hurricane and hurricane wind speeds are combined using the same procedure as described in ASCE 7-22.
 - Change factors were derived as ratios of future basic wind speeds to the ASCE 7-22 basic wind speeds.
 - Future basic wind speeds are based on the target annual exceedance probability and future 3°C criteria.



ASSUMPTIONS AND DECISIONS

- For purposes of reliability analysis, a linear trend in future climate effects on peak wind speeds is assumed between now and the future state, which is a 3°C global warming scenario by 2080.



NONSTATIONARY APPROACH

- A nonstationary, extreme value approach known as Minimax has been adopted, which assures that, over an assumed 50-year reference period for reliability analyses, the annual probabilities of failure will not exceed that which has historically been considered acceptable in ASCE 7.
- A nonstationary Gumbel distribution uses samples from every simulation in the climate model outputs, including both historical and future periods.



ABBIE LIEL; UNIVERSITY OF
COLORADO – SNOW



RELIABILITY-TARGETED GROUND SNOW LOADS (G_L)

- **ASCE 7 Chapter 7: Reliability-targeted loads based on observations** $\phi R = 1.2D + 1.0(G_L * G_{r,i})$
 - G_L ~ Generalized Extreme Value (GEV) probability model with parameters μ [location], σ [scale], & ξ [shape]
- **ASCE 7 Chapter 36: Non-stationary reliability-targeted loads based on Global Climate Model**
 - Assume that the GEV parameters for G_L change with time: $\mu(t)$, $\sigma(t)$, ξ
 - Create a time series from 1950 – 2100 at a 6 km grid across CONUS from Global Climate Models
 - Using Variable infiltration capacity (VIC) model forced with outputs of precipitation and temperature from CMIP5 for two emissions scenarios downscaled to a 6km resolution [31 ensemble members]
 - For all grid cells, fit GEV parameters as a nonlinear function of time using generalized additive model
 - Calculate non-stationary reliability-targeted loads with nonlinear GEV model for hindcast and future projections
 - Determine the ratio of future (2030 – 2080) to historical (1970-2020) reliability-targeted Risk Category II loads and develop factors by EPA Level III Ecoregions
- **Challenges:** snow is a secondary variable from Global Climate Models



KEN KUNKEL; NOAA/NCSU –
RAIN



DESCRIPTION/DEVELOPMENT

- 15-minute duration, 100-yr return level (1% annual exceedance probability) at 3°C global warming level
- Climate model datasets



DESCRIPTION/DEVELOPMENT

- Three statistically-downscaled datasets
 - Seasonal Trends and Analysis of Residuals (STAR)
 - Localized Constructed Analogues, version 2 (LOCA2)
 - University of Wisconsin Probabilistic Downscaling (UWPD)
- Three dynamically-downscaled datasets
 - North American Coordinated Regional Downscaling Experiment (NA-CORDEX)
 - CONUS404
 - Northern Illinois University Convective-Permitting downscaled simulations
- One global simulation-NOAA SPEAR



METHODOLOGY

- Non-stationary Generalized Extreme Value (GEV) analysis
 - Global Warming Level is co-covariate for the location and scale parameters of the GEV distribution
- Blending of model results is in final stage



FINAL THOUGHT

- Leveraging of work on NOAA Atlas-15, Volume 2



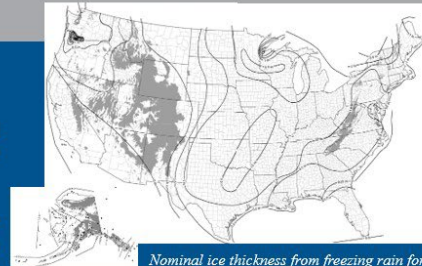
AHMED ABDELAAL; SUNY POLYTECHNIC INSTITUTE – ICE



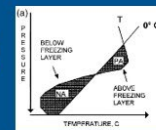
ICE LOAD

Methods

- Integrates multiple datasets to characterize atmospheric icing hazards from freezing rain, both historically and in future climate conditions.
- Future projections are based on dynamically downscaled climate simulations from the NA-CORDEX archive, driven by multiple CMIP5 Global Climate Models (GFDL, MPI, CanESM2, HadGEM2) and the CMIP6 CanESM5 model.
- Key variables include near-surface air and dew point temperatures (2 m), surface pressure, 10 m wind speed, precipitation amount and type, and vertical atmospheric temperature profiles.
- Freezing rain is diagnosed using the different precipitation-type algorithms, including the Bourguin method, which evaluates temperature profiles to classify precipitation types.



Nominal ice thickness from freezing rain for the design of Risk Category II structures from ASCE 7-22.



ICE LOAD

Assumption and Decision

- The analysis assumes that freezing rain occurs when there is precipitation and it is diagnosed as freezing rain by the precipitation-type algorithm, with surface temperatures below freezing.

Items That Could Improve the Current Approach

- **Broader Spatial Coverage:** Filling data gaps in mountainous and rural areas currently excluded from ASCE ice maps.
- **Enhanced Observations:** Upgrading surface stations and sensors to improve accuracy in ice-prone conditions.
- **Data Access:** Making processed freezing rain and ice thickness datasets publicly available to support design and standards development.
- **Uncertainty Quantification:** Enhancing precipitation-type classification in model datasets using gridded reanalysis products and observational data.



THANK YOU



PHOTO & COFFEE BREAK

15 minutes

In person attendees – PLEASE head outside for photo
Virtual attendees – PLEASE TURN CAMERAS ON for photo

PUBLIC attendees – We will restart at 11:00 am



SYNERGISTIC EFFORTS: STRUCTURAL CAPACITY AND FUNCTIONAL UNDERPERFORMANCE

11:00 am – 12:00 pm



PRESENTATIONS

- **Structural Degradation;** Brian Pailes; SGH [15 mins.];
- **Lessons Learned from Bridges and Other Exposed Infrastructure;** Ted Zoli; HNTB [15 mins.];
- **Hidden Effects of Groundwater Changes on Erosion, Saltwater Intrusion, and More;** David Frost; Georgia Tech [15 mins.];
- **Q&A Discussion;** Moderator: Jayantha Obeysekera [10 mins.]



B.2.1.5. Structural Capacity and Functional Underperformance: Structural Degradation; Brian Pailes

STRUCTURAL DEGRADATION

Brian Pailes, PhD, PE – Associate Principal – Simpson Gumpertz & Heger



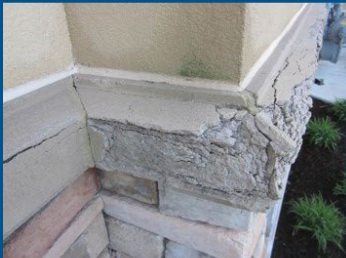
OUTLINE

- Common types and causes of structural material degradation
- Assessment of deterioration
- Material degradation's impact on structural capacity
- What information will be useful in the design to deal with material degradation
- How would a changing environment affect material degradation



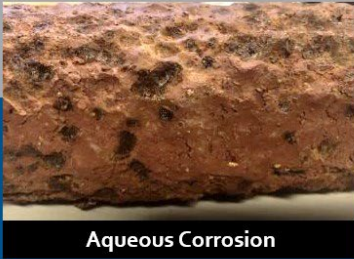
STRUCTURAL MATERIAL DEGRADATION

- Corrosion
 - The most common mechanism for the deterioration of civil infrastructure
- Other deterioration mechanisms can also affect the structural capacity
 - Alkali-silica reaction (ASR)
 - Freeze-thaw damage
 - These also lead to corrosion



STEEL DETERIORATION

SGH



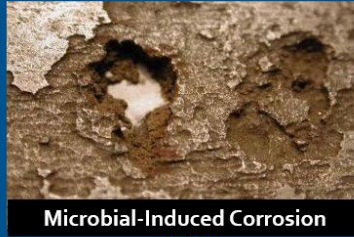
Aqueous Corrosion



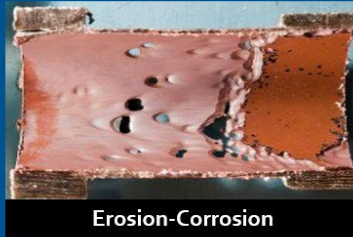
Dissimilar Metals (Galvanic)



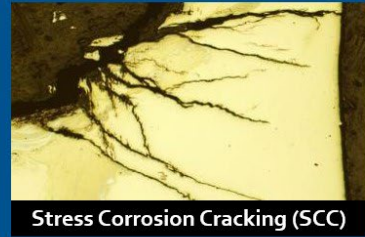
Localized Corrosion (Pitting)



Microbial-Induced Corrosion (MIC)



Erosion-Corrosion

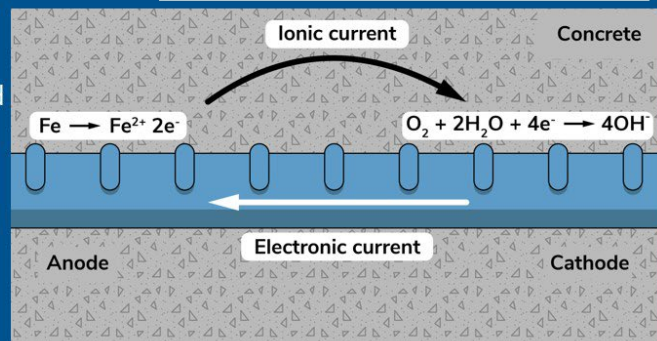
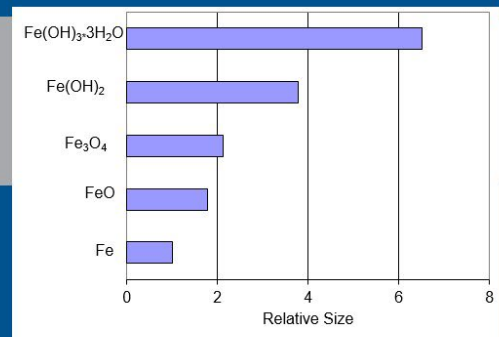


Stress Corrosion Cracking (SCC)



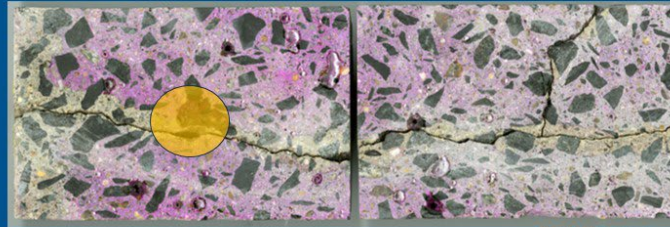
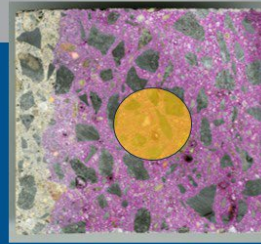
REINFORCED CONCRETE

- Metal section loss
- Formation of iron oxide (rust)
- Expansive properties of iron oxide create tensile stresses in concrete
 - Seizes joints and other movable part
- Leads to cracking, delamination, and eventual spalling



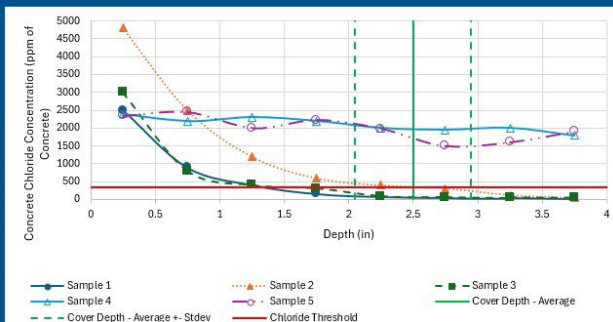
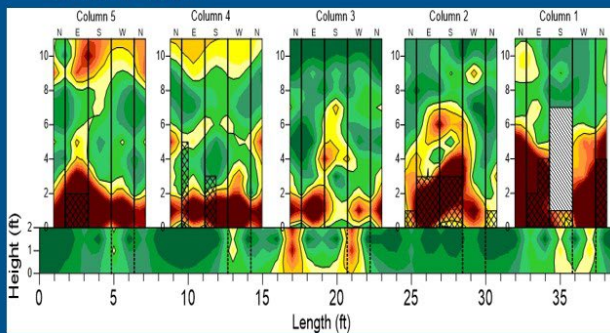
TYPICAL CAUSES OF DETERIORATION

- Exposure to environmental conditions
 - Heat, moisture, aggressive ions (sulfate, chlorides), carbon dioxide.
- Improper use of materials
 - ASR – reactive aggregate
 - Freeze-thaw – no air entrainment
- Detailing or construction impacts
 - Pooling water
 - Low cover
 - Cracking
 - Contaminated construction materials



WHERE IS DETERIORATION

- Subtle changes in cover-depth and cracking can have big impacts on durability and deterioration rates
- Leaking joints cause localized severe deterioration



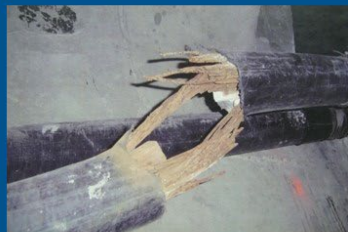
IMPACT OF STRUCTURAL CAPACITY DUE TO MATERIAL DEGRADATION

- Material deterioration affects load carrying capacity by reducing the cross-section or affecting the strength of the material
- Where the deterioration occurs is important
 - Corrosion of reinforcement in the tension zone of a beam is different than steel reinforcement in an arch that is in compression



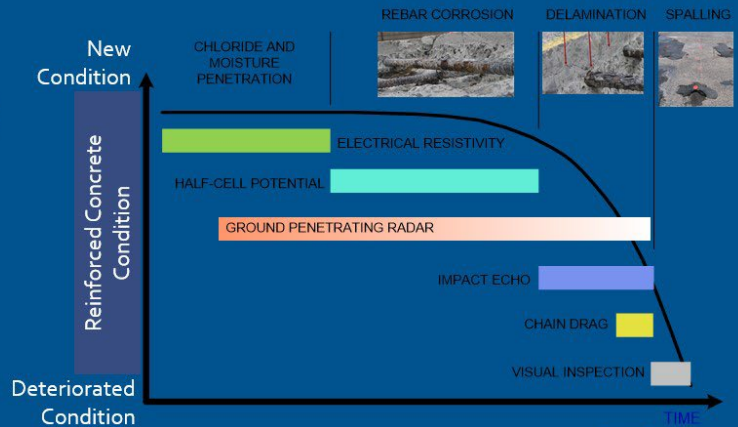
HIGH STRENGTH STEELS

- Conventional Reinforcement
 - Large cross-section
 - Low stress
 - 10-15% section loss can create spalling
- High Strength Strands
 - Small cross-section
 - High surface area ratio
 - High Stress
 - 10-15% section loss creates significantly less corrosion product
 - May not result in significant concrete damage



INSPECTION OF STRUCTURES

- Still relies heavily on visual inspection
- Limited ability to understand the current structure's capacity to carry loads
- The effects of deterioration are not always visually observable
 - Especially not early signs



Source: Pailes, B.M., Damage identification, progression, and condition rating of bridge decks using multi-modal non-destructive testing, Rutgers University, 2014



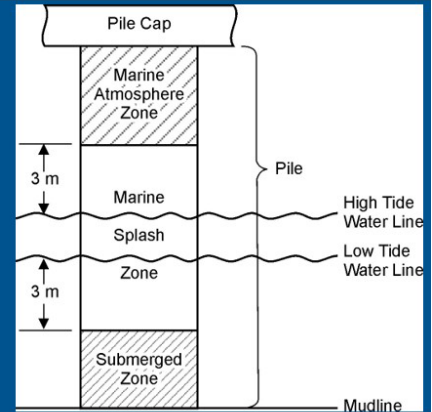
WHAT INFO DO WE NEED FOR DESIGN

- Exposure environment
 - Codes currently do a pretty good job of taking this into account on a general level
 - However, there are microclimates and local effects that need to be understood
- We need to understand the deterioration rate of our materials and account for that reduction in capacity over time
 - Our structure is getting weaker over time
 - Are the loads increasing, or at least staying the same?
 - How does this affect performance over time?
 - New materials are being used all the time. Do we have a firm understanding of their rate of deterioration?
- How and where is the deterioration affecting the structure



CHANGING ENVIRONMENT

- Sea level rise
 - Locations that were not in a marine environment are now
 - Not originally designed for that aggressive of an environment
- Seawater intrusion
 - Groundwater becoming chloride contaminated could affect the deterioration rates of structure foundations
 - Original design based on a non-corrosive environment,
- Increased temperatures
 - Increases the rate of corrosion
- Severe loading events can affect durability
 - Initial cracking due to overloading can allow for chlorides and carbonation to initiate corrosion



B.2.1.6. Structural Capacity and Functional Underperformance: Lessons Learned from Bridges and Other Exposed Infrastructure; Ted Zoli

LESSONS LEARNED FROM BRIDGES AND OTHER EXPOSED INFRASTRUCTURE

Ted Zoli; HNTB

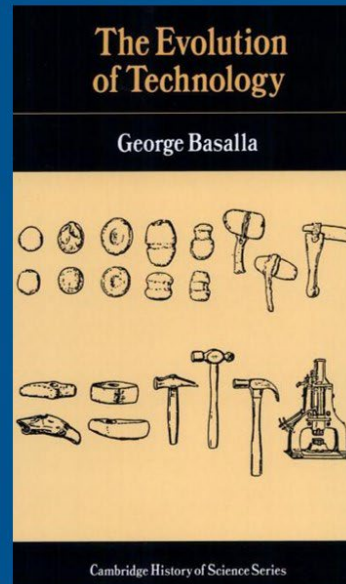


LESSONS LEARNED FROM BRIDGES & OTHER EXPOSED INFRASTRUCTURE

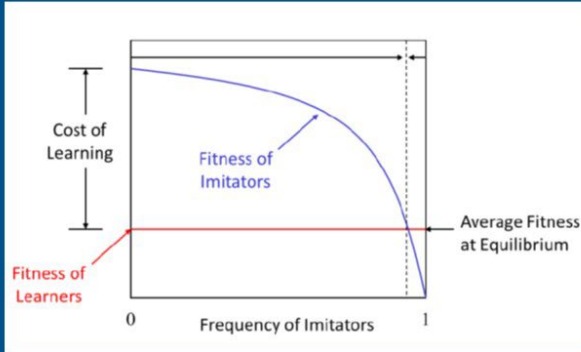


Agenda

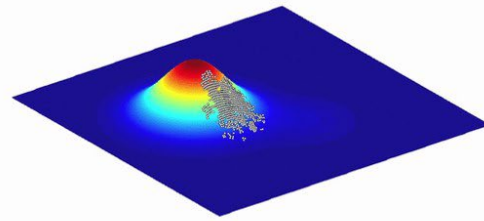
- Adaptation in the Design Process
 - Are load effects evolving effectively?
 - What are we measuring?
 - Is the regulatory environment working?
- Variation (Mutation)
 - What should we change?
 - How often?
 - Based on what?
- Selection
 - What do we copy?
 - What do we abandon?
 - What problems are unique to long service life?



ADAPTATION & ROGER'S PARADOX



Dynamic fitness landscape



Population size, $N = 2,304$
Mutation rate, $\mu = 0.5$ per trait

© Randy Olson and Bjørn Østman

Reference: Boyd, Richerson, Heinrich *Cultural Evolution of Technology: Facts & Theories*



HEAVIER TRUCKS ON HIGHER TIRE PRESSURES

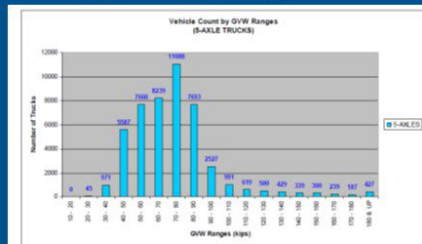
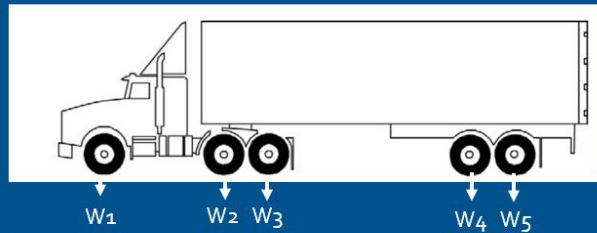
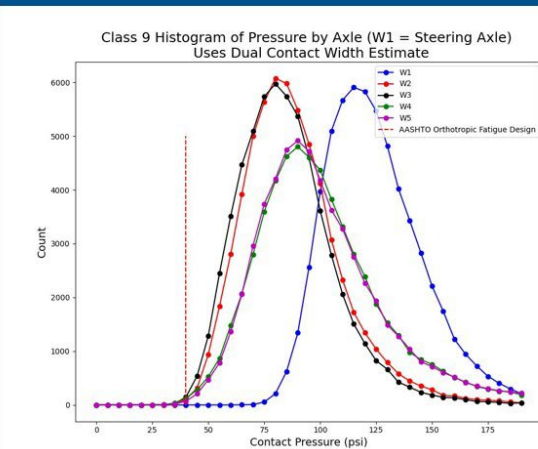


Figure 16 : Histogram of 5 axle truck weigh distribution



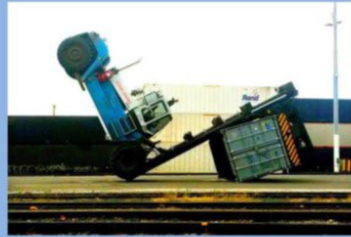
OVERWEIGHT CONTAINERS – INTERNATIONAL REGULATIONS & SOLAS

January 6, 2011, Beira shore crane collapsed:

- Crane out of service for 3 days
- Declared weight 25,000 kg - Actual weight 46,000 kg.



May 9, 2011, Melbourne: An overloaded forklift lies in a container yard in west Melbourne after its load tipped it forward.

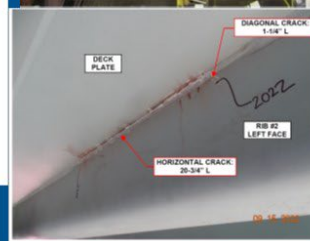
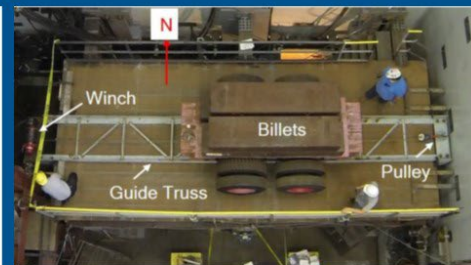
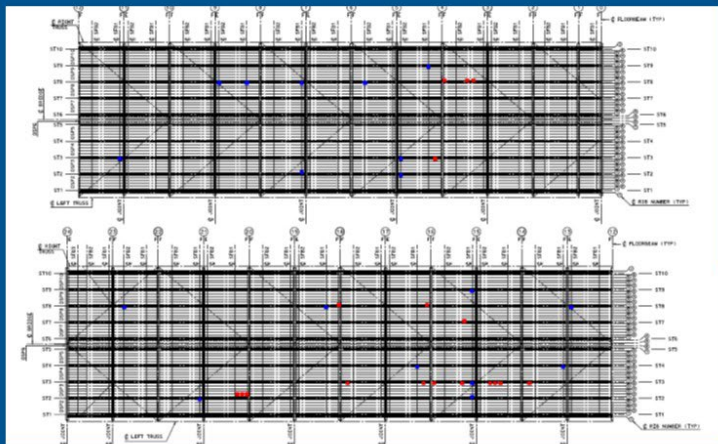


June 2011, M.V. Deneb in Algeiras suffered a significant stability incident:

- ~ 10% of the 160 containers loaded far exceeded declared weights.
- Actual weights exceeded declared weights by an average of 200%.
- Declared weight 93 tonnes - Actual weight 278 tonnes.



CHANGES IN LIVE LOADS – CRACKING IN ORTHOTROPIC BRIDGE DECKS



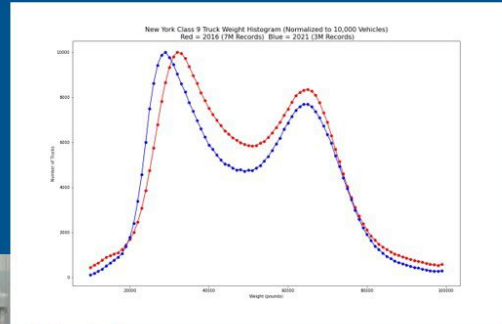
LIGHTWEIGHTING AND BLOWOVER RISK CAN TRUCKS BOTH BE GETTING HEAVIER & LIGHTER?



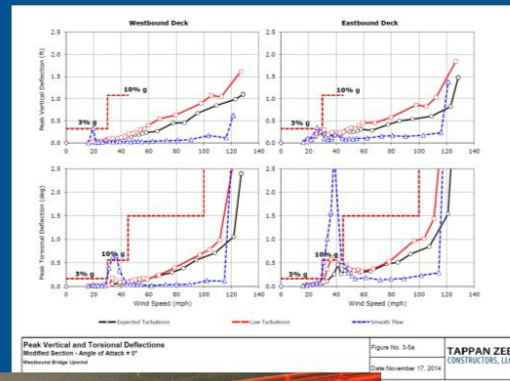
Testing Near the Tower with Baseline Fences



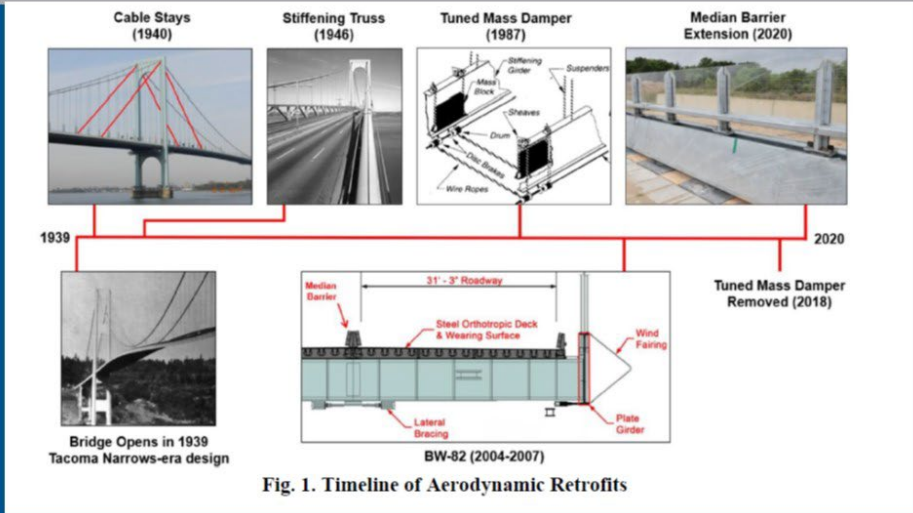
Testing Near the Tower with Mitigation Fences



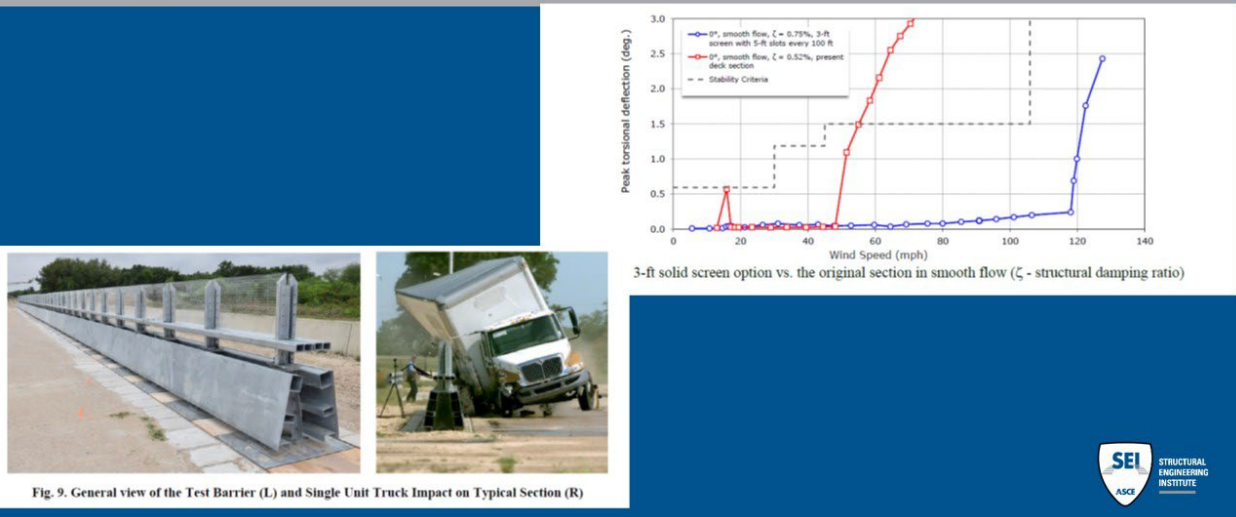
WIND BEHAVIOR - THE PROBLEM OF TWIN BRIDGES – OPEN BARRIERS AEROELASTIC BEHAVIOR



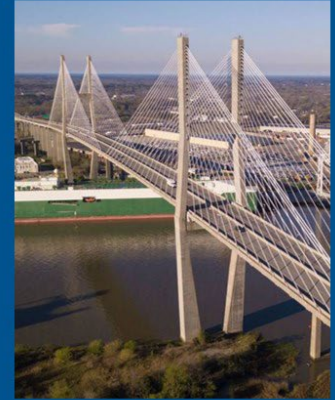
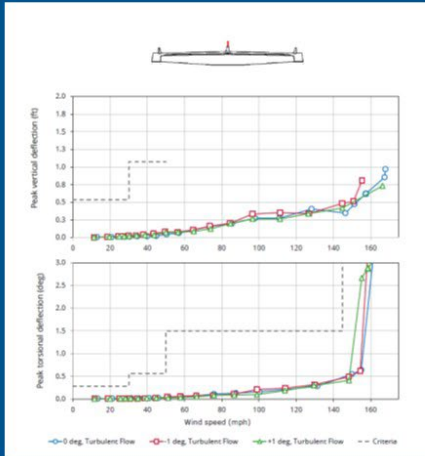
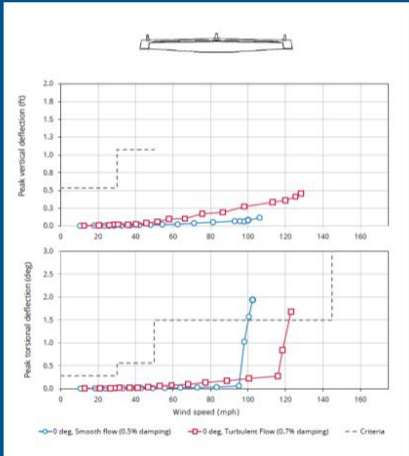
WIND BEHAVIOR AERO-ELASTIC IMPROVEMENTS MEDIAN BARRIER EXTENSION



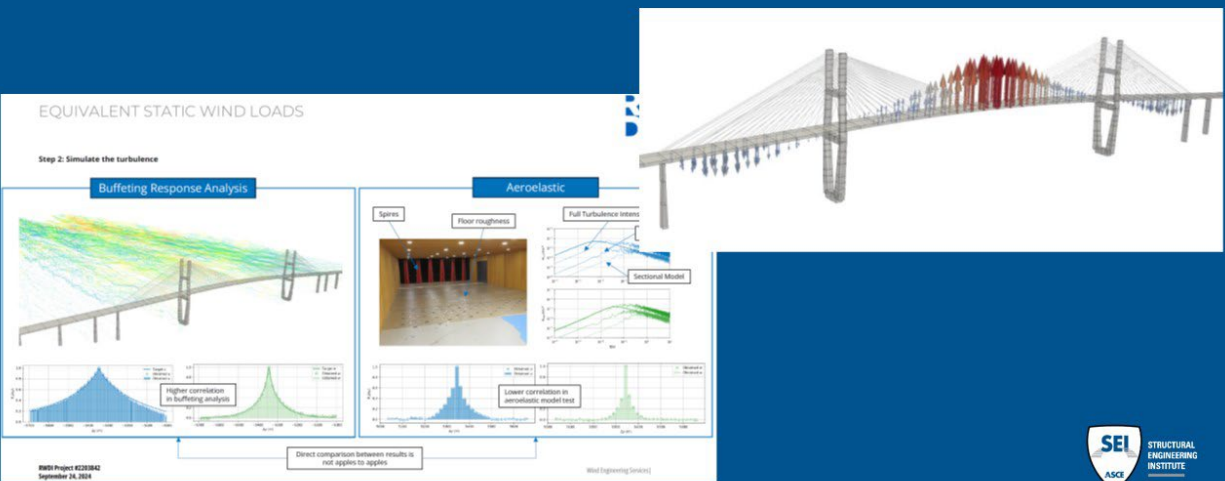
WIND BEHAVIOR - MEDIAN BARRIER EXTENSIONS SIMPLE, COST-EFFECTIVE AND HUGE AERODYNAMIC IMPROVEMENTS



WIND BEHAVIOR - TALMADGE BRIDGE REPROFILING MEDIAN BARRIER EXTENSION – ENHANCING STABILITY

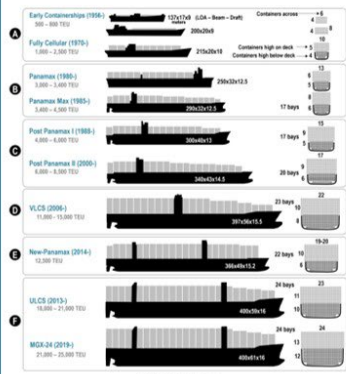


BUFFETING & WIND LOADS FOR MODERN LSB'S ALONG WIND VS ACROSS WIND RESPONSE

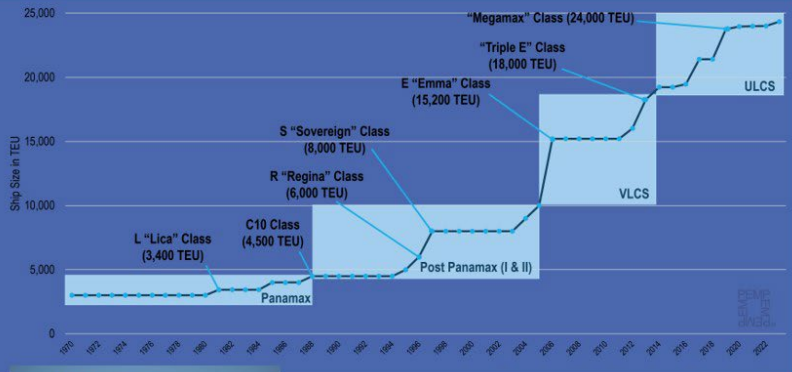


VESSEL IMPACT – GLOBALIZATION AND EXPLOSION OF CONTAINER VESSELS

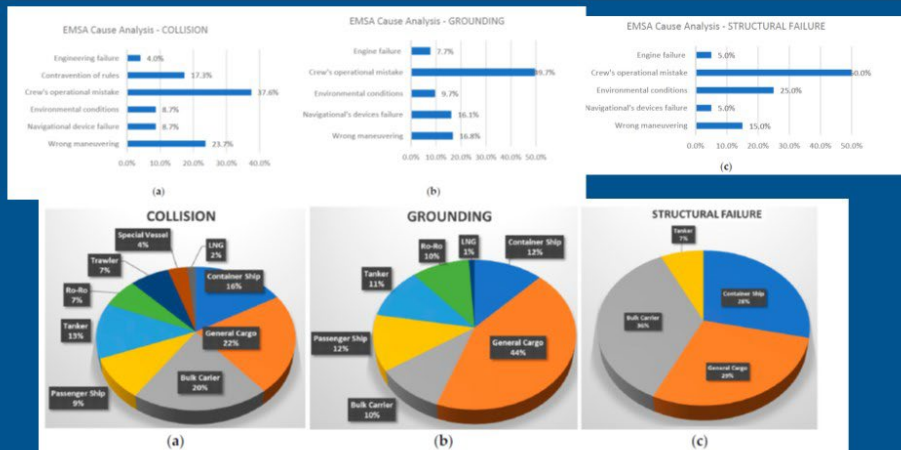
Evolution of Containerships



Source: All dimensions are in meters. LOA: Length overall. The loads displayed on deck represent maximal possible loads, which would involve a large share of empty containers. The loads are usually 1 to 3 containers less in height. Containerships usually carry fewer



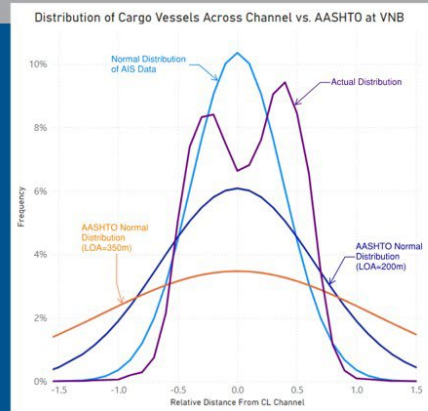
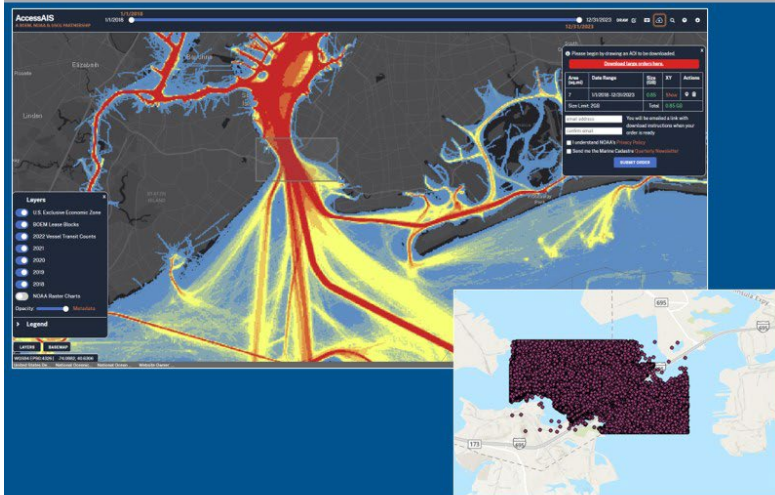
VESSEL ACCIDENT DATASETS RECENT VS HISTORIC DATA SETS



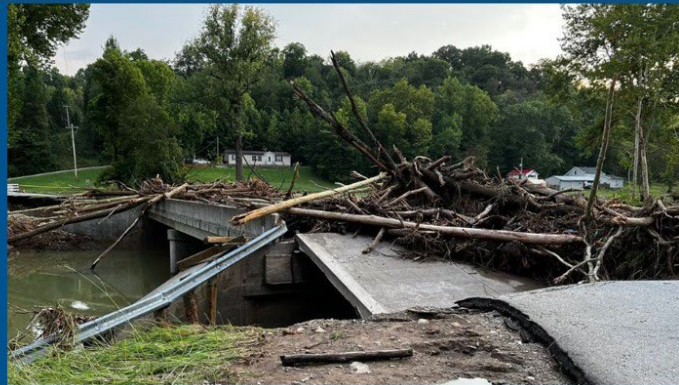
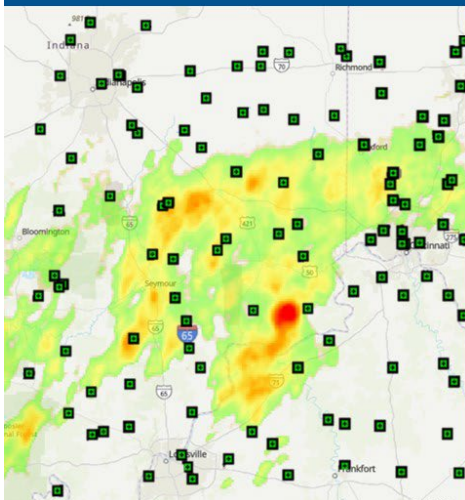
Pilates, et al. A Statistical Analysis of Ship Accidents (1990-2020) Focusing on Collision, Grounding, Hull Failure and Resulting Hull Damage, Journal of Marine Science and Engineering (January 2024)



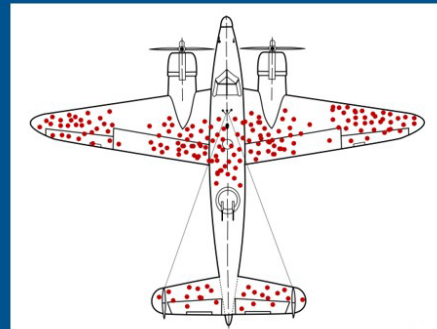
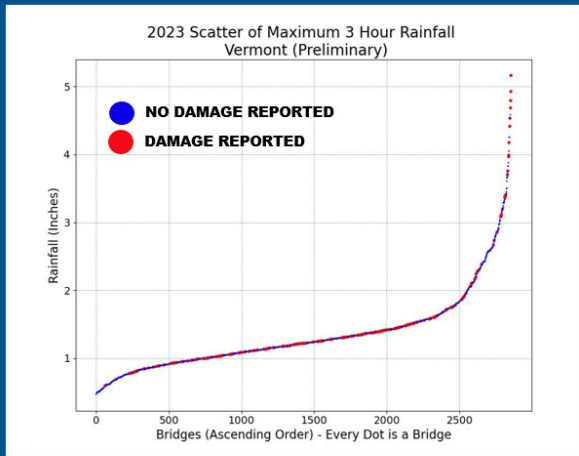
VESSEL IMPACT AIS DATA SETS & CODE



EXTREME RAINFALL – RAIN GAUGES VS MRMS DATA SETS



EXTREME RAINFALL EVENTS BRIDGE PERFORMANCE



Where infrastructure performs well helps identify context that may contribute to performance & inform strategies for resilience investments



SUMMARY & CONCLUSIONS

- Our ability to measure has led to new insights on loads
- Code development is challenged to keep pace
- Enforcement / Permitting presents unique challenges
- Regulatory requirements can create perverse incentives
- Believe a focus on “what’s changing rapidly” should inform future code development.
- Our structures are likely performing better than we think, and we need to better understand why.



B.2.1.7. Structural Capacity and Functional Underperformance: Hidden Effects of Groundwater Changes on Erosion, Saltwater Intrusion, and More; David Frost

HIDDEN EFFECTS OF GROUNDWATER CHANGES ON EROSION, SALTWATER INTRUSION, AND MORE

David Frost; Georgia Tech



Hidden Effects of Groundwater Changes on Erosion, Saltwater Intrusion and More

Contribution to “Future Load Effects”

SEI/NIST Forward Looking Codes and Standards Workshop #2

Presented by

J. David Frost PhD, PE, PEng

Higginbotham Professor and Regents' Entrepreneur

Special Acknowledgment to Dr. Boyoung Yoon

Georgia Institute of Technology

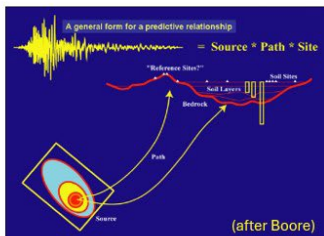


So Why Are They Hidden?

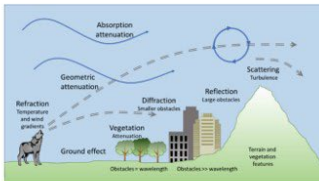
- Maybe they have always been present and we have just ignored them
- Not deliberately - but because our whole structure realization process is “flawed” – we approach it with a top-down philosophy
- Perhaps we need to revisit how we accomplish our work
- This workshop is about “Forward Looking Ideas” but perhaps we first need to take a quick look back
- I would like to propose to you that the result of such an exercise could be:

Foundation Based Architecture: A New Approach for Building Structures from the Ground Up

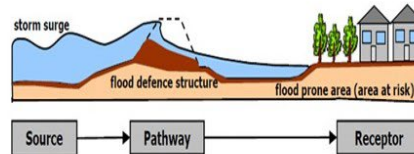
All Events Follow a “Source-Path-Site” Model



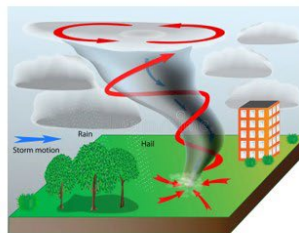
Seismic waves



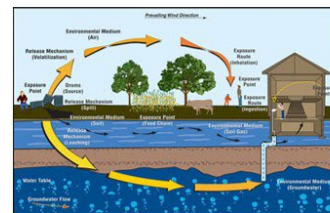
Airborne sound



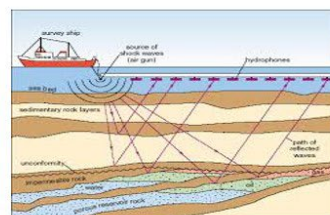
Hurricane



Tornado



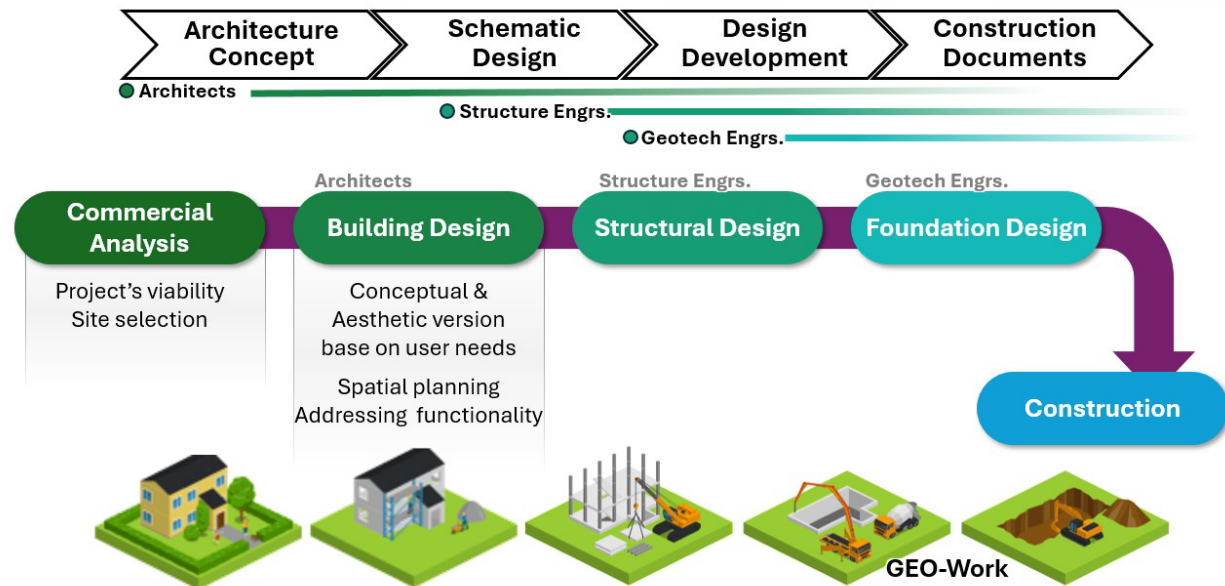
Environmental contamination



Geophysical exploration

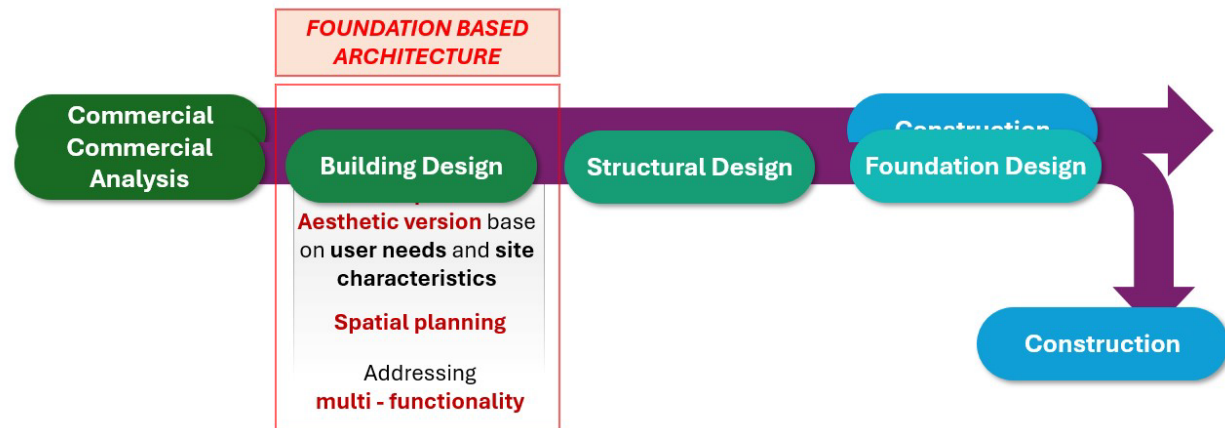
But does the S-P-S model capture the true “hidden” site elements?

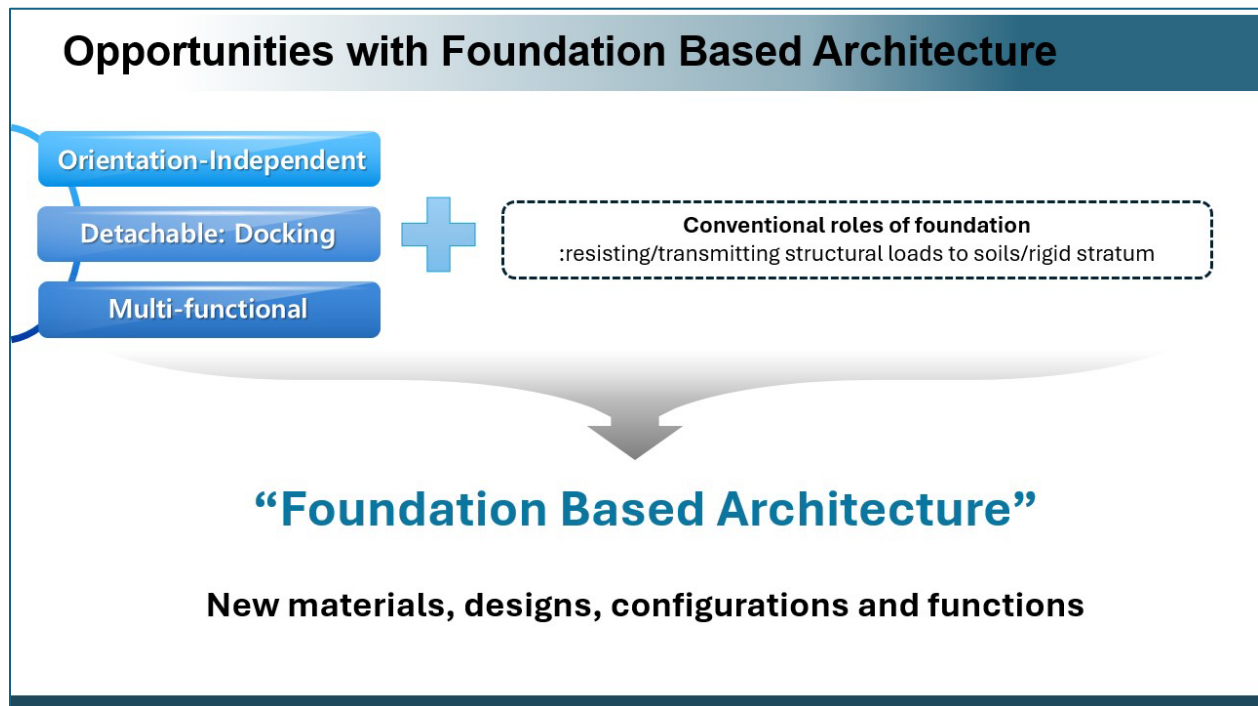
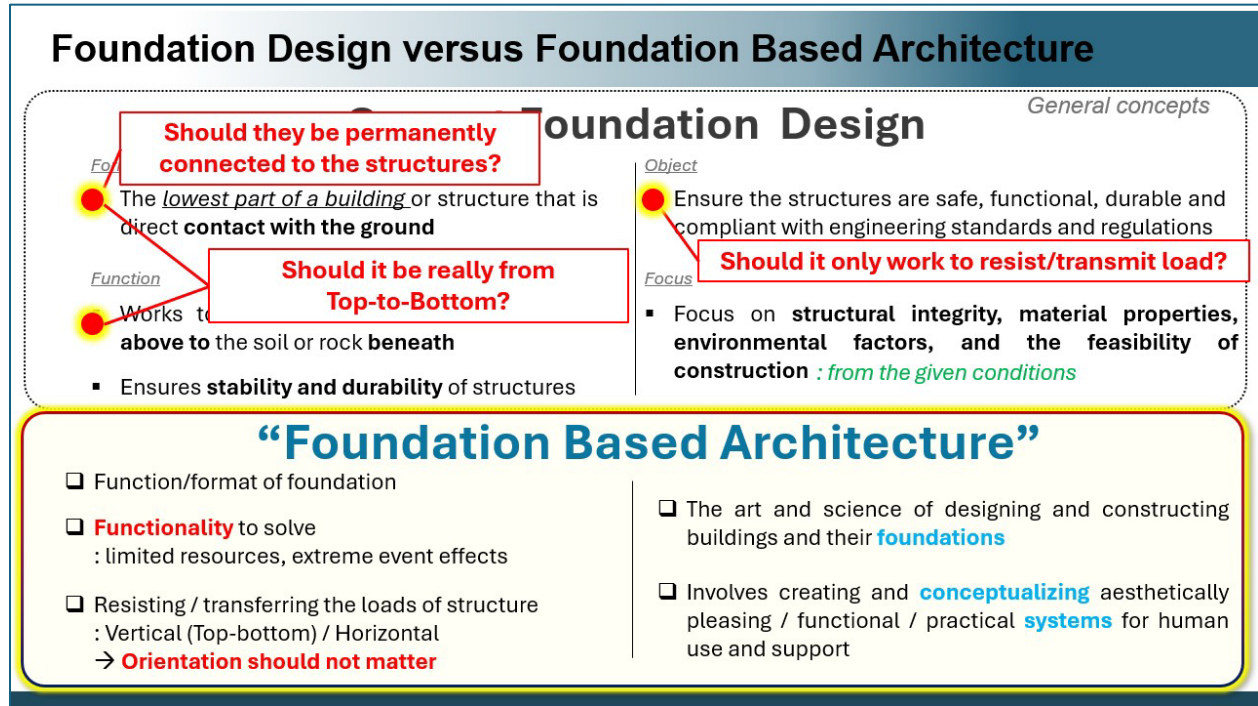
Conventional Design Work Process



Foundation Based Architecture Process

Architecture is the art and technique of designing and building, as distinguished from the skills associated with construction.^[4] It is both the process and the product of sketching, conceiving,^[5] planning, designing, and constructing buildings or other structures.^[6] The term comes from Latin *architectura*; from Ancient Greek ἀρχιτέκτων (*arkhitēktōn*) 'architect'; from ἀρχι- (*arkhi-*) 'chief' and τέκτων (*tēktōn*) 'creator'. (Wikipedia)

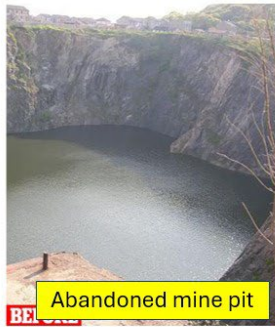




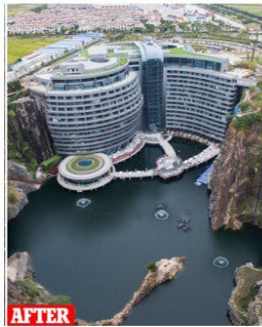
Intercontinental Shanghai Wonderland

Two-point supported structure

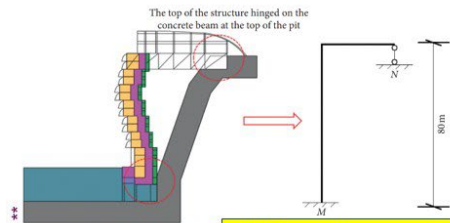
Orientation-Independent



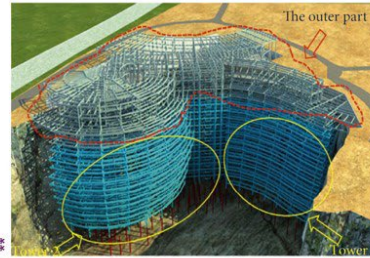
Abandoned mine pit



AFTER



Horizontal-supported



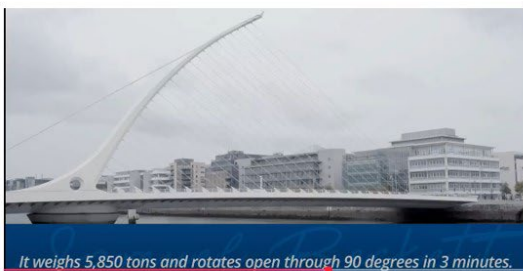
<https://www.dailymail.co.uk/news/article-6303745/Luxury-hotel-opens-ground-inside-ABANDONED-QUARRY-Shanghai.html>

141

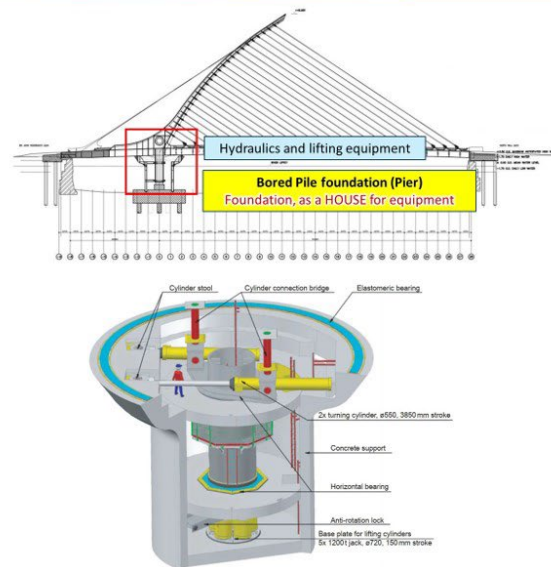
Samuel Beckett Bridge in Dublin

Bridge **rotates** to free the river channel for water transport crossing the river

Docking



It weighs 5,850 tons and rotates open through 90 degrees in 3 minutes.

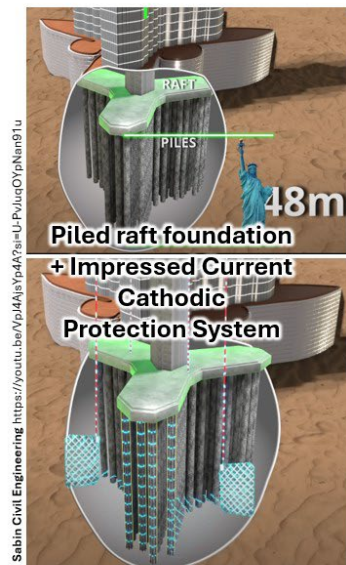


Behind a Great Project
<https://behindagreatproject.com>

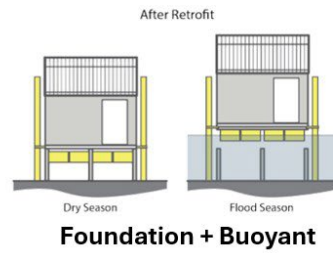
Multi-functional foundations

Piled raft foundation / Buoyant foundation / Energy Pile

Multi-functional

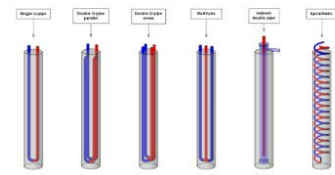


Sabin Civil Engineering <https://youtu.be/Vp4Aj5Yp4A7s>=U-PvUuOYpNan91u



[Convenience store in Korea near Han-river, after flood]

English, E., Chen, M., Zaitins, R., Palanga, P., 2019. A review of the use of energy piles to increase the resilience of flood-vulnerable communities while reducing risk of population displacement and psychological trauma. 8th ICBR Lisbon Book of Papers, 278.



Foundation + Energy



First energy pile in UK
Keble College (2001)

Courtesy of marine construction company Ireland.
Yonhap News Agency photo archive

China railway bridge in Ma'anshan

Rotated/docked after construction to avoid disruption during construction

Multi-functional Construction

Carries 6,000 vehicles per hour at peak



<https://www.bridgeweb.com/China-rail-engineers-swing-two-halves-of-arch-bridge-over-road/9556>

<https://www.newcivilengineer.com/latest/china-rotates-two-halves-of-231m-long-bridge-into-place-over-major-highway-in-world-first-15-11-2024/>

Opportunities with Foundation Based Architecture

Direction-Independent

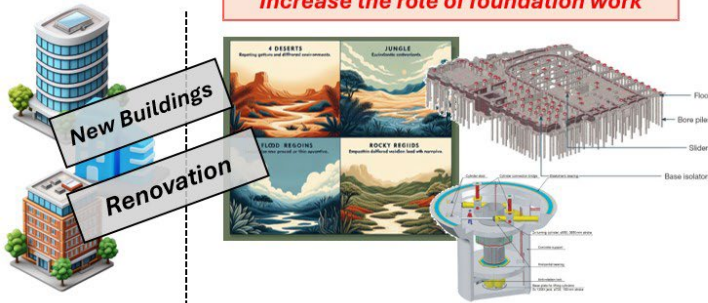
Detachable: Docking

Multi-functional

Foundation Based Architecture can be a solution for...



Increase the role of foundation work



☐ Underground/underwater construction

*Thermal-stability of soils
Moisture content of soils*

☐ Overcome material/resource shortages

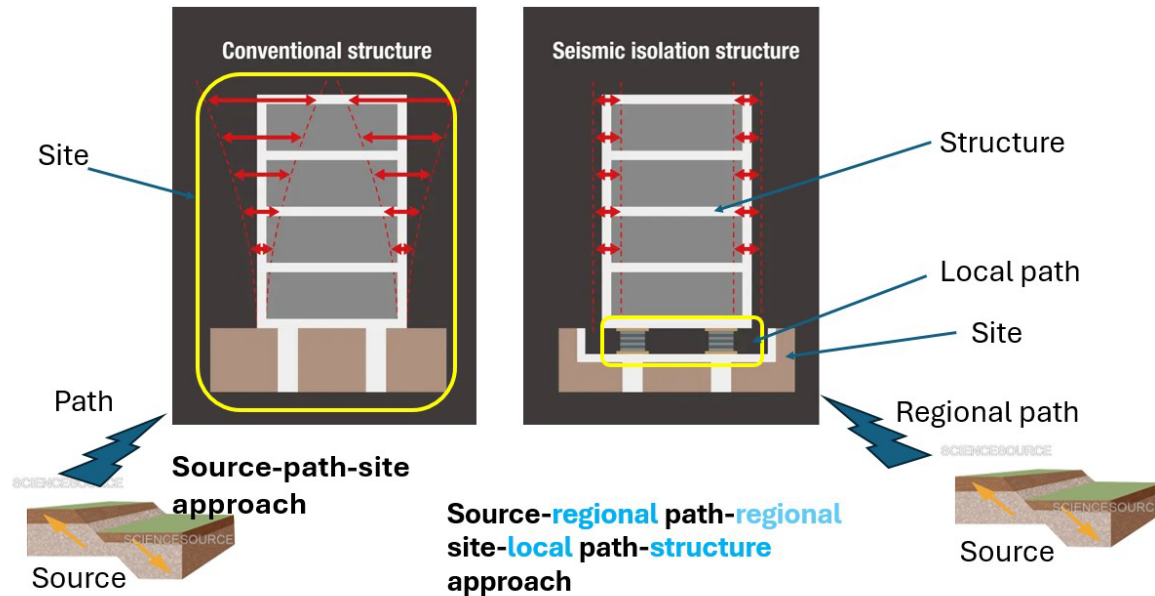
Recycling foundations?

145

So Back to the Hidden Effects Premise

- They are **NOT** hidden...
- Our structure realization process just does not accommodate them a priori – they are treated as after-thoughts...
- When we start with a site, the only thing that exists is the subsurface (including the hidden effects) – the site may be Greenfields or Brownfields (as a result of prior anthropogenic activity)
- Why do our procedures including our codes and standards not begin with the site?
- The emergence of increasing extreme events and natural hazards as well as the need to re-use sites are catalysts for change.
- We need to rethink our simple Source-Path-Site model-based approach as part of this activity.

Seismic Example of Foundation Based Architecture



Are “Hidden” Effects Always Bad Effects?

• What if they are just missed opportunities?

- Can we **reuse old building foundations** from prior site development be a new sustainable opportunity for structure realization (either as foundation components or for thermal functions) – **news flash – they are in Europe!!**
- Could we **prevent erosion** by designing engineered solutions that generate energy from water flow around bridge foundations
- Can structural foundations **incorporate a wicking function** to address shrinking/swelling soil issues for structures
- Can salt-water intrusion be used for **distributed thermoelectric power plant cooling**

Foundation Based Architecture can **reframe our thinking** to identify sustainable resilient solutions to existing and emerging challenges

Underlying guiding principle - Work with nature, not confront it – particularly as nature is dialing up the rhetoric!!

Closing Thoughts

JFK, the 35th President of the United State, famously said...

"Ask not what your country can do for you, ask what you can do for your country."

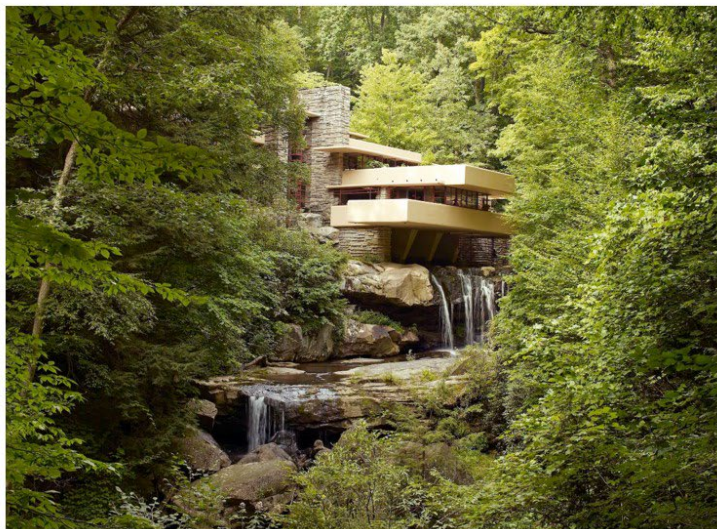
But if he was a Structural Engineer, I believe he would have said...

"Ask not what your structure can do for you, ask what your foundation can do for your structure."



Foundation Based Architecture can guide this approach.

Thank You



Falling Water – Frank Lloyd Wright.

LUNCH

12:00 – 12:30 pm

CONCLUSION of ZOOM Broadcast

Virtual attendees – PLEASE switch to Teams meeting



PLENARY DISCUSSION

12:30 pm – 1:30 pm



PLENARY: NEXT GENERATION GOALS FOR LOAD EFFECTS

Next Generation Goals for Load Effects – [45 mins.]; ALL

- Moderators: Jayantha Obeysekera, Terri McAllister

Discussion to prepare for breakouts

DEVELOP RESEARCH AGENDA FOR FUTURE LOAD EFFECTS

• PROMPTS:

- 1) Identify critical research needs.
- 2) Identify topics not currently considered.
- 3) Prioritize top 5 research needs. (Each written as a sentence.)

GOAL: What do you wish you had?

- GROUP 1-2-3-4: What is needed to characterize future loads and load effects? What are the next generation research needs?
- GROUP 5: What are the most impactful future effects on structural capacity? What are the next generation research needs?



PLENARY: NEXT GENERATION GOALS FOR LOAD EFFECTS

Discussion to prepare for breakouts

- [Terri to add bullets]



PLENARY: BREAKOUTS - DEVELOP RESEARCH AGENDA FOR FUTURE LOAD EFFECTS

- **PROMPTS:**
- 1) *Identify critical research needs.*
- 2) *Identify topics not currently considered.*
- 3) *Prioritize top 5 research needs. (Each written as a sentence.)*

GOAL: What do you wish you had?

- **GROUP 1-2-3-4:** What is needed to characterize future loads and load effects? What are the next generation research needs?
- **GROUP 5:** What are the most impactful future effects on structural capacity? What are the next generation research needs?



PLENARY: CHARGE THE BREAKOUTS

SCHEDULE: BREAKOUT SESSIONS 1:45PM – 4:45 PM

1:45pm – 2:00 pm = Breakout Session Introductions
and Identify *Day 2 Reporter*
(THREETOPICS for approximately 45-60 minutes each)
2:00pm – 2:45pm = *Identify critical research needs.*
2:45pm – 3:30pm = *Identify topics not currently considered*
3:30pm – 3:45pm = BREAK
3:45pm – 4:45pm = *Prioritize top 5 research needs.*

Asking for a
VOLUNTEER for
Day 2 Report Outs

GROUP: **NAME** Top 5 NEEDS

Identify the TOP 5 Priority Items and describe
each in 1-2 complete sentences.

- 1.
- 2.
- 3.
- 4.
- 5.

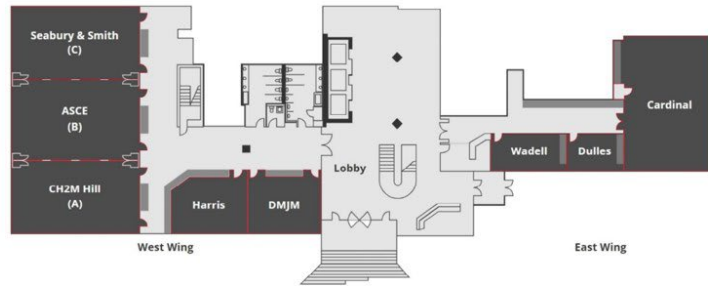
GROUP 1-2-3-4: What is needed to
characterize future loads and load effects?
What are the next generation research needs?
GROUP 5: What are the most impactful future
effects on structural capacity? What are the
next generation research needs?



BREAKOUT GROUPS

Group	Room (all sessions hybrid)	Moderator	Note Takers
1 - Wind	ASCE/ CH2MHill	Sihan Li	Kevin Borth Yating Zhang
2 - Inland Flood/Rain	Seabury & Smith	Keith Dixon	Matt Gilbertson
3 - Coastal Flood/SLR	Harris	Elisabeth Gilmore	Meg Ackerson Amanda McCarty
4 - Snow/Permafrost/Ice	DMJM	Joe Barsugli	Mari Tye Jennifer Helgeson
5 - Structural Capacity	Cardinal	Jennifer Goupil	Michel Ghosn Siamak Sattar

ASCE Conference Center



BREAKOUT SESSIONS

1:45 pm – 4:45 pm



STRUCTURAL
ENGINEERING
INSTITUTE

SUMMARY & ADJOURN

4:45 – 5:00 pm



B.2.2. Day 2 Slides: Overview Presentation

FUTURE LOAD EFFECTS

*The workshop presentations and discussion do not necessarily reflect
the views or policies of NIST or the United States Government.*

July 29-30, 2025

SEI/NIST Forward Looking Codes and Standards Workshop #2



FORWARD-LOOKING CODES AND STANDARDS: WELCOME

Jayantha 'Obey' Obeysekera, Ph.D., P.E.
Research Professor & Director, Sea Level Solutions Center,
Florida International University
Project Director, SEI/NIST Workshops



ASCE/NIST FORWARD LOOKING CODES & STANDARDS WORKSHOPS

1. **JUNE 4-5: Future hazards for design** – confidence/uncertainty in hazard projections, downscaling of global models, converting hazard projections to design criteria
2. **JULY 29-30: Future load effects on the built environment** - (a) load effects for future hazards, (b) changes in load effects relative to historical basis, (c) changes in structural performance, material properties, soils.
3. **TBD: Engineering design guidance and criteria** - non-stationary reliability, service life, design loads, resistance, deterioration
4. **OCT. 28-29: Adaptation and resilience** - buildings and infrastructure system assessment, material durability, mitigation, retrofit.



AGENDA

Digital Package

(password: futureloads)

- *AGENDA*
- *Participant List*
- *Slide Decks*



1:45pm-3:15pm – Concurrent Breakout Sessions

3:15pm-3:30pm – COFFEE BREAK
3:30pm-4:45pm – Concurrent Br

4:45pm-5:00pm – Reconvene

- Summary and Adjourn

Day 2: July 30; 8:00am – 12:00pm Eastern

7:30am-8:00am – NETWORKING CONTINENTAL BREAKFAST PROVIDED

8:00am-8:15am – Welcome

- Purpose and Goals of Day 2

8:15am-10:30am – Report Out

- Breakout Session Report out: [15 mins EACH = 10 mins. + 5 mins Q&A]

15-minute COFFEE BREAK (9:30am)

- Moderated Discussion of Breakout Reports [45 mins.]
Moderator: Jayantha Obeysekera

10:30am-11:45am – Prioritization

- **Prioritization of Research Needs - Survey [15 mins.]**

- Discussion of Survey Results [60 mins.]

11:45am-12:00pm – Conclusion
 Symposium and Follow-up

- Summary and Adjourn Day 2

12:30-3:30pm – Workshop Steering Committee Meeting

SEI/NIST Forward Looking Codes and Standards: Future Effects Workshop

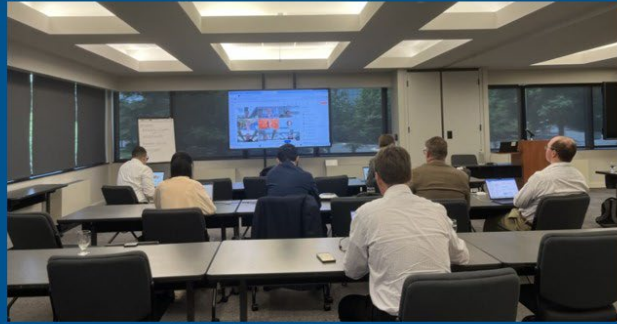
3

REPORT OUT & PRIORITIZATION

8:15 am – 11:45 am



B.2.2.8. Breakout Session Reports



BREAKOUT 1



BREAKOUT GROUP 1 1:45PM – 2:00PM

MODERATOR: **Sihan Li**

NOTE TAKER: **Kevin Borth, Yating Zhang**

DAY 2 REPORTER: **PETER VICKERY**

ATTENDEES:

1. John Allen
2. Han-Ping Hong
3. Don Scott
4. Gus Sirakis
5. Jeff Trapp
6. Yating Zhang
7. David Roegner
8. Terri McAllister
9. Marc Levitan

GROUP 1 - WIND

Wind types that produce damage in order: Tropical cyclones, severe convective storms (excludes tornado), extra-tropical storms, tornado, orographic winds (special regions)

1. Multiple high-resolution (km-scale) simulations for historical and future severe convective storms, bounded by observations, are needed to reduce or better quantify uncertainty.
2. Observational data that has a higher quality and resolution to ensure extreme events for wind types are adequately captured and to improve future hazard models and projections. Data sources should make use of existing, new and emerging data sources, including wind measurement stations, satellite data, and NEXRAD.
3. Assess wind load design assumptions for the range of wind types to determine adequacy for historical and future wind loads. This includes the applicability of the 3-s gust wind speed for severe convective storms, as well as the choice of the appropriate reference period for reliability analyses.
4. Develop methods for improved tornado wind modeling and enhance our understanding of changes in regionalization. This includes characterizing changes to frequency and intensity due to warming and observed trends of increased tornado events east of the central plains.
5. Develop methods and design criteria to capture effects associated with damage due to wind-driven rain, to ensure continued functionality.



BREAKOUT 2



BREAKOUT GROUP 2

1:45PM – 2:00PM

MODERATOR: **Keith Dixon**

NOTE TAKER: **Matt Gilbertson, Abbie Liel**

DAY 2 REPORTER: **ADAM REEDER**

ATTENDEES:

1. Alex Cannon
2. Naresh Devineni
3. Maria Garlock
4. Abbie Liel
5. Kris May
6. Julie Pietzrak
7. Adam Reeder
8. David Frost

GROUP 2 – Inland Flood/Rain

Top 5 NEEDS

1. As a near-term approach until standardized, universal future conditions flood hazard data products are developed, we need to develop a method(s) to adjust or augment currently available flood hazard data from present-day flood maps and studies (i.e., FEMA FIRMs and FISs) to estimate future conditions. This method(s) may consist of multiple scaling factors to account for different future effects (e.g., more severe future precipitation, future floodplain development, etc.).
2. We must improve our current definitions (boundary conditions) and models of various flood characteristics and better understand their associated uncertainties:
 - Develop better riverine velocity models or quantify relationships with other defined flood characteristics (e.g., the floodwater depth).
 - Conduct research into the actual density of floodwater to account for soil and mud.
 - Quantify the rate-of-rise and warning time for design floods, including for future events which may be extreme, short-duration rainfall events.
 - Quantify flood duration and the influence of duration on observed building/structure damage.
 - Conduct research into stream migration, with the long-term goal of identifying these risk areas on flood hazard maps to inform siting decisions.
3. Develop method(s) to account for future development and other non-climate-related future conditions that may impact non-coastal flooding, such as worsening runoff characteristics. This will improve the reliability of our climate change models to reflect the built environment.
4. Institute measures to automate flood mapping and improve the efficiency of flood map development, such as AI or machine learning to develop models and maps. Human effort should focus on oversight and field verification of existing conditions. In addition, we must improve our understanding of hydrological models that translate precipitation into flood characteristics.
5. Develop multi-disciplinary design and mitigation approaches that accommodate flooding rather than simply resist floods or elevate above the flood, such as floating structures, low water-crossing bridges, etc.





BREAKOUT 3



BREAKOUT GROUP #3 1:45PM – 2:00PM

MODERATOR: **Elisabeth Gilmore**

NOTE TAKER: **Meg Ackerson, Amanda McCarthy**

DAY 2 REPORTER: **Ning Lin**

ATTENDEES:

1. Elisabeth Gilmore
2. Meg Ackerson
3. Chris Clavin
4. Erin Rooney
5. Jayantha Obeysekera
6. Ning Lin
7. Jessica Mandrick
8. Amanda McCarty
9. Zoubir Lounis
10. Dan Walker

TOPIC 1: Identify critical research needs 2:00PM – 2:45PM

GROUP 1-2-3-4: What is needed to characterize future loads and load effects? What are the next generation research needs?
GROUP 5: What are the most impactful future effects on structural capacity? What are the next generation research needs?

Research needs with "Flood Loads for ASCE 7-28 Chapter 36 Future Conditions of Flood Loads"

- ▲ **Local analysis:** the code requires designers to utilize local future conditions flood impact and hazard data in place of the FEMA flood hazard maps, putting significant responsibility & cost on local jurisdictions/projects.
 - ▲ Do we need national mapping (like seismic) for design / not necessarily for insurance (FEMA)?
- ▲ **Climate change beyond SLR:** the code utilizes a "bathtub" model wherein the SLR is added to the present-day stillwater elevation.
 - ▲ ASCE 7-28 wind loads accounts for the storm climatology change by applied climate projections and hurricane modeling. Should we apply these wind forcing to coastal flood load to consistently account for the climate change impacts to storms (i.e., rainfall & storm surge in addition to SLR)?
 - ▲ Can we consider 100-yr or 500-yr water levels, including SLR and storm changes, over time?
- ▲ **Uncertainty: the code applies 50-percentile SLR projection under 3-degree warming**
 - ▲ Should extremes of SLR be considered?
 - ▲ What is the uncertainty associated with the specified 3-degree warming?
 - ▲ Gaps in understanding of design professionals on the percentiles and conflicting info. in FEMA insurance maps and USACE design
 - ▲ Can we explore research need of developing risk tolerance/profile and incorporating into code?
 - ▲ Maps would provide clarity. Would need to define deferent percentile/risk levels and confidence limits
- ▲ **Nonstationarity: Design philosophy moving away from stationary MRI.**
- ▲ **Loads beyond depths:** What about velocity & wave action for coastal structures? Site specific and within coastal engineering



TOPIC 1: Identify critical research needs 2:00PM – 2:45PM

GROUP 1-2-3-4: What is needed to characterize future loads and load effects? What are the next generation research needs?
GROUP 5: What are the most impactful future effects on structural capacity? What are the next generation research needs?

Further discussion on research needs:

- **Uncertainty:** Incorporating the uncertainty in latter half of century and the extremes. Communication from academia to engineering community to builders/owners. Defining climate scenarios (3C vs. SSP/RCP)
 - Consistent climate scenario connects across hazards (internal consistent).
 - Shift to global warming levels (e.g. 3C). Would this apply?
 - Path dependency: does it matter how we get to 3C? Does this shape design?
- **Dynamic adaptation pathways:** evaluated in IPCC Working Group 2 and viewed favorably. Netherlands leader in this space. Could this be applicable more broadly in US?
 - E.g., design a seawall that will be increased in height depending on future observation of SLR; in Miami designing pumphouse room for 4 pumps and start with 1.
 - Idea would be to have guidelines / framework included in the code. It's part of design philosophy.
- **Loads beyond depths:** Integration of storm components (wind, precip, storm surge, SLR) into modelling and load development. These should be included in upcoming Manual of Compound Flooding (developed by CAAC).



TOPIC 1: Identify critical research needs 2:00PM – 2:45PM

GROUP 1-2-3-4: What is needed to characterize future loads and load effects? What are the next generation research needs?
GROUP 5: What are the most impactful future effects on structural capacity? What are the next generation research needs?

Not said yet? Roundtable on additional research needs:

- **NBS:** Efficiency of nature-based solutions
- **Expectations from professionals:** What are our expectations from design professionals (i.e. structural engineers) who pick up this future code book that we are contributing to today / with the research outputs? Translational research need ☹ bridge between climate/future & practitioners.
 - Coastal engineers distinct from structural engineers. When coastal requirements put in general standards, are non-coastal engineers stepping outside of their expertise? Concern from coastal engineering community
 - Hydrological & Hydraulic modelling: When is H&H modelling necessary? Not standard study for typical projects.
- **FEMA map efforts:** FEMA initiative to update FIRMs. Unknown status. This effort was intended to fill gaps & map watersheds and intended to incorporate future climate. ASFMP has decks available. "Future of Flood Risk" initiative is name.
- **Other coastal hazards:** particularly Geotech like erosion & shoreline changes (accretion & recession of beaches/sediment for example).
 - Missing consideration of coastal aquifers & SLR. Remote sensing to better understand.
 - Groundwater incorporated into design, and compared against stillwater level.
 - Cross-check with 2024 ASCE NOAA Workshop report that covered multiple hazards: <https://repository.library.noaa.gov/view/noaa/66829>



TOPIC 2: Identify topics not currently considered 2:45PM – 3:30PM

GROUP 1-2-3-4: What is needed to characterize future loads and load effects? What are the next generation research needs?
GROUP 5: What are the most impactful future effects on structural capacity? What are the next generation research needs?

Group brainstorm (1/3):

- ▲ **Impact of frequent events:** Account for impact from smaller, serviceability-level events events (not just 100yr event, e.g.)
- ▲ **Functional recovery:** What is acceptable degradation of function & for how long & under what future scenario? Consider functional recovery in non-eq design.
- ▲ **Probability vs. Benefit-Cost design approach:** Weighing benefits & costs of design choices, and not just design for predefined hazard level. Risk-informed design.
 - ▲ Willingness to pay has dramatic implications for resource allocation. Are decision makers empowered with minimal capacity? Assess how government ability/willingness to pay plays into benefit-cost.
 - ▲ **Benefits & costs & design support / decisions by sectors:** Incorporating ASCE for developers & healthcare ☹ mapping climate-related updates to codes into risk categories and for different sector. Sectors characterize benefits & costs differently.
 - ▲ Incorporate beyond singular asset, but damage to assets/infra and loss of life considerations. What's the line between code of ethics & value of statistical life.
- ▲ **Supporting infrastructure:** System level approach is a gap in our building codes. Utilities like power, potable water, etc. Particularly coastal infrastructure, like ports, have large spatial coverage in the coastal areas. Community infrastructure resilience.
- ▲ **Systems approach:** Design philosophy. Large spatial coverage of coastal flooding. Collective involvement, such as USACE, for entire coastline projects.
 - ▲ Implications of new coastal structures & their impact on existing structures.



TOPIC 2: Identify topics not currently considered 2:45PM – 3:30PM

GROUP 1-2-3-4: What is needed to characterize future loads and load effects? What are the next generation research needs?
GROUP 5: What are the most impactful future effects on structural capacity? What are the next generation research needs?

Group brainstorm (3/3):

- 🚧 **Existing infrastructure:** How new structures impact existing infrastructure? What are implications of future hazards on existing infrastructure?
- 🚧 **Capacity:** Need to understand structural capacity changes over time.
- 🚧 **Human behavior & technology:**
 - 🚧 **Larger impact loads** for coastal structures (consider increased size of ships, e.g.) (which has been included in ASCE 7-22). Higher waves, increases in "passing vessel effect" for design and refinement for vessel distance over land/reach of a debris object especially in urban coastal environments (not included in ASCE 7-22).
 - 🚧 **Adaptive infrastructure** ☞ incorporate human behavior into design. Think about operation of buildings & humans as part of design. E.g. sandbags on top of levee for frequent events or added structural height to levee in future SLR.
 - 🚧 **Hazard** ☞ **Adaptation-hazard interactions.** Will those interaction change in response to climate change / future environmental effects / human behavior & technology?
 - 🚧 **Embedding consideration of nature into design**, example of levees offer flood protection but have negative impacts on ecosystem / change river banks, e.g. Detrimental impacts of coastal structures on environment (sediment, subsidence, ecosystem health impacts).



GROUP: *#3 Coastal Flood* Top 5 NEEDS

GROUP 1-2-3-4: What is needed to characterize future loads and load effects? What are the next generation research needs?
GROUP 5: What are the most impactful future effects on structural capacity? What are the next generation research needs?

Identify the TOP 5 Priority Items and describe each in 1-2 complete sentences.

1. **We need consistent flood hazard maps** (e.g., depth, velocity, wave height, extent) at national level considering various flood drivers (e.g., SLR, storm surge, precipitation, wave action, groundwater rise, erosion, subsidence, coastline change) to provide authoritative, fit for purpose, and regularly updated data source for localized design.
2. **We need to develop techniques for dealing with nonstationarity and uncertainty** of hazards (e.g., SLR, storm surge, precipitation); for example, under a specified warming level (e.g., 3deg C) and the timeline to reach that level, design life of the structures; and impact to reliability considerations in design.
3. **We need to incorporate decision analytic frameworks into design** and provide guidance on how to select an approach in design, such as dynamic adaptive pathways, benefit-cost assessments, risk-based designs, design for functional recovery, and design for serviceability/performance during frequent floods.
4. **We need to research nature-based solutions** (e.g., ecotone levee, oyster reefs) to understand their performance, capacity, and impact on hazard reduction and to develop and validate design criteria. As an industry, we need Tribal partners and incorporate their knowledge of nature-based solutions into design.
5. **We need a new design philosophy that incorporates a systems approach to account for the spatial distribution of infrastructure, environment, and people exposed to coastal hazards**, including changing societal preferences for coastal use (e.g., shipping, residential, recreational, habitat restoration) and their impacts on design (e.g., larger ships wave action, impacts of environmental changes on hazard levels). We need to identify and include key partners in civil society, communities of practice, government agencies, and industry to codevelop code philosophy as part of the code development process.





BREAKOUT 4



BREAKOUT GROUP #4
1:45PM – 2:00PM

MODERATOR: **Joe Barsugli**

NOTE TAKER: **Mari Tye (v),
Jennifer Hegelson**

DAY 2 REPORTER: **Joe**

ATTENDEES:

1. Joe Barsugli
2. Mari Tye (v)
3. Jennifer Hegelson
4. Ahmed Abdelaal (v)
5. Jan Dale
6. Aron Newman
- 7.
- 8.

GROUP: *4 Joe Barsugli* Top 5 NEEDS

GROUP 1-2-3-4: What is needed to characterize future loads and load effects? What are the next generation research needs?

1. Research is needed to relate ground snow to roof and drifting loads, the processes that are involved, and how the climate effects can be incorporated. The goal is to better understand regional differences in how snow moves and accumulates and how this will change in the future.
2. Engineering research is needed to understand building interactions arising from newer roofing materials (e.g. snow sliding), and how management of the risks of falling snow and ice affect loads.
3. Research is needed to leverage reanalysis and climate model data to better characterize freezing rain and ice loads where observations are lacking, including the future. This includes more reliable observations of freezing rain and ice accretion thickness at more locations, validation of reanalysis products and better methods to translate climate model output to local ice. Options include:
 - ▲ Low cost sensors development and leveraging other sensor network such as smart roads and other new technology on infrastructure.
 - ▲ Combining hindcasts from weather models and non-traditional data such as insurance claims to enhance the observational record
 - ▲ Quantifying ice accretion and load on different (non-cylindrical), for example solar panels.
 - ▲ Investigate convection-permitting model simulations for better process understanding of future conditions
4. Investigate ice loads that not covered now, including hail and rime icing. [Hail that can lead to degradation of the structure once the envelope is compromised]. Rime icing is a concern for tall structures in including for power transmission. Potential synergy with aviation research on in-cloud.
5. Research is needed into load distribution effects that are not currently treated, including deflection (beams) leading to secondary ponding concentration of loads or from human intervention e.g. people clearing snow from parking garage.



BREAKOUT 5



BREAKOUT GROUP 5

1:45PM – 2:00PM

MODERATOR: **Jennifer Goupil**
NOTE TAKER: **Michel Ghosn, Siamak Sattar**

DAY 2 REPORTER: **RUOHUA GUO**

ATTENDEES:

1. Scott Jones
2. Fabio Biondini
3. Graziano Fiorillo
4. Ruohua Guo
5. Mohammad Houshmand
6. Roy Lobo
7. Brian Pailes
8. Francisco Presuel-Moreno
9. Ken Snyder
10. Mark Stewart
11. Amin Hariri

STRUCTURAL CAPACITY: RESEARCH NEEDS AND TOPICS NOT COVERED

THEMES

- 1. Structural Degradation and Environmental Effects
- 2. Modeling, Prediction, and Validation
- 3. Structural Capacity, Reliability, and Design Standards
- 4. Component-Level and System-Level Analysis
- 5. Testing, Monitoring, and Inspection



GROUP: *Structural Capacity* Top 5 NEEDS

Identify the TOP 5 Priority Items and describe each in 1-2 complete sentences.

1. Develop models for various deterioration mechanisms accounting for different environmental stressors (temperature, humidity, CO₂, chloride, saltwater, etc.) and implement in open-source tools for practice.
2. Validate deterioration models using advanced numerical tools as well as real-time and accelerated laboratory and field testing.
3. Build reliability models accounting for uncertainties in capacity degradation and apply those to calibrate load combinations factors; generate data-driven, site-specific capacity reduction factors.
4. Improve understanding of localized deterioration and its impact on component and system performance.
5. Provide guidance for monitoring and inspection requirements for evaluating capacity and future performance under climate impacts.



COFFEE BREAK

10 minutes



MODERATED DISCUSSION OF BREAKOUT REPORTS

[45 mins]

• Moderator: Jayantha Obeysekera



PRIORITIZATION OF RESEARCH NEEDS

15 minutes



SURVEY RESULTS (1, 2, 3)

Assess wind load design assumptions for the range of wind types to determine adequacy for historical and future wind loads. This includes the applicability of the 3-s gust wind speed for severe convective storms, as well as the choice of the appropriate reference period for reliability analyses.

Develop multi-disciplinary design and mitigation approaches that accommodate flooding rather than simply resist floods or elevate above the flood, such as floating structures, low water-crossing bridges, etc.

Consistent flood hazard map (e.g. depth, velocity, wave height, extent) at national level considering various flood drivers (e.g. SLR, storm surge, precipitation, wave action, groundwater rise, erosion, subsidence, coastline change) that are authoritative and fit for purpose, can be regularly updated and used for localized design.

Multiple high-resolution (km-scale) simulations for historical and future severe convective storms, bounded by observations, are needed to reduce or better quantify uncertainty.

As a near-term approach until standardized, universal future conditions flood hazard data products are developed, we need to develop method(s) to adjust or augment currently available flood hazard data from present-day flood maps and studies (i.e., FEMA FIRMs and FISs) to estimate future conditions. This method(s) may consist of multiple scaling factors to account for different future effects (e.g., more severe future precipitation, future floodplain development, etc.).

Develop techniques for dealing with nonstationarity and uncertainty of hazards (e.g. SLR, storm surge, precipitation), for example, under a specific global warming level (GWL) (e.g. 3deg C), the timing to that GWL, the design life for the structures, and the impact to reliability considerations in design.



RESULTS CONT. (4 & 5)

Research is needed to relate ground snow to roof and drift-ing loads, the processes that are involved, and how the climate effects can be incorporated into code specifications. The goal is to better understand regional differences in how snow moves and accumulates and how this will change in the future.

Research is needed to leverage reanalysis and climate models, including convection-permitting models, to better characterize freezing rain and ice loads where observations are lacking, including projections of the future. This includes more reliable observations of freezing rain and ice accretion thickness at more locations, validation of reanalysis products and better methods to translate climate model output to local ice.

Develop models for various deterioration mechanisms accounting for different environmental stressors (temperature, humidity, CO₂, chloride, saltwater, etc.) and implement in open-source tools for practice.

Build reliability models accounting for uncertainties in capacity degradation and apply those to calibrate load combinations factors; generate data-driven, site-specific capacity reduction factors.



DISCUSSION – 60 MINUTES

Moderator:

Jayantha 'Obey' Obeysekera – Workshop Director

- Review of findings
- Discussion (ALL PARTICIPANTS)



SUMMARY & ADJOURN

11:45 am – 12:00 pm



ASCE/NIST FORWARD LOOKING CODES & STANDARDS WORKSHOPS

1. **JUNE 4-5: Future hazards for design** - confidence/uncertainty in hazard projections, downscaling of global models, converting hazard projections to design criteria
2. **JULY 29-30: Future load effects on the built environment** - (a) load effects for future hazards, (b) changes in load effects relative to historical basis, (c) changes in structural performance, material properties, soils.
3. **TBA: Engineering design guidance and criteria** - non-stationary reliability, service life, design loads, resistance, deterioration
4. **OCT. 28-29: Adaptation and resilience** - buildings and infrastructure system assessment, material durability, mitigation, retrofit.



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INSTITUTE

THANK YOU to all participants and
to the Workshop Steering
Committee!!!

SUMMARY & ADJOURN

12:00 pm

PLEASE recycle your Name Badges



Appendix C. Workshop Reading Materials

The following summaries were distributed to the participants in advance of the workshop to provide background information on the development of the 2028 edition of ASCE/SEI 7 in the new Ch. 36 Future Conditions: Flood, Ice, Rain, Snow, and Wind:

C.1. Flood Loads for ASCE 7-28 Chapter 36 Future Conditions

Hazard Data Sources

The proposed provisions for future flood loads in Chapter 36 of ASCE 7-28 are generally divided into coastal flood sources (e.g., sea level change, subsidence) and non-coastal flood areas. For both categories, the proposed provisions primarily rely on the basic flood loads (i.e., present-day flood hazard) in Chapter 5 of ASCE 7 for the calculation of various types of flood-related loads, including hydrostatic loads, hydrodynamic loads, wave loads (coastal flooding only), and debris impact loads. Within Chapter 5, the key parameter affecting the magnitude of each of these loads is floodwater depth (or stillwater depth for coastal floods). For example, the flood velocity for hydrodynamic and debris loads is based on the floodwater depth, and the wave height for wave loads is based on the floodwater depth. To that end, for this initial cycle of Chapter 36 of ASCE 7-28, the key objective is to augment the floodwater depth to better reflect future conditions, but rely on the same methodologies and models for load computations used to represent present-day flood loads.

Models/Methods for Future Design Values

A key challenge for flood hazards in Chapter 36 is the lack of a standardized, uniform, and national source for the extents and elevations for future flooding. Chapter 5 (present-day flooding) relies on the FEMA flood hazard maps and studies, which, while imperfect, are relatively universally available and intended to represent a uniform hazard. However, FEMA maps do not reflect future conditions. While FEMA is exploring new mapping initiatives that may be useful in the future, such as the Future of Flood Risk Data Initiative (FFRD), those tools will not be available for this current ASCE 7 cycle.

Meanwhile, some local jurisdictions have independently undertaken future conditions mapping programs, and in many cases, have already utilized the maps and corresponding flood hazard data for enhanced floodplain management ordinances, zoning regulations, or local building code requirements. However, these local mapping initiatives are non-standard in the future condition they are meant to represent (both in terms of the warming scenario and time horizon represented, but also in the source and recency of the data). Further, they are very localized to the municipality or jurisdiction that funded the study.

Assumptions and Decisions

Compared to other hazards in the scope of ASCE 7, flood hazards are very localized hazards. A local analysis is required to accurately define the hazard at a level suitable for design. For example, a hydrologic and hydraulic (H&H) analysis of a particular watershed, a stormwater

analysis of a specific urban area, or a coastal analysis of a reach of coastline. As a result, determining the magnitude of the primary climatic parameters that drive future flood conditions (sea level change for coastal flooding and future rainfall frequency/intensity for non-coastal flooding) is only the first step; localized flood analysis based on those selected parameters must then be performed at individual locations across the nation.

For this initial cycle of ASCE 7-28 Chapter 36, the current proposals aim to:

- Where locally adopted, require designers to utilize local future conditions flood maps and hazard data in place of the FEMA flood hazard maps and studies for the computation of flood loads on buildings.
- For coastal flood hazard areas, require the incorporation of future sea level change projections from the [2022 Interagency Task Force on Sea Level Change Report](#) in place of the historical/observed sea level change rates currently adopted by Chapter 5. Sea level projections are localized to the nearest NOAA tidal station or nearest one-degree lat/long grid point, accounting for regional variations in relative sea level change, such as vertical land movement. The current approach adopted by Chapter 5 and the proposed Chapter 36 provisions utilizes a “bathtub” model wherein the projected sea level change value is added to the present-day stillwater elevation.
- Provide commentary to allow users to understand how flooding will change in the future, and provide resources for gathering data and estimating future flooding where data is unavailable.

Nonstationary Analysis

The reliability analyses performed to support the proposed Chapter 36 provisions for sea level change in coastal flood hazard areas utilize a first-order nonstationary process. The mean value of the projected sea level added to the probabilistic stillwater elevation is nonstationary over time. Historic variability of stillwater elevation around the nonstationary mean value is modeled based on the observed historic variability record at the applicable NOAA gauge.

Items That Could Improve the Current Approach

The long-term ambition for future conditions of flood loads in ASCE 7 would be to rely upon a standardized, uniform, and national source for the extents and elevations of future flooding. Such maps would need to present future conditions scenarios aligned with the mandate of Chapter 36 (currently three-degree Celsius warming by the end of the century). However, other potential items that could improve the current proposed approach in the near term may include:

- Simplified methodologies for determining future coastal flood elevations (i.e., stillwater) that estimate the non-linear effects of sea level change instead of the “bathtub”

approach. Such methodologies might utilize an amplification factor or a similar approach.

- Simplified but reasonably accurate methodologies for estimating the extents and elevations of future conditions flood elevations for non-coastal / riverine flood hazard areas.
- Practical methods to allow designers to accurately determine the extents of future flooding scenarios based on local topography.

C.2. Ice Loads for ASCE 7-28 Chapter 36 Future Conditions

Hazard Data Sources

This work integrates multiple datasets to characterize atmospheric icing hazards from freezing rain, both historically and in future climate conditions. Historical data include long-term, hourly observations from U.S. ground weather stations and gridded reanalysis products. These serve as the baseline for model validation. Future projections are based on dynamically downscaled climate simulations from the NA-CORDEX archive, including Regional Climate Models (RCMs) such as WRF and CRCM5. These are driven by multiple CMIP5 Global Climate Models (GFDL, MPI, CanESM2, HadGEM2) and the CMIP6 CanESM5 model. Key variables include near-surface air and dew point temperatures (2 m), surface pressure, 10 m wind speed, precipitation amount and type, and vertical atmospheric temperature profiles. This multi-model, multi-resolution dataset supports robust spatial and temporal representation of freezing rain events across the U.S. and Alaska.

Models/Methods for Future Design Values

Freezing rain is diagnosed using the different precipitation-type algorithms including the Bourgouin method, which evaluates temperature profiles to classify precipitation types. A freezing rain event is defined as a continuous period where freezing rain is detected, ending when surface temperatures exceed 0.6°C. Ice accretion is calculated using two models: the Cold Regions Research and Engineering Laboratory (CRREL) heat-balance model, which accounts for thermodynamic processes, and a simplified conservative model based on wind-blown precipitation. Both models simulate radial ice thickness on a 1-inch diameter horizontal cylinder at 10 m elevation, consistent with ASCE 7 design specifications.

Nonstationary Analysis

Extreme value analysis using the Generalized Pareto Distribution (GPD) is applied to the resulting time series of ice thickness to estimate design loads for selected recurrence intervals (e.g., 250, 500, 1000, and 1400 years), including the effects of concurrent wind-on-ice conditions.

Assumptions and Decisions

The analysis assumes that freezing rain occurs when there is precipitation and it is diagnosed as freezing rain by the precipitation-type algorithm, with surface temperatures at or below freezing. Surface temperature exceeding 0.8°C marks the end of an event, based on assumptions about melt and ice shedding. Ice accretion is modeled on standardized structural geometries (1-inch horizontal cylinder at 10 m height) to match ASCE 7 load definitions

Items That Could Improve the Current Approach

- **Broader Spatial Coverage:** Filling data gaps in mountainous and rural areas currently excluded from ASCE ice maps.
- **Enhanced Observations:** Upgrading surface stations and sensors to improve accuracy in ice-prone conditions.
- **Data Access:** Making processed freezing rain and ice thickness datasets publicly available to support design and standards development.
- **Uncertainty Quantification:** Enhancing the evaluation of statistical uncertainty by incorporating differences in precipitation-type classification between model datasets, gridded reanalysis products, and observational variability.

C.3. Rain Loads for ASCE 7-28 Chapter 36 Future Conditions

Hazard Data Sources

The ASCE 7 Rain Load Standard requires the use of the 15-minute duration, 100-yr recurrence interval (i_R).

Future changes to the rainfall intensity arising from global warming are being estimated from analyses of climate model simulations. The objective of the climate model analyses is to determine global warming adjustment factors (AF) that are applied to values derived from historical observational data. Specifically,

$$i_{R_FC} = AF_{FC} * i_R$$

where

i_{R_FC} = rainfall intensity adjusted for conditions at the 3°C global warming level

i_R = rainfall intensity based on analysis of historical, observed rainfall data.

AF_{FC} = multiplicative adjustment factor for the 15min, 100-yr rain load standard to adjust for 3°C global warming by 2100.

Models/Methods for Future Design Values

The current source for the rainfall intensity (i_R) for most areas of the U.S. is NOAA Atlas-14. It was originally assumed that, by the time ASCE7-28 is released, NOAA Atlas-15 (NA15) would be published and provide all three of the above variables. Thus, i_{R_FC} could be obtained directly from the NA15 website. Earlier this year, NA15, Vol. 2 (which would deliver these three variables) was removed as a deliverable. However, in the past week, that decision was reversed. The impact of this latest change on the delivery of the Rain Loads standard has not yet been addressed by the Future Conditions subcommittee.

The estimation of AF_{FC} is being done using a number of climate model datasets. These include three statistically-downscaled datasets, three dynamically-downscaled datasets, and two global climate model datasets. The three statistically-downscaled datasets (Localized Constructed Analogues, Seasonal Trends and Analysis of Residuals, University of Wisconsin Probabilistic Downscaling) are developed from 13 common global models and consist of daily precipitation at high spatial resolution for the period of 1950-2100 for the continental United States (CONUS). This suite of datasets of large ensemble size provides robust estimates of adjustment factors at the daily resolution, which are used as the foundation. The three dynamically-downscaled datasets are the North American Coordinated Regional Downscaling Experiment (NA-CORDEX), the CONUS404, and the Northern Illinois University (NIU) simulations. All of these cover CONUS. The NA-CORDEX data consist of 7 models simulations at 25 km resolution for the period of 1970-2100. The CONUS404 is a 4 km resolution simulation for the period of 1979-2065. The NIU dataset is a set of 3.75 km resolution simulations for five 15-year time slices. The CONUS404 and NIU simulations are both at convection-permitting resolutions. These dynamically downscaled datasets are used to establish relative relationships between daily duration and 15-minute duration adjustment factors. The global climate model datasets are the National Center for Atmospheric Research Large Ensemble simulations (LENS) and NOAA's Seamless System for Prediction and Earth System Research (SPEAR) model simulations. These global model datasets are being used to estimate adjustment factors for the U.S. regions outside of the coterminous U.S. (oCONUS).

Nonstationary Approach

Research will be completed soon to establish estimates of AF for both CONUS and oCONUS areas of interest. The analyses of all climate model datasets use non-stationary Generalized Extreme Value methods with global warming level used as the non-stationary co-variate in the location and scale parameters of the GEV statistical distribution.

Assumptions and Decisions

Adjustment factor estimates are derived from the GEV parameters for 3°C GWL. For CONUS, the daily AFs, derived from the LOCA2, STAR, and UWPD datasets, are used as the baseline. Adjustment factors are derived from the dynamically downscaled datasets for daily, hourly, and 15-min durations. The change from daily down to the short durations are quantified and used as a relative adjustment to the baseline daily AFs.

Items That Could Improve the Current Approach

- Given the recent rapid developments regarding the NA15, Vol. 2 publication, discussions are ongoing as to the next steps, including whether the hosting of the AF and i_R values by ASCE is desirable.

C.4. Snow Loads for ASCE 7-28 Chapter 36 Future Conditions

Hazard Data Sources

Future projections of snow load rely on hindcast (1950 - 2006) and future projections (2006 - 2100) of snow loads (derived from snow water equivalent) from a variable infiltration capacity (VIC) model forced with Global Climate Model (GCM) outputs of precipitation and temperature from the Coupled Model Intercomparison Project - Phase 5 (CMIP5) for two emissions scenarios (RCP 4.5 and RCP 8.5) that have been downscaled to a 6km resolution.

Models/Methods for Future Design Values

Ground snow loads in Chapter 7 of ASCE 7 are “reliability-targeted,” which means that the specified ground snow loads directly meet the failure targets set forth in Chapter 1 of ASCE 7 for each risk category for a target structure. The target structure used to determine the reliability is a flat roof supported by a single steel beam defined by the limit state:

$$\phi R = 1.2D + 1.0(GI*Gr)$$

where R represents the structural resistance (multiplied by a strength reduction factor ϕ), D represents the dead load, GI represents the ground snow load, and Gr represents the ratio between the annual maximum ground snow load and the annual maximum roof snow load. The variables R, D, GI, and Gr all represent random variables, meaning that their values are determined by probability distributions. ASCE 7 Chapter 7 assumes that GI follows a Generalized Extreme Value (GEV) probability distribution with parameters location (μ), scale (σ), and shape (ξ) that are calculated at more than 7900 locations across the Conterminous United States (CONUS) and Southern Canada.

Nonstationary Analysis

Current snow loads assume that all of these random variables are characterized by stationary probability distributions, which means that the probability distribution parameters remain constant over time (t). However, in a future condition, the distribution of GI is no longer assumed to remain constant, but rather to be a function of t, i.e.,

$$GEV(\mu(t), \sigma(t), \xi)s$$

The parameter ξ is assumed to remain constant over time due to insufficient sample sizes to reliably estimate three time-dependent parameters simultaneously.

The future projection data is used to estimate a time dependent ground snow load GEV distribution at each grid point in the climate map using generalized additive models. This allows for the trends in the probability distribution parameters to be non-linear as informed by the data. Then, a “historical period” (1970 - 2020) and “future period” (2030 - 2080) are set for the time dependent analysis. The historical period was selected to reflect the typical date range for snow loads in Chapter 7 of ASCE 7, which contain data through July 2020. The future period was selected to reflect the 50-year time period in which snow might be the greatest threat for which ASCE 7-2028 might first be feasibly used.

A time dependent snow load simulation is run for these two reference periods with the aforementioned GEV distribution and assuming that all other components of the simulation (D, GI and R) are stationary. This time dependent reliability analysis simulates many 50-year reference periods, with a different set of probability distribution parameters used for each year in the reference period. Only the maximum value is retained from each 50-year reference

period. In locations with declining snowpacks, the maximum values are more likely to come from earlier in the reference period. The opposite would be true in locations with increasing snowpacks (which is very rare) or locations with constant snowpack but increasing variance.

The Risk Category II Reliability-Targeted Ground Snow Load is then calculated for both reference periods in order to determine their ratio. This process is repeated for 31 future projection ensemble members and aggregate change factors for Risk Category II snow loads across regions. Regions will be determined using the Environmental Protection Agency's Level III Ecoregions and change factors will be assumed to remain constant across eco-regions. It will also be assumed that the same change factors can be applied to other risk categories.

Assumptions and Decisions

This approach relies on the assumption that the change factors obtained from the GCM output are consistent even if the raw snow values are biased relative to actual measurements of snow. One issue is that biases in the VIC modeling approach may influence snow accumulations dynamics in non-linear ways which would obscure the results. That said, estimates of accumulated snow are always a secondary variable from GCM output, so alternative future projections of snow would suffer from the same limitation.

Ideas That Could Improve the Current Approach

The reliability-targeted load approach relies on extrapolations of extreme events from statistically-derived probability distributions. This process is already uncertain when using historical data and even more uncertain when using future projections. This is one of the reasons why the future climate factors are prevented from being less than 1.0, which ensures that future construction is at least as safe as current/past construction.

Future work should quantify the diminishing returns that come with downscaled climate data, since site-specific reliability analyses are computationally costly.

C.5. Wind Loads for ASCE 7-28 Chapter 36 Future Conditions

Hazard Data Sources

The current ASCE 7 basic wind speed maps in Chapter 26 incorporate separate analyses of three different storm types: tropical cyclones (e.g., hurricanes), synoptic winds, and thunderstorms (tornadoes are treated separately in Chapter 32). The non-hurricane winds are based on extreme value analysis of observed peak gust data from many anemometer stations across the U.S, which is quality controlled and standardized to equivalent 3-second peak gust values at 10 m height over flat, open terrain. Hurricane winds are developed using a Monte Carlo hurricane simulation model seeded with historical environmental data (see ASCE 7-22 section C26.5.1 for more information).

Wind speed projections that form the basis for the non-hurricane components of future conditions basic wind speeds are drawn from the North American component of the Coordinated Regional Downscaling Experiment (NACORDEX) and Environment and Climate Change Canada (ECCC). These datasets were selected based on the relatively finer temporal

and spatial resolutions compared with other data sources. The future conditions hurricane wind speeds are simulated using environmental data from the National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM), specifically, sea surface temperature, tropopause temperature, meridional winds, and zonal winds.

Models/Methods for Future Design Values

The future projections of non-hurricane wind speeds don't directly provide 3-s gust wind speeds, so hourly mean wind speeds were obtained from the future projections. Gust factors provided in Chapter 26 were used to convert hourly mean wind speeds to 3-s gust wind speeds, which were then used to derive the future conditions basic wind speed change factors for the non-hurricane wind speeds.

The future condition hurricane wind speeds are developed using the same Monte Carlo simulation model used to develop the hurricane wind speeds incorporated in the basic wind speed maps in ASCE 7-22. The hurricane track methodology, developed using historical hurricanes and environmental reanalysis data, reproduces the frequency and geometric characteristics of hurricane tracks as well as the variation of storm size and intensity along the tracks. To define the future condition hurricane wind speeds, the same simulation framework is used where environmental data is instead sourced from climate model output representative of the desired future climate state. where the GMST has increased 3°C above the pre-industrial baseline.

The non-hurricane and hurricane wind speeds are combined using the same procedure as described in ASCE 7-22 Section C26.5. Change factors were derived as ratios of the future conditions basic wind speeds to the ASCE 7-22 basic wind speeds. The future conditions basic wind speeds were the value that associates the target annual exceedance probability and meet the future condition criteria. The future conditions wind speed change factors were applied to the basic wind speeds in Chapter 26 to obtain the future conditions basic wind speeds.

Assumptions and Decisions

For purposes of reliability analysis, a linear trend in future climate effects on peak wind speeds is assumed between now and the future state, which is 3°C global warming level (GWL) around 2080 to 2100.

Nonstationary Approach

An approach known as Minimax has been adopted, which assures that, over an assumed 50-year reference period for reliability analyses, the annual probabilities of failure will not exceed that which has historically been considered acceptable as defined in Chapter 1 and design practices in Chapters 26 through 31. The future conditions non-hurricane basic wind speed change factors are determined using the Minimax approach for each target annual exceedance probability (AEP) between the present condition and when the 3°C GWL is reached by 2080. A nonstationary Gumbel distribution is developed using all available samples from every simulation in the climate model outputs, including both historical and future periods.

Items That Could Improve the Current Approach

- More refined spatial and temporal scale models: The resolution of global climate models is too coarse to explicitly simulate fine scale processes such as the convection that drives thunderstorms.
- Improved methods for thunderstorm wind modeling: Peak gusts from thunderstorms drive most of the extreme wind climate in the US (except for areas where hurricanes dominate), particularly for design of buildings in the higher risk categories (with associated smaller AEPs). Current methods for modeling of future thunderstorm winds are very limited and underrepresent their contribution to the extreme wind climatology.
- Physics-based full scale nonstationary evolving hurricane modeling: hurricanes winds are modeled by separate components and unlike climate models, the “numerical” mechanisms that translate from basic environmental variables to wind field and trajectory are quantified by historical records and reanalysis. This mechanism is assumed maintained the same and static in future conditions. Physics-based full scale climate models are currently incapable for projecting long term large ensemble of basin-wide hurricanes in future conditions.

Appendix D. Workshop Participants

Following is the list of workshop participants including their self-identified organization, listed in alphabetical order.

Ahmed	Abdelaal	SUNY Poly
Meg	Ackerson	Arup
John	Allen	Central Michigan University
Ahmed	Attar	NRC Canada
Michele	Barbato	University of California
Joseph	Barsugli	University of Colorado Boulder, NOAA Affiliate
Fabio	Biondini	Polytechnic of Milan, Italy
Kevin	Borth	HGA
Alex	Cannon	University of British Columbia
Chris	Clavin	NIST
Jan	Dale	RWDI
Shideh	Dashti	University of Colorado Boulder
Naresh	Devineni	The City College of New York/City University
Keith	Dixon	NOAA Geophysical Fluid Dynamics Laboratory
Bruce	Ellingwood	Colorado State University
Graziano	Fiorillo	University of Manitoba
David	Frost	Georgia Institute of Technology
Maria	Garlock	Princeton University
Michel	Ghosn	CUNY
Matt	Gilbertson	Simpson Gumpertz & Heger
Elisabeth	Gilmore	Carleton University
Jennifer	Goupil	ASCE/SEI
Ruohua	Guo	
Amin	Hariri	NIST
Jennifer	Helgeson	NIST
Han-Ping	Hong	University of Western Ontario
Mohammad	Houshmand	NIST
Scott	Jones	NIST
Ken	Kunkel	NOAA/NCSU
Debbie	Lee	
Marc	Levitan	NIST
Sihan	Li	RWDI
Abbie	Liel	University of Colorado Boulder

Ning	Lin	Princeton University
Roy	Lobo	HCAI
Zoubir	Lounis	NRC Canada
Jessica	Mandrick	GMS
Kris	May	Pathways Climate Institute
Therese	McAllister	NIST
Amanda	McCarty	NOAA
Aron	Newman	NIST
Jayantha	Obeysekera	FIU
Brian	Pailes	Simpson Gumpertz & Heger
Julie	Pietzrak	Thornton Tomasetti
Francisco	Presuel-Moreno	Florida Atlantic University, Dir SeaTech
Sara	Pryor	Cornell University
Adam	Reeder	CDM Smith
David	Roegner	University of Illinois Urbana-Champaign
Erin	Rooney	HDR Inc
Siamak	Sattar	NIST
Don	Scott	Consultant
Gus	Sirakis	NYC Department of Buildings
Ken	Snyder	NIST
Katie	Stueckle	ASCE/SEI
Billy	Sweet	NOAA
Jeff	Trapp	University of Illinois Urbana-Champaign
Mari	Tye	Johns Hopkins University
Peter	Vickery	ARA
Dan	Walker	University of Maryland
Yating	Zhang	NIST
Ted	Zoli	HNTB
Erik	Zuker	HNTB