NIST Grant Contractor Report
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Forward-Looking Codes and Standards

Final Report
March 31, 2026

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Abstract

Forward Looking Codes and Standards: Final Report includes a summary and synthesis from the four workshop reports: *Future Hazards*, *Future Load Effects*, *Design Guidelines and Criteria*, and *Adaptation and Resilience*. The final report includes a summary state of the art discussion and a thorough synthesis of next generation codes and standards including Future Hazard Data and Information; Future Loads, Load Effect and Infrastructure Conditions; Design Guidelines, Criteria, and Tools; Resilience and Adaptation; Planning and Design Frameworks; and Codes and Standards. Conclusions and research recommendations are integrated.

Keywords

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

Contents

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* based on contributions by scientists, natural hazard experts, structural engineers and design professionals, and standard and code development experts.

The following were the themes of the four workshops:

1. **Future hazards for design:** Confidence and 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 that anticipate future hazards, material durability and structural capacity degradation, resilience and recovery of key functions, and strategic planning methods for evolving hazards and conditions.

The impetus for the project is 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 discussion and recommendations synthesizing the collective input from the workshops to identify current needs and next-generation research needs in codes, standards, and engineering design practice. The research topics were divided into groups with the following six themes, which the report discusses in detail: Future Hazard Data and Information; Future Loads, Load Effects, and Infrastructure Conditions; Design Guidelines, Criteria, and Tools; Resilience and Adaptation; Planning and Design Frameworks; and Codes and Standards.

SEI is indebted to the leadership of Jayantha “Obey” Obeysekera, Ph.D., P.E., 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 four workshops. Refer to the individual workshop reports included in the references for additional details about each event and its participants (Obeysekera et al. 2026a, b, c, d). 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 Manager and drafted and edited the final report.

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Managing Director, Structural Engineering Institute and
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1. Project 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 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 the Disaster and Failure Studies Program and the 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.

The first workshop *Forward-Looking Codes and Standards: Future Hazards*, was held on June 4–5, 2025 (Obeysekera et al. 2026a). The second workshop *Forward-Looking Codes and Standards: Future Load Effects* was held on July 29–30, 2025 (Obeysekera et al. 2026b). The third workshop *Forward-Looking Codes and Standards: Engineering Design Guidelines and Criteria* was held on September 25–26, 2025 (Obeysekera et al. 2026c). The fourth workshop *Forward-Looking Codes and Standards: Adaptation and Resilience* was held on October 29–30, 2025 (Obeysekera et al. 2026d).

1.1.1. 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 communities in the United States.

The workshops focused on the research and development efforts needed to advance codes and standards. Specifically, the workshop sought to elicit 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 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.

For the purposes of the entire project and this report, the following terms are explained:

Hazard: A hazard in structural engineering is an external event due to natural or anthropogenic causes that can impose demands on engineering components or systems but exists independently of a structure. In particular, a climate hazard refers to the subset of environmental hazards that result from weather, climatic, and hydrologic phenomena with an emphasis on future conditions.
Load: A physical action applied to the structure that is caused by hazards, such as wind pressures; hydrostatic and hydrodynamic pressures; and the weight of rain, ice, or snow.
Load effects: Structural responses to the loads applied, such as axial forces, bending moments, stresses and strains, drift, and deflections.
Adaptation for Infrastructure: Adjustment of planning, design, construction, operation, management, maintenance, and retrofitting and recovery? to reduce occurrence and effects of damage from current and future hazards for existing and new structural systems.
Infrastructure Resilience: The ability of infrastructure systems to withstand and recover from hazards while minimizing the loss of functionality.

1.1.2. Report Organization

This report is organized to reflect the interconnected components required to move toward forward-looking codes and standards. Drawing on insights from the four workshops, Section 2.2 summarizes the current state of practice, while Section 2.3 outlines a coordinated vision for next-generation codes, standards, and future practice across six key themes: Future Hazard Data and Information; Future Loads, Load Effects, and Infrastructure Conditions; Design Guidelines, Criteria, and Tools; Resilience and Adaptation; Planning and Design Frameworks; and Codes and Standards.

Sections 3.1 through 3.6 describe each theme and detail the overview of findings, list the major research needs, identify necessary enabling activities and research dependencies or enabling efforts, discuss the gaps or further study needed, and summarize how the theme is necessary to advance the next generation of codes and standards. Together, these sections present a systems-level perspective that connects evolving climate science and hazard modeling with evolving engineering practice toward next-generation codes and standards to address nonstationary hazards and infrastructure performance under future conditions.

Section 4 includes Conclusions and Recommendations, which is followed by Sections 5 and 6 with Acronyms and Abbreviations and References. The appendices include research needs organized according to the six themes of Section 3.

1.2. Current State of the Art

One of the stated goals of the workshop series is to understand and build on existing knowledge and work. The workshop series presented current thinking, activities, and research to establish a baseline, consensus understanding of the state of the art so that participants could envision and articulate research needed to develop the next generation of codes and standards (see Section 2.3).

To establish this baseline understanding, both for the benefit of the participants and to document collective knowledge, several highly knowledgeable professionals were invited to attend each workshop and deliver presentations that would articulate the many facets of the current state of the art and practice for processes, fundamentals, and development aspects of design codes and standards for infrastructure. This section summarizes and synthesizes the common understanding of the current state of the art.

1.2.1. Summary

This section summarizes the presentations and discussions from each separate workshop to present a well-rounded current state of the art and practice. For more details on each workshop, see the individual workshop reports included in Section 6 (Obeysekera et al. 2026a, b, c, d).

Future Hazards. Scientific analysis of climate, weather, and hydrological hazards has been ongoing for decades and has yielded a deep understanding of present-day hazards and data to help reduce consequences of natural hazards. However, the focus on developing and applying forward-looking hazard data for the design of civil infrastructure is more recent. The first workshop, on Future Hazards, identified ongoing synergistic efforts of environmental hazard data development and the challenges facing practitioners.

SEI of ASCE is working toward developing a new chapter in the nationally adopted structural engineering loading standard, ASCE/SEI 7-22, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures,* to provide provisions for future conditions of environmental design loads for wind, snow, ice, rain, and floods. Additionally, federal agencies working with standards development organizations such as ASCE are evaluating how to develop and deliver environmental hazard data to stakeholders in formats and timelines to be consumed directly in standard and code development processes.

The Memorandum of Understanding between ASCE and the National Oceanic and Atmospheric Administration (NOAA) established a formal collaboration framework to consider and provide fit-for-purpose NOAA data and products that can be implemented into engineering processes, design approaches, and documents. The *Climate Risk Reduction: Hazards and Processes for Operationalizing Climate Information into ASCE Standards and Manuals of Practice* (Barsugli 2025) report summarizes efforts by the ASCE-NOAA partnership to understand the evolving needs of civil engineers for climate, weather, and other Earth system data to support engineering standards and the broader engineering practice. The report examines the status of understanding for temperature extremes, heavy precipitation, compound flooding, Earth materials, snow, and wind extremes, specifically addressing the future hazard data needs for many ASCE standards.

ASCE supports many committees and committee efforts to advance the understanding of impacts of the changing climate on civil infrastructure performance. Two committees in particular—the ASCE Committee on Adaptation to a Changing Climate and the ASCE/SEI Effects of Climate Change on Life-Cycle Performance of Structures and Infrastructure Systems special project task committee—provide durable efforts to educate the profession and practice with reports, manuals of practice, and other technical resources.

The workshop also presented challenges design professionals, owners, and other stakeholders face in understanding and using these data and knowledge for projects being built today. Specific challenges presented by practitioners include evaluation and use of environmental hazard data and future design conditions absent consensus documents, conflicting expectations for project performance and standard of care, and realization of design team needs to extend beyond the traditional team approach.

Future Load Effects. The second workshop was the first of its kind to draw attention to the load effects for design of infrastructure and structural capacity that future environmental hazards will impact. In a similar approach to the first workshop, this one also started with a review of current practice and assumptions, focusing on the current development of how national and international design standards and codes include load effects and how the capacity of the structure is approached in design, especially the assumption of stationarity. A deep discussion of current development approaches for American and Canadian national standards to treat load effects derived from environmental hazards yielded a common understanding of how these regulatory documents evolved and how they will change in upcoming editions. While the development cycle for the 2028 edition of the U.S. loading standard ASCE/SEI 7 is still underway, the current edition of the National Building Code of Canada (NBC 2025) includes forward-looking provisions for some environmental hazards by defining load effects to be used for design. Detailed work and explanations of what changes were included and how the load effects were addressed within the Canadian Code provided a solid basis for comparison and contrast of the efforts underway in the United States. The ASCE/SEI standards development efforts for ASCE 7-28 are in mid-stream; however, a robust discussion about the approaches to development of the forward-looking provisions for flood, wind, snow, rain, and ice clarified how the evolution was happening within the design standards, comparing both to former editions and the newly developed Canadian approaches.

Structural capacity, the stated or implicit assumptions in how current codes and standards treat it, and the provisions governing design approaches spotlighted the need to include both the load and the resistance sides of the equation in the discussion and ultimate development of forward-looking design standards and codes. A one-sided approach that considers only hazards will not serve the intent for structural reliability in the future. Recognizing and understanding how the assumptions of stationarity and service life are inextricably linked and must be considered jointly is important. Developing a base understanding of structural performance of exposed structures such as bridges and parking garages and of the effects of groundwater changes on foundations provides critical insights into how the design assumptions need to change and be addressed as codes and standards evolve to consider the impacts of changing environmental hazards.

Engineering Design Guidelines and Criteria. To identify and prioritize needs for next-generation design guidelines, the third workshop started with an examination of the current state of practice with a focus on the gaps—areas that are not currently defined or lie outside of the current provisions of design standards and codes—and the basis for decision-making absent appropriate design guidelines. Beginning with structural capacity and design at the component level, discussions of modeling assumptions coupled with practitioner design decision-making regarding uncertainty and degradation provided a base understanding of how the current prescriptive approach is limiting for many designs. The current state-of-the-art discussion highlighted that changes in the design assumptions—inclusive of but not limited to changes in environmental hazard conditions—frequently affect the structural performance of component design.

Building on this background, the discussion expanded to explore decision science with a spotlight on design scenarios considering deep uncertainty. Specific case studies of civil infrastructure design grounded the discussions. This discussion of system-wide structural performance provided a common framework from which to evaluate next-generation processes and development of design guidelines that do not exist in current practice.

Finally, real-world case studies of decision-making to establish project-specific design guidelines or jurisdiction-wide code provisions illustrate how this work is being accomplished currently and further identify the gaps that need to be overcome and the future outcomes desired. Use cases falling outside of traditional provisions provide unique visibility into the needs to develop next-generation codes and standards for single projects, such as high-speed rail, and for jurisdictions, such as New York City.

Adaptation and Resilience. The final workshop focused on the use of codes and standards as next-generation tools for bolstering the use of adaptive design to deliver resilient infrastructure. To establish a common framework and the current state of the art for adaptation and resilience in modern design standards and codes, discussions included ongoing efforts in community resilience, robust decision-making and scaling, barriers for design, and policy implications. Case studies illustrated how current practice can incorporate adaptation and resilience into single-asset projects, city-wide asset assessments, or jurisdiction-wide plans, and clarified how robust decision-making approaches differ for community versus asset-based projects. Adaptation and resilience are broad topics, reaching far into many aspects of civil infrastructure. Given this, the discussions focused on the built environment and omitted the use and discussion of nature-based solutions. While nature-based solutions are important and extremely additive, the discussion was purposefully scoped to reflect the development and regulatory environment based on codes and standards for buildings and other structures.

The discussion of community resilience, what this means and how to achieve it, defined the parameters of how to imagine next-generation codes and standards. Revisiting the system-of-systems approaches identified in a previous workshop enabled a more specific discussion about decision scaling, barriers, and robust decision-making that provided a shared foundation and understanding of how traditional approaches of “predict then act” will no longer serve the needs of the next generation of codes and standards for design of civil infrastructure. Illustrations of alternative approaches and novel methodologies demonstrated how to flip the approach to decision-making to a much more iterative process, such as “agree on decision points,” to account for uncertainty. Case study discussions of policy successes and synergistic efforts to develop design and policy concurrently rounded out the current state of the art and practice around adaptation and resilience, offering new ways of approaching design decisions.

Case studies of projects that have been designed and built informed decisions by the participants on state-of-the-practice solutions for adaptation and resilience. Solutions embraced approaches of “most plausible” future designs using robust decision-making and dynamic adaptive policy pathways in lieu of “most likely” future designs of traditional “predict then act” methodologies. Individual project-specific solutions for a bus facility in Boston, city-wide solutions for transit development zones and sea-level-change mitigation designs in Honolulu, and existing building seismic-hazard-mitigation efforts in Salt Lake City provided robust solutions built with adaptive design for resilience outcomes for each community.

1.2.2. Synthesis

The clearly stated goal of building on ongoing and synergistic efforts was purposefully leveraged to articulate and define the current state of the art and of practice. This was done strategically in all four workshops to provide a common baseline of understanding and agreement on the current state of the art so that the next generation of codes and standards could be imagined.

A critical topic to understand about current practice is the distinction between prescriptive and performance-based standards and design. Most current design standards are prescriptive in format and define minimum requirements, primarily for collapse prevention and life safety. Prescriptive requirements are specific and detailed, providing exact methodologies for many aspects of design for typical projects. However, prescriptive requirements inherently cannot address many site-specific or project-specific needs. By contrast, performance-based design (PBD) standards and approaches specify the performance objectives for the design and accompanying metrics on acceptance criteria required to demonstrate compliance with those defined objectives. Performance-based procedures identify the source of loss or disruption and seek to reduce undesirable outcomes through value-based design decisions informed by design objectives. While some frameworks exist to implement performance-based design, such as for seismic (FEMA P-58), wind (ASCE 2023), and structural fire (ASCE 2022), by nature the process is flexible, offering designers and project partners latitude to develop innovative solutions to address challenges involved in specific projects at individual sites. This advanced, analysis-driven approach relies on designers' expertise and judgment, demanding more from them compared with satisfying prescriptive code minimums. Performance-based procedures are often viewed as a leading strategy for the next generation of designs seeking to include additional performance objectives beyond life safety.

Synthesizing the foundational knowledge from the collective discussions, the current state of the art and of practice is described as follows:

> Codes and standards used for the design of civil infrastructure are developed, used, and required separately by asset types, primarily on a project-by-project basis. Current design standards and codes are primarily prescriptive and rely on historical environmental hazard measurements, which assume that the underlying processes are stationary when extrapolating load effects for a single hazard at a time. While the codes account for the uncertainties in estimating hazard and structural capacity, assumptions of stationarity for both hazard and structural capacity are shared when design equations and criteria are calibrated to ensure structural component reliability. Current code and design standard development approaches embrace traditional "most likely future" approaches that then employ "predict then act" methods. While a few evolutional approaches to adaptive and resilient design can be found, those designs are still limited to discrete hazards and to specific asset types or to specific hazard-asset pairs.

1.3. Next-Generation Codes and Standards, Methods, and Design Tools

The primary goal of this project is identifying the research necessary to develop forward-looking codes and standards based on consistent and credible information under future conditions. For workshop participants to be able to identify such needs, a common understanding of what is meant by "next-generation codes and standards"—including what is incorporated, how they will be developed, used, and required—had to be established.

To create this collective description, highly knowledgeable professionals invited to the workshops were charged with answering the primary question: What do you wish you had? They were invited to imagine themselves, or their successors, about 10 years in the future and to articulate the ideal state of next-generation codes and standards needed for design of civil infrastructure. This section summarizes and synthesizes the collectively developed desired future state for next-generation codes and standards.

1.3.1. Summary

This section summarizes the plenary discussions and a distilled 10-year vision from each separate workshop to present a balanced description of next-generation codes and standards. For more details on each workshop, see the individual workshop reports in Section 6 (Obeysekera et al. 2026a, b, c, d).

Future Hazards. The workshop participants envision a future in which engineers and climate scientists will work in close partnership to co-produce data, tools, and guidelines that are scientifically robust and usable. This vision includes the following:

- Climate hazard data that will be seamlessly integrated into engineering workflows, with clear national consensus on which datasets are most appropriate for different design contexts and how they should be applied.
- Downscaling techniques for climate data that will be applied with discernment, guided by rigorous scientific assessments that clarify when and how local-scale projections are credible and fit for purpose. The limitations of downscaling models, whether statistical or dynamic, will be acknowledged openly, without paralyzing progress.
- Engineers and design professionals with access to scalable, transparent, and well-documented resources that account for nonstationary conditions and multiple future scenarios and address a fuller range of uncertainty—empowering them to design resilient infrastructure that anticipates future hazards.
- Project teams equipped with practical guidelines to evaluate future hazard datasets, understand their appropriate applications, and navigate associated uncertainty with confidence.

Future Load Effects. The workshop participants envision future design tools, methods, data, and standards in which nonstationary load effects and capacity are considered together. This vision includes the following:

- Load effects that incorporate nonstationary and compounding and cascading effects and long-term structural degradation;
- Design approaches that include time-varying loads and structural capacity and shift toward structural performance objectives and design acceptance criteria;
- Engineers and design professionals 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 with 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 new and existing projects.

Engineering Design Guidelines and Criteria. The workshop participants envisioned future design tools, methods, data, and standards in which design guidelines are available for every asset type and interdependent system and provide robust outcomes through flexible applications. This vision includes the following:

- Structural capacity acceptance criteria data, methods, and models that allow projects to be evaluated for nonstationary hazards and degradation effects;
- Adaptive, flexible design guidelines that link climate uncertainty, environmental hazard data, load effects, structural capacity, design, risk management, and community resilience goals;
- Engineers and design professionals with access to flexible design approaches outlined in guidelines, design standards, and codes to satisfy project needs; and
- Project teams empowered to meet project performance objectives by achieving consensus-based acceptance criteria in a manner that accommodates new information within a flexible process.

Adaptation and Resilience. The workshop participants envisioned a future design and regulatory environment in which adaptation and resilience are at the forefront of civil infrastructure design and funding and financing requirements have the full support of infrastructure decision-makers. This vision includes

- Next-generation guidelines, standards, and codes that will provide flexible pathways for adaptive design and compatible policy thresholds that enable resilient infrastructure outcomes for communities;
- Regulations and requirements that local governments and decision-makers can employ with consistent funding and alignment of short-term priorities with long-term goals;
- Engineers and design professionals equipped with the consensus, flexible design guidelines needed to consider broad, system-wide, adaptable approaches to resilient infrastructure design; and
- Project teams that can systematically and fully engage stakeholders, including the community, in the adaptation design strategy for ensured long-term infrastructure resilience success.

1.3.2. Synthesis

Every workshop included a plenary session discussion among the participants to articulate and document the vision for next-generation codes and standards. This collective vision served as the backdrop for the breakout discussions to identify the research needed to advance codes and standards from the current state of the art toward the 10-year vision.

Synthesizing the declared 10-year vision for next-generation codes and standards from the collective discussions is described as follows:

> Codes and standards for design are developed, used, and required holistically, considering the systems of civil infrastructure, influenced by but not focused on a single project or asset success. Next-generation design standards and codes rely on forward-

looking environmental hazard projections that incorporate nonstationary methodologies for extrapolating load effects for multiple or cascading hazards. Uncertainty and nonstationarity are addressed uniquely for both hazard and structural capacity to meet short- and long-term demands and are calibrated for system structural reliability. Next-generation code and design standard development embraces approaches of "multiple plausible futures" designs using methods that include but are not limited to robust decision-making under uncertainty and dynamic adaptive policy pathways, which strengthen the durability of design decisions across a range of scenarios and preserve the ability to adapt as hazards and conditions evolve. Engineers and design professionals are equipped with the knowledge, education, and design guidelines needed to consider broad, system-wide, adaptable approaches to resilient infrastructure design. Project teams are able to systematically and fully engage stakeholders, including the community, in the adaptation design strategy for ensured long-term infrastructure resilience success.

2. Next Generation of Codes and Standards

Based on the current state of the art and next-generation discussions, the priority research needs determined by participants during the *Forward-Looking Codes and Standards* workshop series are identified and organized into the following six themes for deeper consideration: Future Hazard Data and Information; Future Loads, Load Effects, and Infrastructure Conditions; Design Guidelines, Criteria, and Tools; Resilience and Adaptation; Planning and Design Frameworks; Codes and Standards (Figure 3-1).

Within each theme, the research needs are explained using the same format to provide context relative to each theme and external to this project. Each theme section is organized to include the following: Overview of Findings; Identification of Major Research Needs; Identification of Enabling Activities and Research Dependencies; Discussion of Gaps and Further Study; and a Summary.

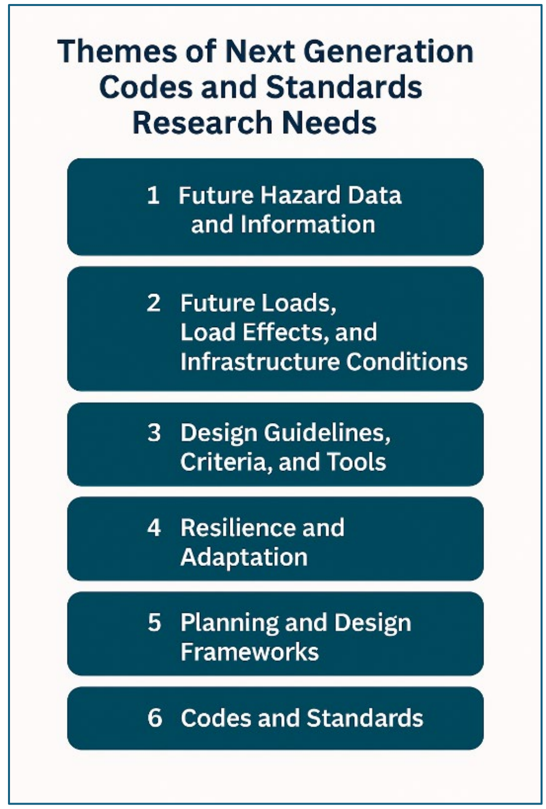

Figure 3-1. The research needs are organized into six themes.

2.1. Future Hazard Data and Information

This section summarizes research needs regarding the development of fit-for-purpose and future-ready climate hazard data that are scientifically robust and directly usable in engineering and planning decisions.

The current state of climate science as it applies to civil engineering is well summarized in many resources including in ASCE reports (2018, 2021, 2024). Previous efforts used expert elicitation to identify specific climate hazard data needs to update current ASCE standards and manuals of practice for a nonstationary climate (e.g., ASCE-NOAA 2023, 2024). In addition, several projects are in progress that address these needs (e.g., NOAA's Atlas 15 (NOAA 2026) for present and future extreme precipitation frequency). This section focuses on research needs for the next 10 years as identified during this series of workshops and through subsequent effort by the steering committee to put these needs into the larger contexts of climate science and engineering practice.

2.1.1. Overview of Findings

The need for improved data, methods, and knowledge about future climate hazards was a recurrent theme across the four workshops. Climate data will play a critical role in many facets of engineering design, from quantification of future extreme hazards that inform prescriptive standards to addressing nonstationary reliability analysis, predicting materials and structural degradation, informing performance-based design, modeling resilience, planning functional recovery, and developing adaptive design methods.

An overarching finding of the workshops is that gap remains between what civil engineers need and what the climate-modeling community provides when it comes to characterizing future climate hazards. Significant challenges arise because of the need to shift from a largely observational basis to increased reliance on projected data derived from climate models to estimate future hazards. These challenges include the need for engineering-specific validation of model results; translation of climate model output to fit-for-purpose, engineering-relevant spatial and temporal scales; and the addition of new sources of uncertainty.

2.1.2. Identification of Major Research Needs

Up-to-Date, Scientifically Credible and Fit-for-Purpose, Nationwide Hazard Data

Throughout the workshop, participants expressed a strong desire for national-scale up-to-date, scientifically credible and fit-for-purpose data on present and future climatic hazards. To be more useful, several requirements were consistently mentioned, including the following:

- The hazard data should be aligned with its treatment in engineering standards in terms of variables, spatial and temporal resolution, statistical treatment, and other attributes to streamline its adoption into engineering applications through a standardized process.
- The data should be regularly updated to reflect the observed trends and advances in climate science.
- The projections used for quantifying the hazard level should be treated consistently across multiple hazards to reflect physically consistent future scenarios.

The determination of data suitability depends on context and audience. Climate data referenced in an engineering standard derives appropriateness from the standards processes in which the data are evaluated for technical credibility and fitness-of-purpose using consensus-based standards development processes. Standards committees, and engineers performing analyses beyond those required in standards, rely on many sources of climate (and other hazard) data, model projections, and analysis methods. Scientific appropriateness of these elements is paramount and relies on peer-reviewed publication, expert review, the use of well-established and well-documented methods, reproducibility, and traceability. Nonetheless, determining whether a model-derived projection is fit for a particular engineering purpose requires considerable expert judgment; a step that workshop participants noted is often lacking. Workshop participants consistently noted the need for better information and procedures to navigate the technical issues and the uncertainty landscape.

Participants suggested the following as priority research needs in this area:

- **Development of nationwide open-source services for hazard data** and maps for present-day and future conditions to specifically support the use of these data in the implementation of standards. Implementation will benefit from the development of requirements for specific variables, spatial and temporal scales, data formats, and other attributes, along with sufficient metadata to ensure transparency and traceability.
- **Needs for a data service** include easy access to relevant model output and corresponding validation results, descriptions of the physical meaning of modeled variables (e.g., how modeled quantities may differ from their observational counterparts), and a clear characterization of uncertainty.
- **Validation of model-derived hazard data** for specific engineering uses, including for use by standards committees.
- **Regular updating of key hazard datasets** that reflect future conditions. Recognizing that this is not always possible, the **development and validation of interim tools** for datasets that are not updated in time for the standards update cycle until full datasets are refreshed.
- **Development of a database of concurrent and compounding hazards** for improved calculation of load combinations and to anticipate probability of future occurrence of compound and cascading hazards.

Research Needs for Specific Hazards

The individual workshop reports detail many specific needs by hazard, including the following:

- **Improve data and modeling for multiple flooding mechanisms**, including riverine, coastal, stormwater, groundwater, and compound flooding, with the aim of creating national maps of flood hazard under future scenarios;
- **Improve observations and modeling of freezing rain, rime icing, and hail** for determining ice loads on structures and power lines and effects on the building envelope, including through higher vertical and horizontal resolution models;
- **Improve characterization of sub-daily rainfall extremes**, including through convective resolving models and process understanding;
- **Advance hydrological modeling to account for interactions among riverine, coastal, and groundwater flood responses**, with engineering-relevant outputs such as discharge rate, flood depths, flood velocities, storm surge, and wave action;
- **Project snow accumulation metrics at fine spatial scales,** including annual maximum accumulation, snow events duration, intermittency, density, and wind speed when snowing used for quantifying snow drift;

- **Advance understanding and estimates of future thunderstorm and tornado extreme winds** through convective-scale permitting modeling;
- **Characterize temperature-related hazards for specific engineering applications**, including changes in frost penetration depth, frequency and duration of freeze-thaw temperature cycling, thawing of permafrost, and snow and ice melting or redistribution;
- **Develop data and projections for hazards that affect the building envelope,** including wind-driven rain, hail, wind-blown snow, and temperature extremes;
- **Provide projections of subsurface data for foundation design,** including future groundwater levels, groundwater chemical composition, seawater intrusion, soil temperature and water content, erosion, and settling; and
- **Consider the indirect effects of changing climate** on seismic loads due to changes in soil properties and on tsunami effects due to changing coastal water levels.

High-Resolution Climate Modeling/Earth System Modeling

The workshops identified several aspects of physics-based global and regional climate modeling that do not currently meet the needs of engineering applications focusing on the prospect of convection-permitting numerical models to give greater insight into heavy rainfall extremes and convective-scale wind extremes:

- Develop and analyze a suite of multidecadal regional and/or global climate model simulations at convection-permitting spatial resolution (4 km or finer; high vertical resolution) with output variables relevant to engineering standards, including rainfall and frozen precipitation, stored at temporal and spatial resolutions appropriate for the design of projects;
- Perform and analyze multiple high-resolution (km-scale) simulations for historical and future severe convective storms, bounded by observations, to improve process understanding and reduce or better quantify uncertainty; and
- Support co-production between the engineering and climate-modeling communities through participation of engineers in the design of model experiments, specification of output variables, and the analysis of model outputs.

Consideration of Uncertainty

Participants see the difficulty of choosing data and methods for future conditions in the face of emissions and model uncertainty as a key barrier to the use of future hazard projections. Two commonly used frameworks are the scenario/time-period approach and the Global Warming Level (GWL) approach:

- Develop efficient methods and procedures to identify fit-for-purpose, site-specific hazard data, including the choice of models and scenarios.
- Evaluate the implications of different treatments of model and emissions uncertainty to determine future design hazard levels, including the implications for nonstationary

reliability analysis and for engineering risk assessment over (and beyond) the nominal service life of a project.
- Evaluate the implications of different GWL assumptions for engineering applications, particularly for characterizing nonstationary behavior in extreme value statistical applications. This is particularly critical for hazards that are cumulative or for those that have a nonlinear or nonmonotonic behavior with time and/or GWL.
- Incorporate recent developments in statistical methods for extreme value analysis and spatial statistics into hazard estimation for engineering standards, including improved spatial modeling and copula methods and other multivariate statistical methods for extremes.
- Develop machine learning methods to fill gaps in uncertainty (for example using model emulators) and improve downscaling and the treatment of observed data.

Translation of Climate Model Output to Engineering-Scale Hazard Data

Many environmental hazards are not well-represented in climate models due to their small spatial scale, including tornado winds, short-duration heavy precipitation, freezing rain, and many flooding mechanisms. In addition, systematic bias in regional and local model-based projections compared with observational estimates was discussed as a critical challenge. Empirical or physics-based models are often used to translate climate model scales to fine-scale hazards.
- Develop methods for improved tornado and convective-scale wind modeling to enhance understanding of changes in regional occurrence of these extremes;
- Develop improved methods to combine observational data and models focusing on the extreme tails of the probability distribution; and
- Identify minimum requirements for spatial and temporal resolution of hazards (by type), the length (past and future) of datasets needed to accurately estimate extremes, and the need for continuous time-series versus “time-slice” estimates of hazards.

Climate Data Needs for Advanced and Emerging Engineering Design Frameworks

Climate data needs go beyond understanding for loads and load effects, described as follows:
- **Provide future hazard scenarios to support engineering design under deep uncertainty and adaptive design frameworks (see Section 3.5).** Elements of this research theme include the characterization of deep climatic hazard uncertainty that aligns with engineering risk assessment methods, the development and provision of multiple future scenarios for adaptive pathway design, improved understanding and characterization of multihazard interactions, and the provision of climatic indicators to inform adaptation triggers.
- **Provide projections of future environmental stressors related to materials and structural degradation (see Section 3.2)**, including projected air temperature and

atmospheric humidity, soil characteristics, temperature differentials such as freeze-thaw cycles, the chemical composition of the air (e.g., carbon dioxide (CO2) concentration), precipitation (e.g., pH) and runoff, and chloride ion deposition rates from sea salt and the weather-related use of deicing chemicals.

- **Provide projections of serviceability design level events** (**see Sections 3.2 and 3.4**) that lead to fatigue and cumulative damage and motion and comfort considerations.
- **Provide climate data to support performance-based design methods and frameworks (see Sections 3.3 and 3.6) for future conditions and other data-intensive methods,** including life-cycle analysis, community resilience modeling, and functional recovery modeling. These methods typically have more complex data needs than single-hazard estimation and often require time-series of multiple, synchronous climate variables.

2.1.3. Identification of Enabling Activities and Research Dependencies

The climate hazard research component provides foundational information to support the other components of the scaffolding and as such depends on understanding the use cases and requirements in each of these areas. The research needs discussed here depend strongly on knowledge and products from the larger Earth system science research community, including climate, weather, hydrology, and oceanographic sciences.

Research Needs Identified for Future Hazards that Will Benefit from the Following Efforts of the Larger Earth System Science Research Communities

- The continued production of ensembles of climate model projections, including future phases of the Coupled Model Intercomparison Project (CMIP) and coordinated downscaling projects, is critical.
- The continuation of successful agency and multiagency efforts on specific climate hazards, including those for sea-level change (Sweet et al. 2022) and precipitation frequency (NOAA Atlas 15) is critical.
- Improving projections of heavy rainfall will benefit from the current effort to modernize the estimation of probable maximum precipitation (NASEM 2025) through its production of convection-permitting climate model ensembles.
- Future hazard data rely on the continued production of national-scale downscaled climate model output datasets.
- Constraining the uncertainty of future climate scenarios relies on recent advances in the monitoring of global climate drivers (e.g., IEA 2025; UNEP 2025).

Co-development between engineering and climate science communities is critical for success. Such co-development may range from providing input on engineering data needs and engineering-relevant validation metrics to bodies such as CMIP, collaborating on the analysis of model results, and developing modeling protocols.

Areas that Would Benefit from Research on Future Hazards

Improved climate hazard data and understanding and the development of fit-for-purpose datasets would support the development of forward-looking codes and standards in the following ways:

- Practicing engineers would benefit from the availability of fit-for-purpose design level hazard data that can be directly used in calculations specified in codes and standards.
- Improved climatic hazard projection data will facilitate the transition of current codes and standards to treat future, nonstationary hazards.
- Provision of data for emerging climate hazards and data to meet the needs of advanced engineering methods will facilitate the incorporation of new and emerging hazards into codes and standards.

2.1.4. Discussion of Gaps and Further Study

Discussions in workshop groups raised important issues and research topics that were not highlighted in the final list of research topics and yet are considered essential for developing approaches for supporting resilient engineering design. These topics include the following:

- **Advanced sensor technology** for fine-scale temporal and spatial measurements of winds, freezing rain, and other hazards including wildfire. Such data would aid in validation of model-based estimates and the translation of large-scale model output to engineering-scale hazards.
- **Development of an engineering framework for considering compounding and cascading hazards** and the data needed to support such an analysis. While treatment of combined loads such as compound flooding are advancing, new consequences may nonetheless arise in the future from compounding and cascading hazards.
- Extension and **coordination of hazard characterization across other branches and subfields of engineering** to ensure overall consistency of future designs.
- **Wildfire** was discussed as an emerging hazard that will likely have increasing impacts on structures and communities. The data needs to characterize wildfire hazard on multidecadal time scales are complex, but the topic was nonetheless seen as an important, though challenging, area of research.
- **Machine learning (ML) and artificial intelligence (AI) models** are rapidly proliferating in climate science. Their use currently includes ML climate model emulators that can be used to generate extremely large ensembles of model runs to more thoroughly explore uncertainty and ML algorithms to downscale and bias correct models. AI weather models are already competitive with traditional models for a 10-day weather forecast, and fully AI climate models are in development. These trends must be monitored and the models evaluated with respect to the tails of the probability distributions.

2.1.5. Summary

Hazards are changing and will continue to change in the future. In many cases these hazards are increasing in frequency and intensity and could lead to increasing likelihood of structural failure, reduction in reliability below assumed levels, reduced serviceability, and enhanced structural degradation.

Continued coordination and collaboration between the engineering community and the climate, weather, and hydrological modeling communities will facilitate these advancements while avoiding needless duplication of effort. Significant areas for collaboration identified in the workshops include development of climate and Earth System Modeling (ESM) capabilities, including emerging AI/ML models; the design of climate model experiments and protocols to better support engineering applications; analysis of convection-permitting model simulations; improvement of post-processing, downscaling, and empirical/statistical modeling capability for hazards that are not well-represented at ESM scales; and the communication and characterization of uncertainty to facilitate engineering hazard estimation and risk assessment.

2.2. Future Loads, Load Effects, and Infrastructure Conditions

This section discusses research needs and identifies barriers related to analyzing the load effects of future hazards and their compound effects on deteriorating new and existing structures. The discussion includes methods and models for converting hazards into load effects and estimating structural material degradation while accounting for nonstationarity and uncertainty.

2.2.1. Overview of Findings

Methods for analyzing the load effects on structures of major types of climate hazards such as dynamic wind forces; flood water pressure; and the weight of rain, ice, and snow have long been established in design codes and standards. The design of structures to resist these load effects has traditionally assumed that the characteristics of loads and load effects can be modeled using probability distributions with statistical parameters that do not vary with time, for example, that the load effects are stationary and that structures retain their original load-carrying capacities throughout their service lives.

However, discussions and presentations during the workshop identified several climate hazards with incompletely understood load effects. Participants also identified other load effects that have not been traditionally considered, despite the potential to reduce structural serviceability and functionality or to degrade structural member capacity, thus increasing repair and maintenance costs and the likelihood of failures. The nonstationary nature of the load effects and degradation mechanisms have also been identified as major challenges for advancing practice and updating codes and standards.

2.2.2. Identification of Major Research Needs

The workshop participants identified the following major research needs to address issues related to future load effects and infrastructure conditions.

Load Effects Not Currently Considered

The following load effects need to be better understood and require the development of new models so they can be considered during the design and safety assessment of structures and infrastructure systems:

- Damage due to wind-driven rain that may affect building functionality;
- Effects of freezing rain and characterization of ice loads on structures, including on noncylindrical surfaces;
- Effects of rime icing on power transmission lines;
- Hail-related damage to building envelopes and other components;
- Analysis of ponding and secondary deflections and geometric nonlinearity associated with the redistribution of rain, snow, and ice loads due to structural interactions with the hazards or human interventions; and
- Nonstationarity in future conditions.

Improved Hazard-Specific Load-Modeling Tools and Methods

Advanced tools and updated methods are needed for modeling the load effects of several climate hazards. The workshops identified the following topics that require further research:

- Advanced tools, including AI and ML algorithms, to automate and continually update flood-risk maps;
- Improved flood models that consider the combined effects of various flood drivers (such as sea-level change , storm surge, precipitation, wave action, groundwater rise, erosion, subsidence, coastal change);
- Identification and modeling of factors that better relate ground snow to drifts and roof loads;
- Modeling of the interaction among roofing materials, snow sliding, and the probability of falling snow and ice loads;
- Regional databases of concurrent/compounding hazards for creating improved load combination models for calibration of load factors and site-specific risk assessments; and
- Improved assessment of wind load design assumptions for the range of wind types to determine adequacy for analyzing historical and future wind loads.

Infrastructure Conditions

Modeling the long-term behavior of deteriorating structural components and their vulnerability to increasing hazards and applied loads remain challenging topics of research. The workshop participants identified the following priorities for research:

- Improved characterization of the effects of climate data (e.g., temperature, humidity, CO2, chlorides, saltwater, freeze-thaw) and their interactions with the properties, long-term behavior, and deterioration mechanisms of various traditional and new-generation structural materials;
- Understanding of where, when, and how degradation takes place in structures, including spatial variability to improve the effectiveness of retrofits and improve design methods and reliability assessments;
- Multiscale modeling of structural behavior to better understand how microscale material degradation impacts components and how local degradation affects the behavior of structural systems;
- Characterization of the effects of concurrent and compounding material degradation mechanisms, including the impact of mechanical stressors;
- Modeling of the deterioration of protective systems, including coatings and sealants;
- Validation of degradation models and transitioning of laboratory and accelerated testing results to full-scale real-time field conditions;
- Development of structural monitoring systems and data analysis tools to help update degradation models under service conditions and validate life-cycle projections and study the performance of degrading structures under different environmental conditions, such as accelerated degradation or extreme hazards; and
- Development of an open-source database of degrading structures, including environmental conditions, in situ material characteristics, and structural system behavior to calibrate long-term performance models under working conditions and hazard events. Such a database would include information gathered during post-hazard assessments or upon demolition.

Consideration of Uncertainties and Nonstationarity

The characterization of future hazards and modeling of their load effects and structural degradation involve the analysis of nonstationary processes associated with high levels of epistemic and aleatory uncertainties. Two distinct research areas were identified to help reduce or better quantify the uncertainty for predicting climatic load effects and performing reliability-based calibrations and probability-based, life-cycle risk assessment of structures and infrastructure systems.

First, establishing clear lines of communication and collaboration among climate scientists, engineers, and design teams is key. Such collaborations will facilitate the development of uniformly applicable protocols to characterize climate hazards; describe climate model results, assumptions and metrics, and the statistical models used to quantify hazards; and describe how to combine simulated hazards with structural modeling uncertainties for improved structural reliability assessments.

The second area involves building nonstationary reliability models that account for uncertainties in structural capacity degradation and applying those to calibrate load combination factors and generate data-driven, site-specific capacity reduction factors.

2.2.3. Identification of Enabling Activities and Research Dependencies

Research on improving understanding of the load effects of climate hazards and the time-dependent reduction in the load-carrying capacity of structural systems cannot be achieved in isolation. It requires advances in other related subjects and the development of new tools and methods. However, improved understanding and modeling of the effects of climate loads will assist designers and engineers in developing advanced design methods, tools, and criteria to mitigate the effects of climate hazards. The following lists research topics that would help improve our ability to assess the load effects of climate hazards and the degradation of structural performance and provide feedback to develop advanced design methods that mitigate the impact of climate hazards.

Topics that would benefit research on load effects and infrastructure conditions include the following:

- Developing robust statistical analysis techniques to detect nonstationarity and transitions between stationary and nonstationary hazards and degradation mechanisms for reliability analysis and adaptation of design criteria to nonstationarity
- Developing machine learning algorithms and engineering software to fill gaps in characterizing uncertainty in downscaled climate hazard projections and in the treatment of observable data and their propagation in structural simulation models to improve structural reliability assessment.
- Identifying and reducing uncertainties in existing structural analysis and assessment models to better define the effects of future hazards on structural performance.
- The load effects of climate hazards on a structure (such as wind loads, flood levels, temperature differentials, etc.) are influenced by the built environment in which the structure is located. Therefore, quantifying the effects of current and future developments and changes to the built environment and other nonclimate factors would improve understanding of existing and future variability in the loads, their effects on structural response and structural material degradation (e.g., how built-up areas affect wind turbulence and how it changes the dynamic response of structures, or how it changes snow drifts on building roofs, or how local factors may affect structural degradation).
- Analyzing the reduction in structural capacity requires an improved understanding of localized deterioration and how it relates to component behavior and system

performance, as local deterioration may lead to changes in a structure's load path and failure mechanism. Alternatively, load-induced stressors and cycling loadings are known to accelerate deterioration processes. Therefore, understanding the interaction between member deterioration and load effects is essential for ensuring the long-term safety of structures.

- Developing a database of actual building performance (failures and successes) under extreme events including cost-benefit analysis would help validate and improve our ability to model the response of structures to applied loads and assess structural safety and functionality.
- Developing an open-source database including in situ material characteristics and structural system behavior will help calibrate performance models under hazard events.

Topics that would benefit from research on load effects and infrastructure conditions include the following:

- Accurate modeling of the effects of loads on structures and structural deterioration processes provide necessary input for developing tools for adaptive pathway designs including multihazard assessment, fragility curves, and system degradation for implementation in Performance-Based Design.
- The effects of floods on structures can be reduced through the development of multidisciplinary design and mitigation approaches that accommodate flooding, such as encouraging the construction of floating structures, low water-crossing bridges, and so forth.
- Improvement of our understanding of nature barriers (e.g., ecotone levee, oyster reeds), their performance, and impact on risk reduction will help in the development and validation of nontraditional design methods that reduce the effects of climate hazards.
- Investigation of the load effects on natural formations and work with tribal partners to incorporate their knowledge of nature-based solutions could potentially lead to developing nontraditional geometries and design approaches that reduce the impact of extreme events on structures.

2.2.4. Discussion of Gaps and Further Study

Discussions in workshop groups raised important issues and topics of research that were not highlighted in the final list of research topics and yet are considered essential for developing approaches for modeling the load effects on structures and infrastructure conditions. These topics include the following:

- Current research on structural health monitoring has emphasized the instrumentation and analysis of data collected on bridge systems through various tools including remote sensing (such as UAV and satellite) and attached sensors (such as climbing robots, accelerometers, strain transducers, tilt gauges, deflectometers, corrosion-monitoring

Linear Polarization Resistance, LPR, and Electrical Resistance, ER, sensors, acoustic emission, etc.). The applicability of these tools and data analysis techniques for monitoring the performance and the deterioration over time of buildings and other types of structures needs to be ascertained to validate models for the analysis of the effects of hazards on structures and deterioration models.

- Currently available models to convert the intensity of climate hazards into loads (such as, converting wind intensity to pressure, freezing rain to ice thickness, snow depth to weight on building roofs, coastal floods and wave intensities to water pressure, etc.) involve large levels of uncertainties. Research is needed to improve these models and reduce the associated uncertainties as this will enhance the ability to estimate structural performance, reliability analysis, and risk assessment.
- Current structural analysis techniques seek to estimate the reliability of structural components by analyzing the probability that the applied load effects remain within analytically specified limit states. Correlating these limit states to actual physical structural damage and its relation to system behavior remains an elusive goal. Research to close this existing gap is important for assessing the resilience of structures and implementing resilience-informed design criteria that have been set as important objectives by many agencies concerned with the safety of the built environment.
- Current design criteria, analysis techniques, and hazard datasets focus on estimating the effects of the most extreme expected loads. Yet, structural damage and structural member deterioration may be due to the repeated application of lower intensities of the same type or of different types of hazards. The long-term performance of structural systems under the effects of various combinations of hazards of various intensity levels needs to be better understood.
- Currently developed load combination factors used for the analysis and design of structures have assumed that load occurrences and their intensities and load effects are statistically independent phenomena that follow stationary processes. Research is needed to verify the validity of these assumptions in view of future nonstationary variations in the occurrence of loads and their intensities, which may be controlled by the same basic climate characteristics leading to the simultaneous application of different loads and related cascading and compounding effects.

2.2.5. Summary

This section reviewed the most important research topics related to improving our understanding of the effects of climate hazard on structural behavior and infrastructure deterioration that were identified during the four workshops. These topics included the effects of loads not currently considered in the design of structures, the development and application of tools and techniques for assessing the effects of loads on structures and the long-term deterioration of structural components. The need to improve existing approaches for the consideration of uncertainties and non-stationarity of loading and deterioration processes was also discussed. The relation between these identified research topics and how they inform and benefit from other research efforts related to the development of traditional and nontraditional design configurations and techniques that assess and mitigate the effects of extreme loads and structural deterioration have also been identified.

2.3. Design Guidelines, Criteria, and Tools

This section summarizes research needs associated with the development of design guidelines, criteria, and tools to enable practitioners to design safe, resilient, and cost-effective infrastructure for a future defined by change.

2.3.1. Overview of Findings

The synthesis of recent stakeholder input reveals that conventional design guidelines, criteria, and tools are lagging behind the accelerating pace of changes in environmental hazards, material science, infrastructure performance requirements, and social equity impact. Existing codes and standards often remain static for years, constraining the ability of practitioners to address evolving hazards and nonstationary effects. As a result, the engineering field has identified an urgent need to modernize design procedures, moving from a rigid, prescriptive design framework to an adaptive, data-driven, and performance-based approach that can reliably inform decision-making, which at times is required under situations of uncertainty.

Key themes include the following:

- **Treatment of evolving science in code cycles:** Most current codes and standards are founded on the assumption of stationary environmental hazards and structural material capacities, making them ill-suited for considering nonstationarity and continually evolving hazard projections. The slow cycle of developing and adopting codes and standards conflicts with the present reality in which scientific data on hazards and the hazards themselves are constantly changing. Also no guidelines nor manuals of practice provide timely updated best environmental hazards for design practice that fill the gap between codes and standards updates.
- **Inadequate hazard and performance data resources:** Practitioners frequently lack access to up-to-date, design-ready datasets and tools to interpret future hazards.
- **Lack of frameworks for adaptive and performance-based design:** Published design guidelines and tools do not commonly support nonprescriptive design approaches such as adaptive pathways, decision-making under uncertainty, and life-cycle performance optimization.

The consensus is that the ability to design safe, resilient, and cost-effective infrastructure will be compromised without targeted interventions and modernization of design guidelines.

2.3.2. Identification of Major Research Needs

Drawing upon technical breakout reports and consensus priorities, the following research needs are found to be fundamental to advancing design guidelines, criteria, and tools for the next generation of codes and standards.

Hazard Data and Modeling Tools

To successfully advance next-generation design, developing national, transparent, open-access data platforms that provide practitioners and stakeholders with credible, fit-for-purpose hazard data and information is essential. These platforms should comprehensively address wind, riverine and coastal flooding, compound flooding, wildfire, snow, ice, and emerging natural hazards. Regular updates to these platforms are critical, and each update must be accompanied by clear traceability and rigorous documentation of all underlying assumptions, methodologies, and associated uncertainties. Additionally, new methods are needed to efficiently integrate historic observational data with model-based projections, with a particular emphasis on recognizing and addressing the transition from stationary to nonstationary hazard behavior. Finally, clarifying requirements for the spatial and temporal resolution of hazard datasets—ensuring that the level of detail is sufficient to meet the needs of discrete design event estimation and broader life-cycle performance assessments—is imperative. This comprehensive approach will greatly enhance the usability, reliability, and effectiveness of hazard information in engineering design practice.

Frameworks for Adaptive and Performance-Based Design

A growing need exists to expand and refine frameworks for performance-based design (PBD) beyond the current acceptable practice for PBD seismic, wind, and structural fire, prioritizing the integration of rigorous approaches for flood and wildfire hazards. To facilitate more resilient and adaptive infrastructure, design guidelines should support flexible adaptation pathways. This includes the development of clear decision rules, several optional design pathways, and the identification of trigger mechanisms that define when interventions or upgrades should be implemented over a structure’s service life. Equally important is defining service life, including optional service lives, life-cycle cost, and functional recovery objectives using risk- and performance-based criteria, allowing for greater alignment of project goals with contemporary resilience and adaptation strategies. Finally, advancing the field will require the establishment of robust methods for modeling and designing for compounding and sequential hazard scenarios, ensuring that structures perform reliably under the complex and evolving risks posed by multiple, interacting environmental threats.

Guidelines for Structural Capacity, Degradation, and Monitoring

Advancing predictive models for the deterioration mechanisms of structural materials and protective systems is a critical research priority, with particular emphasis on establishing clear linkages between microscale processes and their macroscale impacts on overall structural performance. To support this effort, open-source tools and repositories that facilitate in situ material testing, enable robust performance assessments, and systematically document post-event damage are needed. In addition, developing standards for integrating monitoring data and digital twin models into both ongoing structural assessment and the broader context of design procedures will be essential. Together, these initiatives will enable more accurate, timely, and actionable insights into the evolving condition and resilience of buildings and infrastructure across their life cycles.

Flexible Guidelines

To maintain the relevance and effectiveness of design guidelines in a rapidly evolving landscape, developing robust processes for issuing interim updates—such as technical bulletins and digital supplements—that bridge the gap between formal code cycles and ensure practitioners have prompt access to the latest guidelines is essential. In parallel, the field should work to standardize practices for creating peer-reviewed, site-specific guidelines and facilitating their rapid dissemination and consistent use across diverse projects and locations. Furthermore, a critical need exists to develop and articulate clear, risk-informed reliability and uncertainty criteria; establish well-defined benchmark thresholds; and set comprehensive standards for both scientific and practitioner review.

Decision Support, Communication, and Education

Developing practical tools for practitioners—such as intuitive design calculators, scenario planning templates, and economic or life-cycle analysis software—will be essential for translating complex guidelines into daily engineering workflows, particularly when these tools are seamlessly integrated into digital environments. Simultaneously, a need exists to expand continuing education resources to ensure that engineers and associated professionals are equipped to address evolving hazards, apply advanced methodologies for the effects of nonstationarity, and implement performance-based and adaptive design strategies. Additionally, formalizing effective risk communication strategies for building owners, regulatory agencies, and the broader public is critical. This entails aligning technical language and design objectives with clear messages about resilience and functionality, so that all stakeholders can make informed decisions in support of community safety and long-term building performance.

2.3.3. Identification of Enabling Activities and Research Dependencies

The following framework and mechanisms are necessary to support research needs and the advancement of design guidelines:

- **Centralized data repositories:** Establishment of national, open-access data sources (e.g., by NOAA, U.S. Geological Survey, ASCE) for hazard data and design tools;
- **Cross-disciplinary standardization:** Coordination of codes, standards, and guideline documents across multiple disciplines and sectors to enable a systems-level approach to multihazard adaptation and resilience;
- **Code development:** Creation of formal procedures for iterative, transparent, and rapid update cycles, including governance frameworks for interim requirements;
- **Multidisciplinary collaboration:** Promotion of interdisciplinary partnerships through joint working groups, integrated research funding streams, and boundary organizations to align climate, engineering, and economic expertise;
- **Accessible digital platforms:** Investment in cloud-based platforms that facilitate access, analysis, and application of requirements in real-world practice; and
- **Incentive and data-sharing structures:** Development of policies and incentive mechanisms to overcome barriers to proprietary data access, particularly for post-event damage, loss, and building performance datasets.

Section 3.6 discusses these supporting elements further, describing how data, interim requirements, validation steps, and governance processes help new approaches move from research into formal codes and standards over time.

2.3.4. Discussion of Gaps and Further Study

Despite significant advances, the following persistent gaps and needs for further study underpin the agenda for next-generation design guidelines:

- **Nonstationarity detection and reliability calibration:** Methods for real-time detection of nonstationarity in hazard data and for transitioning code and standard development procedures for targeted reliability from stationary to nonstationary conditions remain underdeveloped.
- **Design for multihazards:** Integration of guidelines on concurrent, cascading, compound, and sequential hazard effects is in its infancy and demands robust probabilistic modeling coupled with scenario-driven design frameworks.
- **Real-world performance data:** The lack of comprehensive, systematically collected databases on building/system performance under extreme events (including failures and successes) limits the calibration and risk assessment of new guidelines.
- **Guidelines for adaptive pathways:** Best practices for adaptive design trigger thresholds, monitoring, and assessment over time are not clearly articulated or widely adopted in codes, leading to uncertainty in implementation and liability.
- **Service life and functional recovery criteria:** Research is needed to define practical, risk- and resilience-based service life and performance targets, including quantifiable functional recovery objectives.

- **Alignment of policy, economic, and technical drivers:** Effective design guidelines requires alignment across regulatory, insurance, and financial sectors, which currently operate under divergent timelines, risk tolerances, and decision frameworks.

Additional areas requiring continued or new investments include the following:
- Pilot studies for adaptive and performance-based design, especially for nonstationary environmental hazards;
- Multihazard digital twin and monitoring platforms for operational and asset management use; and
- Applied social science research into risk communication, stakeholder engagement, and the practicalities of code and standard adoption.

2.3.5. Summary

Design guidelines, criteria, and tools link scientific knowledge and real-world infrastructure outcomes. The previously discussed research needs emphasize adjusting the framework for developing these resources to accommodate the reality of nonstationary hazards and help practitioners obtain and utilize the best available data. Meeting these needs will require
- Developing hazard data resources fit for engineering use;
- Institutionalizing frameworks for adaptive design and PBD that are pragmatic and scalable and accommodate inherent uncertainties;
- Leveraging digital innovations, interdisciplinary standards, and real-world monitoring to inform and refine requirements;
- Aligning the pace of climate research with the rigid cycles of codes and standards through more agile mechanisms for knowledge delivery; and
- Supporting practitioners, regulators, and the public with education and communications that foster consistent understanding and implementation.

By addressing these priorities, the design community will be equipped with the guidelines, criteria, and tools necessary to create, maintain, and adapt the built environment for a future defined by change, complexity, and opportunity.

2.4. Resilience and Adaptation

This section focuses on research needed to evolve codes, standards, and design practice to include resilience and adaptation outcomes into decision-making processes.

2.4.1. Overview of Findings

Workshop discussions revealed a broad consensus that traditional approaches in codes and standards for climate adaptation and infrastructure resilience are insufficient to meet the dynamic and uncertain challenges posed by evolving natural hazards. Prescriptive methods, historical baselines, and fixed risk categories that inadequately capture effects of future hazards, recovery needs, and the full complexity of community resilience continue to dominate current engineering practice.

2.4.2. Identification of Major Research Needs

Drawing from the last workshop report and consensus priorities, the following needs are identified as major areas for elevating adaptation and resilience in engineering practice and code and standards advancement.

Decision Frameworks and Design Approaches

The need to incorporate decision analytic approaches and frameworks into design processes and to provide guidelines on how to select the approaches is critical. This encompasses several decision-making models and approaches, such as adaptation pathways, benefit-cost assessments, risk-based designs that are consistent with reliability-based design and economic and behavioral components of risk, and approaches focused on functional recovery and serviceability performance during frequent hazard events. Future requirements must also foster the creation of adaptation-focused design approaches that integrate resilience planning and decision-support tools that can inform planning needs and consultations across diverse stakeholder groups. Research should continue to develop methodologies for adaptation pathway design, emphasizing multihazard scenarios, vulnerability assessments and fragility curves, system degradation modeling, and the implementation of performance-based design principles. Also imperative is investigating the most appropriate conditions for applying prescriptive or performance-based design approaches and the relative benefits and trade-offs for adaptive building design. This includes establishing clearly defined service life “windows” of future hazard data to extend the useful life of buildings and infrastructure beyond 50 years and developing adaptive design methods that enable proactive, risk-informed decision-making. These methods should define criteria for scenario selection, modeling, and stress-testing and establish strong thresholds and economic models to balance cradle-to-cradle life-cycle costs for critical structures. Expansion of guidelines to integrate uncertainties related to future structural capacity in risk evaluations is needed, along with clearer means to handle uncertainty and reliability, such as benchmark thresholds and peer-reviewed processes. The evaluation of risk categories to determine their relevance for varying hazards and asset scales is also a component for future research.

Performance-Based Design and Functional Recovery

Expanding performance-based design (PBD) approaches for environmental hazards beyond seismic and wind is a growing priority, particularly as these methods offer the flexibility needed to address complex and evolving effects from future hazards. Future requirements should enable the overlay of current and future hazard conditions at the site level, allowing codes and standards to become adaptable and responsive rather than strictly prescriptive. Research and practice must also focus on extending functional recovery objectives for current and future hazards, applying these standards to new construction and existing assets. Requirements must be developed for performance-based approaches to hazards that are not yet fully addressed in common design codes, such as fire and flood, while maintaining a pathway for straightforward, prescriptive methods to support minimum design requirements on smaller projects or in resource-constrained cases.

Monitoring, Assessment, and Existing Structures

Comprehensive guidelines for monitoring existing structures are needed as are robust methods for establishing criteria and thresholds for adapting assets to future conditions. These guidelines should address performance evaluation for adaptive designs over time, incorporating feedback from real-world monitoring and structural health assessments. Simultaneously, a need exists for improved standards and guidelines for the validation of data used during interim updates that fall between major code cycles. Such procedures would support the evaluation of existing structures for evolving hazards and regulatory conditions and the systematic review and refinement of established criteria. The profession should also capitalize on leveraging existing hazard and building performance data to facilitate the translation of emerging research findings directly into actionable insights and design practices.

Tools and Data for Practitioners

A high priority is the development of practical tools, grounded in common frameworks and fed by accessible, up-to-date data, to enable practitioners and building owners to accurately define and address future hazards. This includes providing simplified, user-friendly applications for computing design values, supporting scenario planning, and facilitating economic analyses. An equally important need is for accurate and timely measurement and characterization of factors influencing community resilience outcomes. Reliable, measured data are vital for tracking trends, supporting continuous improvement in design, and producing evidence-based guidelines that is both actionable and defensible under scrutiny.

Policy, Incentives, and Implementation Barriers

A central challenge in advancing adaptation and resilience is to better understand and harness the financial, behavioral, and policy-based incentives that drive stakeholder investment. Research should focus on mechanisms by which these incentives can promote adaptation and resilience strategies that align with long-term community value, not just immediate project returns. Identifying the legal, political, and policy barriers to the implementation of adaptive strategies over time, such as regulatory uncertainty, insurance requirements, and transfer of responsibility, is also essential. Furthermore, a more deliberate effort is needed to quantify and articulate the tangible benefits of resilience to encourage wider adoption in codes, standards, and design practice.

Understanding Communities and the Need for Multidisciplinary Collaboration

Future-ready design guidelines must recognize that risk and resilience preferences span from individual asset to community levels, and these differences correspondingly affect practical engineering decisions on a project scale. Priority should be placed on articulating how these preferences and capacities play out in different contexts and on supporting approaches that bridge community-led resilience to broader policy and planning efforts. Collaboration must be multidisciplinary, bringing together engineers, planners, economists, social scientists, and community representatives to ensure that technical design aligns with community-driven resilience objectives. Research should also emphasize the development of data and models that facilitate functional recovery for facilities, infrastructure networks, communities, and their multifaceted interactions.

Hazard-Specific Information to Inform Adaptation

Investing in research to inform adaptive design for specific hazards such as wildfire and hail is paramount. For wildfire, efforts should prioritize better hazard characterization, including the development of common descriptive languages and intensity metrics and improved quantification of demands on structures using advanced structural health monitoring and sensor technology. For time-dependent structural capacity degradation in conjunction with nonstationary load effects, future work should focus on developing reliability-based design standards that reflect these complexities. Research should also ensure that geographically targeted, standardized datasets are consistent with evolving design standards and provide practitioners with actionable, future-oriented data for resilience modeling and adaptation planning.

2.4.3. Identification of Enabling Activities and Research Dependencies

Progress on resilience and adaptation depends on foundational inputs from engineering; inputs from economics and decision science and innovations in policy; and new outputs that strengthen decision-analytic frameworks, performance-based design, and implementation practices. The following identifies the research areas that inform resilience and adaptation and the direct benefits from their advancement:

- **Stakeholders and community resilience:** Understanding the outcomes for economies and communities that the buildings and infrastructure serve is key to determinants of resilience. This involves engaging with acceptable performance levels and understandings and perceptions of risks and identifying community-driven priorities to ensure that design guidelines reflects the full range of stakeholder needs and improves alignment with how communities experience and recover from hazard events.

- **Economics and life-cycle models:** Benefit-cost frameworks, life-cycle cost analyses, and models that quantify the long-term value of resilience investments are necessary inputs for justifying adaptive design approaches to building owners, policymakers, and regulators. Research that improves the accuracy and accessibility of these models directly supports the adoption of resilience strategies in practice.
- **Policy innovations:** Understanding the legal, regulatory, and institutional landscape, including barriers such as liability transfer, insurance requirements, and regulatory uncertainty, is essential for developing adaptation strategies that are implementable. Research on policy incentives and innovations and governance frameworks informs where and how design guidelines can be implemented.

Benefits will also be derived from activities that are core to other efforts, namely improvements in future hazard characterization and climate modeling to define plausible future conditions against which adaptive design strategies can be evaluated and research into load effects and structural capacity that can help establish criteria for adaptive design “triggers” and intervention points.

Topics that would benefit from research on resilience and adaptation for buildings include the following:

- **Decision-analytic approaches and frameworks:** Scenario-based design, adaptive pathways, and multihazard assessment methods produce the empirical foundation on which robust decision-making frameworks are built and calibrated.
- **Performance-based design:** Resilience and adaptation research strengthens the evidence base for PBD by establishing functional recovery objectives, performance levels under future hazard conditions, and the fragility and degradation data needed for next-generation standards, particularly for hazards such as flood, wildfire, and compound events.
- **Load effects and structural capacity modeling:** The performance thresholds and service-life criteria produced through resilience and adaptation research provide essential inputs for load modeling, capacity assessment, and the development of design standards that reflect changing hazard conditions over time.

2.4.4. Discussion of Gaps and Further Study

The workshop discussions revealed several important issues that are considered essential for advancing resilience and adaptation for building codes and standards.

Resilience and adaptation strategies for compound and cascading hazards were highlighted as a gap as most current assessments focus predominantly on single-hazard scenarios. The simultaneous or sequential occurrence of multiple hazard events, compounded by concurrent structural degradation, represents a critical gap in current methods. Frameworks for multihazard resilience assessments that account for these interactions are needed to accurately characterize risk and inform adaptive design decisions.

Adaptation strategies for existing buildings and infrastructure, including prioritization frameworks, condition assessment methods, and retrofitting approaches suited to current and future hazard conditions, are a pressing need. Similarly, many of the tools and frameworks proposed during the workshops assume levels of analytical resources and technical expertise that smaller jurisdictions, communities, and building owners may not possess. Scalable solutions are needed to ensure that adaptive design is accessible across the full range of project types and resource contexts, not only on large or well-funded projects. The gap between the current state of resilience and adaptation research and the tools available to practitioners is persistent. Research is also needed to develop user-friendly guidelines, simplified design tools, and training resources that make advanced adaptive design methods actionable in design workflows.
Research that connects project-level engineering decisions to community-scale outcomes remains limited. Understanding how design decisions affect infrastructure network performance, functional recovery timelines, and the distribution of resilience investment is essential for aligning technical guidelines with how communities absorb and recover from hazard events. Finally, long-term evaluation of the performance and effectiveness of resilience and adaptation strategies is largely absent. Sustained monitoring programs with feedback and learning mechanisms can capture lessons from real-world performance and feed them back into the continual refinement of design guidelines.

2.4.5. Summary

Decision frameworks that support adaptive design and clear guidelines to practitioners on the selection of appropriate adaptation strategies for different contexts help ensure applicability across diverse project types and scales. Performance-based design approaches are viewed as a promising pathway for incorporating future hazard conditions, enabling innovation and resilience for new and existing infrastructure without relying solely on updates to prescriptive codes. To be effective in practice, tools and resources must be both practical and accessible, closing the gap between advances in climate science and everyday design workflow. Achieving community resilience requires moving beyond the scale of individual buildings to explicitly understand and guide the relationship between engineering design decisions and broader community outcomes. Research that connects project-level actions to community-wide benefits is essential for future-ready, adaptive, and resilient design guidelines.

2.5. Planning and Design Frameworks

This section focuses on planning and design frameworks to embed forward-looking thinking into codes, standards, and projects.

2.5.1. Overview of Findings

Across the four workshops, participants strongly converged on the need to evolve planning and design frameworks from static, prescriptive decision-making toward adaptive, time-aware approaches that explicitly manage uncertainty and changing risk over infrastructure life cycles. Workshop participants consistently emphasized that existing design workflows, which are largely anchored to historical hazard characterization, stationary reliability assumptions and infrequent code cycles, are not systematically structured to address accelerating effects from hazard and material nonstationarity.

A central concern identified throughout the workshops was the growing temporal misalignment between (1) the long service lives and irreversibility of infrastructure investments, (2) the evolving trajectory of climate hazards, and (3) the periodic nature of regulatory and code cycles. This misalignment increases the likelihood of lock-in, either through overdesigning based on a single projected future or by underpreparing for plausible hazard escalation. The emerging consensus is that the decision architecture that governs how infrastructure is planned and designed needs to be reconfigured using new frameworks that support structured decision-making across multiple plausible futures rather than a single-point optimization for a predicted future. Such frameworks would operate within and beyond traditional codes and standards and would integrate phased adaptation, scenario-informed design criteria, transparent treatment of uncertainty, and formal mechanisms for monitoring conditions and revisiting decisions as new information becomes available.

2.5.2. Identification of Major Research Needs

Workshop participants identified a set of cross-cutting research needs required to modernize planning and design frameworks for hazard nonstationarity and uncertain future conditions. Importantly, these needs extend beyond advancing hazard projections or load modeling and into how infrastructure decisions are evaluated, sequenced, and governed over time. The following research priorities were emphasized.

Risk, Cost, and Economic Decision Frameworks

Research is needed to integrate hazard projections, structural degradation models, and performance objectives into economic decision models that explicitly account for uncertainty and evolving risk. Priority areas include

- Methods to evaluate life-cycle costs under multiple plausible hazard trajectories, including maintenance, degradation, service disruption, and recovery. For example, extending time-dependent reliability and reliability–availability–maintainability (RAM) frameworks traditionally used to model degradation, inspection intervals, and downtime to account for evolving hazard intensities would enable structured evaluation

of intervention timing, resilience investments, and recovery costs under nonstationary conditions.
- Quantification of the value of flexibility, phased adaptation, and avoided lock-in under deep uncertainty, particularly compared with traditional planning and design methods.
- Development of decision frameworks that distinguish between irreversible capital commitments and adaptive, staged investments over infrastructure life cycles.
- Integration of service disruption and functional recovery metrics alongside damage and replacement costs into economic evaluations of infrastructure performance.

Such research would support a transition from static safety-factor-based evaluations and designs toward design scenarios of continuous life-cycle reliability and risk management under future changing conditions.

Uncertainty Characterization for Decision-Making

Research is needed to translate nonstationary climate hazard data into usable decision-support frameworks that distinguish between different types of uncertainty (such as aleatory and epistemic, inclusive of scenario model, statistical, and deep uncertainty) and clarify their implications for design and planning purposes. Priority areas include the following:
- Methods that incorporate deep uncertainty into planning decisions and reduce reliance on insufficient probabilistic optimization methods;
- Structured stress-testing under various future design scenarios aligned with engineering performance objectives;
- Criteria for selecting design scenarios, models, and stress conditions that maintain acceptable risk trajectories over infrastructure life cycles; and
- Deeper integration of nonstationary reliability methods into planning-level decision-making frameworks.

Additionally, while not discussed specifically in the workshops, research is needed to apply Value of Information (VoI) methods to infrastructure planning efforts with an evolving risk profile. Under conditions of deep uncertainty, not all uncertainty reductions have equal decision relevance. Research is needed to distinguish uncertainty that materially influences infrastructure performance outcomes from uncertainty that does not and to prioritize monitoring and modeling efforts accordingly. Key areas include applying VoI methods to determine when reducing uncertainty through monitoring, inspection, research, or improved modeling materially alters infrastructure decisions and developing VoI approaches to guide adaptive trigger thresholds, inspection intervals, model refinement priorities, and phased investment strategies under evolving hazard conditions.

Acceptable Residual Risk and Risk Tolerability Frameworks

Under changing hazard conditions, infrastructure design cannot eliminate risk entirely. Even when design standards are met, some level of remaining or "residual" risk, defined here as the probability and consequences of failure or disruption after planned design, mitigation, and adaptation measures are implemented, will persist. Research is needed to define acceptable residual risk over an asset's service life and to clarify how risk tolerability should evolve as hazards intensify and societal expectations shift. Priority areas include

- Adaptation of structured risk tolerability frameworks, like "As Low As Reasonably Practicable" (ALARP), to infrastructure systems exposed to evolving climate hazards;
- Development of methods to document and justify residual risk under scenario-based and adaptive planning approaches along with governance structures to periodically revisit and possibly reduce residual risk over a project life cycle;
- Establishment of quantitative risk tolerance bands and intervention thresholds that support adaptive pathway implementation; and
- Evaluation of whether existing building code risk categories adequately reflect time-dependent, multihazard risk conditions.

Such work would provide transparent and economically defensible stopping rules for risk reduction while preserving accountability and public trust.

Adaptive Pathway Methods and Time-Dependent Reliability

While planning literature increasingly refers to adaptive pathway concepts, research is needed to operationalize these concepts within engineering and regulatory contexts. Priority areas include

- Extending time-dependent reliability models to incorporate structural capacity degradation and evolving hazard intensities,
- Defining acceptable risk profile and performance expectations over infrastructure life cycles;
- Establishing quantitative monitoring indicators and decision-revisiting mechanisms that trigger reassessment or intervention, and
- Developing adaptive capacity metrics that complement traditional safety-based risk classifications.

This research would enable a shift from designing static assets for a single projected future toward designing adaptive decision processes capable of responding to evolving hazard information and infrastructure performance data.

Regulatory and Code Evolution Models

The current three- to six-year cycles for codes and standards are often too long to incorporate rapidly evolving climate science and engineering research. Mechanisms are needed to publish vetted interim requirements or supplements without confusing practitioners or undermining the authority of codes. This effort should include providing requirements for nontraditional entities that regulate development through local land-use ordinances. Research is needed to explore models for more responsive incorporation of evolving science into codes and standards without undermining regulatory clarity or practitioner confidence. Priority areas include the following:

- Evaluation of modular, tiered, or flexible code structures that accommodate adaptive criteria;
- Mechanisms for issuing vetted interim requirements between formal code cycles; and
- Methods for aligning building codes with land-use planning, infrastructure funding requirements, and asset management frameworks that influence long-term risk exposure.

Research Governance and Knowledge Translation

The development of next-generation codes and standards requires clarity on how research is funded, coordinated, and translated into practice. Modernization of planning and design frameworks depends on effective coordination and translation mechanisms across disciplines. Priority areas include

- Governance models that facilitate sustained collaboration among climate scientists, engineers, economists, planners, and local regulators;
- Mechanisms for aligning research funding priorities with code development timelines;
- Translational pathways to ensure that advances in hazard science, reliability modeling, adaptive planning, and economic evaluation are usable by practitioners; and
- Communication strategies that normalize uncertainty as a component of professional judgment while maintaining public and professional confidence.

Collectively, these research priorities shift the focus of next-generation codes and standards from defining static design thresholds toward structuring adaptive, economically informed, and uncertainty-aware decision processes over infrastructure life cycles.

2.5.3. Identification of Enabling Activities and Research Dependencies

To support implementation of modernized planning and design frameworks, participants identified needs for institutional, procedural, and technical scaffolding in addition to advancing research. These enabling structures are necessary to translate adaptive decision models into practice. Five key elements were emphasized as follows.

Structured Planning-to-Design Frameworks

A clear, shared definition of the planning-to-design process should delineate the phases from concept design to final design. This clarity is needed to support the development of explicit requirements for each phase. The planning-to-design framework should include this explicit requirement on appropriate data resolution, treatment of uncertainty, and decision authority at each phase. Explicit requirements is needed on the following:

- Appropriate data resolution and scenario selection at different project stages,
- Documentation of uncertainty assumptions and acceptable residual risk, and
- Integration of adaptive pathway triggers and monitoring requirements into project development processes.

Governance and Decision Transparency

Modernized frameworks require formalized governance structures that clarify accountability for key decisions. This includes the following:

- Transparent documentation of scenario selection and assumptions,
- Explicit articulation of risk tolerance and acceptable residual risk, and
- Clear authority for establishing and revisiting adaptation thresholds.

In addition, mechanisms are needed to formally recognize and adopt nonbuilding code guidelines such as planning directives, technical bulletins, or agency-level standards that influence long-term infrastructure exposure and performance. Transparent governance is critical to maintaining public trust while managing evolving risk.

Update Mechanisms and Living Requirements

Traditional code cycles alone may be insufficient to respond to rapidly advancing climate science and engineering practice. Participants emphasized the need for “living requirements” mechanisms that allow for interim updates without undermining regulatory stability. Such mechanisms may include the following:

- Supplemental technical requirements between code cycles;
- Modular or tiered criteria that explicitly account for evolving loads, structural capacities, and performance expectations; and
- Structured processes for incorporating new hazard data into planning assumptions.

Infrastructure for Data and Tools

Adaptive and uncertainty-aware planning depends on accessible, credible, fit-for-purpose data infrastructure. This includes the following:

- Nationally consistent hazard datasets suitable for planning and design;
- Transparent documentation of assumptions, limitations, and uncertainty; and

- Interfaces and analytical tools that support scenario exploration and stress-testing rather than single deterministic outputs.

Capacity Building/Workforce Development

Implementation of adaptive planning frameworks requires expanded professional capacity. Participants emphasized the need for

- Training for planners, engineers, and decision-makers in adaptive pathways, scenario-based planning, and risk tolerability concepts;
- Shared terminology across engineering, climate science, economics, and public policy disciplines; and
- Education that normalizes structured uncertainty treatment as a component of professional judgment.

2.5.4. Discussion of Gaps and Further Study

The workshops demonstrated that a wide range of compelling and technically robust planning, design, and decision-making frameworks already exist. Participants shared effective applications of Decision Making Under Deep Uncertainty (DMDU), Robust Decision Making and Robust Decision Scaling, Adaptation Pathways, PBD, ALARP-based risk tolerability approaches, and related methodologies. While not always explicitly presented, established engineering disciplines such as reliability–availability–maintainability (RAM), reliability-centered maintenance, life-cycle cost accounting, and Value of Information (VoI) analysis also provides clear and relevant foundations for managing uncertainty, degradation, and phased intervention over time.

The central gap identified is not the absence of decision frameworks, but the limited integration and operationalization of these approaches within formal codes, standards, infrastructure funding mechanisms, and local regulatory systems.

Several areas for further study were highlighted:

- While adaptive and robust decision methods have been successfully applied in individual projects and pilot programs, evidence of systematic incorporation of these frameworks into building codes, infrastructure funding requirements, and cross-jurisdictional regulations are limited. Additional study is needed to evaluate pathways for scaling these methods beyond project-specific applications.
- Clearer alignment is required between established reliability-based methods and adaptive planning frameworks. Time-dependent reliability modeling, life-cycle economic analysis, ALARP-based tolerability concepts, and VoI approaches offer relevant tools. However, research is needed to integrate these methods into coherent requirements that is usable within code development and planning practice.

- Operational thresholds and acceptable residual risk trajectories under nonstationary hazard conditions remain insufficiently defined. Further work is needed to determine how risk categories, intervention triggers, and tolerability bands should evolve over time as hazards intensify and infrastructure ages.
- Governance models that enable interim updates and living requirements require deeper evaluation. Although technical methods exist, regulatory processes often lack mechanisms to incorporate evolving science and adaptive criteria without creating inconsistency or uncertainty for practitioners.
- The interaction between adaptive planning frameworks and broader societal objectives warrants additional exploration. This includes distributional impacts of phased investment decisions, long-term equity implications of acceptable residual risk, and alignment of economic optimization with community resilience goals.

In summary, the workshops revealed that the intellectual and technical building blocks for adaptive, uncertainty-aware planning are well developed. The primary challenge is translating these methods into structured, transparent, and scalable implementation within codes, standards, and infrastructure governance systems.

2.5.5. Summary

Planning and design frameworks must evolve from static, prescriptive processes toward adaptive, economically informed, and uncertainty-aware decision architectures. Achieving this shift requires methodological advances and institutional scaffolding.

Research is needed to extend life-cycle reliability modeling, incorporate value of information principles, define acceptable residual risk trajectories, and operationalize adaptive pathways under deep uncertainty. Equally important are governance mechanisms, data infrastructure, structured planning processes, and workforce capacity to implement these advances.

Together, these elements support a transition from designing infrastructure for a single projected future toward managing infrastructure performance and risk dynamically over time. Such an evolution is essential to ensure that next-generation codes and standards remain credible, responsive, and aligned with effects from accelerating changes to environmental hazards.

2.6. Codes and Standards

The workshops focused on codes and standards as a central mechanism for translating advances in climate science, hazard characterization, adaptation, and resilience research into everyday design and construction practice. Participants emphasized that while codes and standards have historically been effective at disaster risk reduction, their traditional structure, assumptions, and development processes are not well suited to address rapidly changing environmental conditions, nonstationary hazards, and long-term performance objectives.

Existing codes and standards are largely based on historical observations, fixed hazard levels, and prescriptive requirements intended to ensure minimum life safety at the time of construction. These approaches have provided consistency and reliability for decades, but they are increasingly strained by climate- and development-driven changes in hazard frequency, intensity, and spatial distribution. Workshop discussions highlighted the need for codes and standards that can evolve alongside scientific understanding, while maintaining clarity, credibility, and broad usability across jurisdictions and disciplines.

Advancing the next generation of codes and standards will require coordinated research, new governance approaches, and deliberate efforts to support adoption and implementation. Participants stressed that abundant climate data and technical innovation alone will be insufficient without parallel efforts to address institutional, procedural, and communication barriers.

2.6.1. Overview of Findings

Across the workshops, participants expressed a shared concern that current codes and standards are not designed to explicitly account for future conditions or structural performance that lasts longer—often double the service life assumptions. Traditional frameworks for developing codes and standards assume that environmental hazards are **stationary** over time and that historical data can provide a reliable basis for extrapolating those hazards throughout the entire future life cycle of a given project. As environmental conditions change, this assumption becomes increasingly difficult to justify, particularly for assets with long service lives or significant societal importance.

Participants also noted that current code development and adoption cycles, which typically span several years, are not aligned with the **pace** of scientific and engineering advances related to climate impacts. While climate models, hazard projections, and performance-based design methods continue to improve, pathways to integrate this information into codes and standards in a timely and consistent manner are limited. As a result, practitioners may rely on outdated assumptions or develop ad hoc approaches that vary widely across regions and projects.

Another key finding was the growing gap between prescriptive code provisions and the need for more flexible, adaptive, and performance-based **approaches**. Participants emphasized that prescriptive requirements can limit the ability to accurately address compounding hazards, site-specific conditions, and evolving risk profiles. In contrast, adaptive and resilient design strategies and performance-based design frameworks offer the potential to evaluate how buildings and infrastructure perform under several future scenarios, while allowing designers and decision-makers to select appropriate strategies based on local context. The adaptive and resilient design strategies also offer an overarching framework for multihazard risk mitigation and management from individual asset to the community level and pathways for actionable intervention and decision-making under evolving risk during the life cycle of infrastructures.

Finally, participants highlighted the importance of viewing codes and standards as part of a **broader system** that includes land-use planning, monitoring, maintenance, and governance. Codes do not operate in isolation; their effectiveness depends on how they interact with planning decisions, regulatory enforcement, data availability, and institutional capacity.

2.6.2. Identification of Major Research Needs

The workshops identified several primary research needs to advance the evolution of codes and standards for future hazards and conditions.

A primary need is the development and validation of adaptive design strategy and performance-based design frameworks that explicitly incorporate future hazard conditions. Participants emphasized the importance of moving beyond static design values toward approaches that consider a range of plausible future scenarios throughout the life of a structure or system. Such frameworks would allow codes and standards to address uncertainty, compounding hazards, and long-term performance in a more transparent and adaptable manner.

Closely related is the need for standardized, nationally consistent hazard data and modeling approaches for buildings, structural systems, and building envelopes. Participants called for open, transparent methodologies for developing and updating hazard maps and datasets that can be referenced directly by codes and standards. This includes research on how to process and downscale global and regional climate data relevant for the design of individual structures and how to communicate uncertainty in ways that support decision-making, rather than impede it.

Research is also needed to better understand material performance, degradation, and strength loss throughout a project's lifetime and under future environmental conditions. Participants noted that many codes and standards focus on extreme events, while long-term exposure to changing temperature, humidity, corrosion, and other environmental factors can also significantly affect structural performance and a structure's useful service life. Improved data on these effects would support more realistic design assumptions, evaluation methods, and maintenance strategies.

Another important research need is assessing existing structures and infrastructure under future conditions. Although guidelines exist for structural condition assessment of existing buildings (ASCE 1999), participants highlighted the lack of standardized guidelines for evaluating existing assets against projected hazards and the need for methods that can inform retrofit, adaptation, or replacement decisions. This research would support both interim requirements and long-term code development.

Finally, participants emphasized the importance of research that links resilience outcomes to code provisions. This includes developing methods to quantify benefits such as reduced downtime, improved functional recovery, and system-level performance, and translating those benefits into metrics that can inform standards development and policy decisions.

2.6.3. Identification of Enabling Activities and Research Dependencies

In addition to technical research, the workshops identified several forms of scaffolding needed to enable the effective integration of future hazards into codes and standards.

Governance and coordination emerged as critical needs. Participants noted that responsibility for funding research, developing standards, and adopting codes is distributed across many agencies and organizations, including standards bodies, government agencies, industry groups, insurers, and academic institutions. Stronger coordination mechanisms are needed to align research priorities, reduce duplication, and ensure that findings are translated into usable guidelines.

Participants also emphasized the need for mechanisms to support interim updates between formal code and standard revision cycles. As scientific understanding evolves, credible pathways must be available to publish vetted requirements or supplemental materials that can inform practice without undermining the authority or consistency of codes. These mechanisms must balance flexibility with clarity, ensuring that practitioners understand when and how to apply interim requirements.

Standardized protocols for monitoring, data collection, and data sharing were identified as another key scaffolding element. Sensor-based monitoring and performance data from existing infrastructure offer valuable opportunities to improve understanding of real-world behavior under future conditions. However, participants noted barriers related to the consistency, accessibility, liability, and long-term stewardship of historical data. Addressing these issues will be essential to support feedback loops between observed performance and code development.

Education, training, and dissemination were also highlighted as essential components of scaffolding. Participants stressed that forward-looking codes and standards must be understandable and usable by a wide range of stakeholders, including designers, planners, policymakers, regulators, and owners. Clear communication, guideline documents, and professional development will be necessary to ensure consistent interpretation and application.

2.6.4. Discussion of Gaps and Further Study

Despite broad agreement on the direction of change, participants identified several gaps that warrant further study. One key gap involves defining acceptable levels of risk and reliability under nonstationary conditions. Existing frameworks are based on implicit assumptions about hazard probability and performance targets, which may need to be revisited as conditions evolve. The gap also involves how to define adaptation and adaptive capacity categories, which would either augment or complement the current four risk categories.

Another gap relates to balancing national consistency with regional and local variability. Participants emphasized the importance of maintaining a coherent national framework, while allowing flexibility to address regional and site-specific hazards, community priorities, and differing levels of risk tolerance.

Institutional and regulatory barriers also require further study. Participants noted that even well-developed technical methods may face challenges related to legal frameworks, liability concerns, cost considerations, and administrative capacity. Understanding these barriers will be essential to support meaningful adoption of forward-looking codes and standards.

Finally, participants highlighted the need for additional research on how resilience benefits are perceived and valued by different stakeholders. Improved understanding of these perspectives could help inform how resilience considerations are integrated into standards development and communicated to decision-makers.

2.6.5. Summary

The workshops underscored that advancing codes and standards for future hazards will require a comprehensive and coordinated effort. Progress will depend on continued research to support performance-based, adaptive and resilient, and forward-looking design approaches; standardized hazard data and methodologies; and improved understanding of long-term performance and resilience outcomes.

Equally important will be the development of governance structures, interim guideline mechanisms, monitoring protocols, and education efforts that provide the necessary scaffolding for adoption and implementation. By addressing technical and institutional challenges, future codes and standards can better reflect evolving hazards, support adaptive and resilient design, and provide a stable and credible foundation for decision-making in an uncertain and changing environment.

3. Conclusions and Recommendations

Drawing on the six thematic components—future hazard data and information; future load effects and infrastructure conditions; design guidelines, criteria, and tools; resilience and adaptation; planning and design frameworks; and codes and standards—this project establishes a clear and compelling case for accelerating the evolution of building codes and standards to support engineering design practice that can address nonstationary climate hazards and time-dependent infrastructure performance. The workshops revealed that while significant scientific and engineering knowledge exists, it is not yet sufficiently integrated, standardized, or operationalized within codes and standards to meet the demands of a rapidly changing hazard landscape. The current system—which is largely built on historical observations, stationarity assumptions, and a single-hazard and project-by-project focus—cannot fully address emerging realities such as compounding hazards, time-varying structural capacity, the full range of uncertainties in future conditions, and community resilience goals.

Altogether, the *Forward-Looking Codes and Standards* workshop series and accompanying reports examine future hazards and evolving infrastructure conditions for engineering practices and guidelines. As this final report shows, the challenges facing the built environment are not isolated technical gaps but interconnected issues covering data, methods, design frameworks, governance, and more. The many top priorities that workshop participants identified—and the research and work needed in these areas—scaffold into an understanding of what the next generation of codes, standards, and design could accomplish and the challenges it will take to achieve. Addressing these needs will require multidisciplinary efforts that move beyond incremental updates to current practice. Progress toward next-generation codes and standards is an evolutionary process. Rather than defining a fixed ideal end state, stakeholders emphasized the need for adaptable and scalable approaches such as performance-based design methodologies that can be updated as scientific understanding, modeling capabilities, and observational data improve.

3.1. Conclusions

The transition from stationary to nonstationary design is unavoidable.

Hazards are evolving in frequency, intensity, spatial distribution, and interaction. Likewise, structural capacity is time-dependent due to material degradation and environmental stressors. The assumption that load and resistance can be treated as stationary is increasingly inconsistent with observed trends and projected future conditions. Forward-looking codes and standards must explicitly address nonstationarity in hazard characterization and reliability.

Hazard science and engineering practice remain insufficiently aligned.

A recurring theme across workshops was the persistent gap between climate model outputs and engineering-ready hazard datasets. Engineers require credible, validated, transparent, and fit-for-purpose data products that are directly usable in standards and design calculations. Climate science continues to advance rapidly; however, translation from science to practice, validation protocols, and uncertainty communication frameworks are not yet mature enough to support widespread integration into design codes and standards under future conditions.

Load effects and structural degradation must be treated as coupled processes.

Future load effects cannot be considered independently of infrastructure conditions. Structural deterioration due to increased temperature and cycling, saltwater intrusion, corrosion, freeze-thaw processes, and repeated loading alter resistance over time. Reliability estimation in future codes and standards must consider time-varying load and resistance models, including cumulative damage and compounding hazard interactions.

Prescriptive design alone is insufficient for future conditions.

Traditional code provisions are often project-specific, static, and hazard-specific. The workshops identified the need to supplement prescriptive methods with performance-based, adaptive, and resilience-informed approaches. Design frameworks must support multiple plausible futures, adaptive pathways, and decision-making under uncertainty.

Institutional and procedural barriers are as significant as technical barriers.

Code update cycles are typically slower than advances in hazard science. Inconsistent funding, fragmented data systems, limited coordination among agencies, and the absence of interim requirement mechanisms constrain timely implementation of forward-looking design provisions. Addressing these institutional constraints is essential for progress.

The findings of this workshop series indicate that next-generation codes and standards will require sustained national leadership, coordination across disciplines, and targeted investments in research and standards infrastructure. Given its statutory mission and long-standing role in advancing measurement science, structural reliability, and standards development, NIST is uniquely positioned to guide this transition. The following recommendations are presented in narrative form to articulate suggested strategic directions for NIST over the next decade. The collective vision articulated across the workshops describes a future in which codes and standards are forward-looking, adaptive, scientifically grounded, consistent, and consensus-based. Achieving this future will require coordinated research investments, institutional innovation and co-production, cross-disciplinary collaboration, and modernization of the code-development process.

3.2. Recommendations

Key recommendations from the *Forward-Looking Codes and Standards* series are as follows.

Moving toward forward-looking codes and standards will require clear national leadership in developing fit-for-purpose **hazard information** that engineers can actually use. Across multiple discussions, practitioners emphasized that what is often missing is not data, but data that are transparent, credible, validated, well-documented, and directly usable in design and reliability calibration. Engineers need hazard datasets that clearly communicate assumptions, uncertainty, and intended applications. Establishing consistent validation procedures, metadata standards, and standardized uncertainty characterization would provide a much stronger foundation for incorporating future hazard conditions into design practice.

At the same time, engineering **reliability methods** must evolve. Environmental loads are changing over time, and infrastructure capacity often declines due to aging and exposure. Traditional reliability frameworks assume stationary conditions and fixed resistance assumptions that are increasingly difficult to justify. Research is needed to develop nonstationary load models, time-dependent resistance factors, and reliability targets that account for multiple plausible future scenarios. Without such advances, recalibration of load and resistance factors in national standards will remain incomplete.

Another major need is to treat **hazard loading and infrastructure degradation** as interconnected processes rather than separate problems. Structures do not experience future hazards with a fixed capacity; they do so after years of exposure, cumulative service-level events, and material deterioration. Improving hazard-to-load conversion models, reducing uncertainty in force estimation, and improving understanding of cumulative damage mechanisms are essential steps. Laboratory validation, field monitoring, open performance databases, and integration of structural health monitoring into life-cycle models can significantly strengthen the scientific basis for updating resistance provisions in codes.

Design guidelines must also be modernized. PBD approaches, adaptive planning and design strategies, and life-cycle optimization methods offer pathways for managing uncertainty more effectively. These approaches require hazard inputs that extend beyond a single “most likely” projection and instead allow evaluation across several credible futures. Demonstration projects and applied case studies can help show how adaptive design decisions perform under changing conditions, helping practitioners translate research advances into practice.

Governance challenges must be addressed. Scientific knowledge about environmental hazards and impacts from changing hazards is advancing faster than the traditional multiyear cycles used to update codes and standards. Without mechanisms for interim technical requirements, vetted supplements, or structured pathways for incorporating validated updates, standards can lag behind the best available science. More consensus-based processes are needed to maintain credibility while improving responsiveness.

Finally, success depends on people as much as methods. Engineers must be educated and equipped to interpret uncertainty, understand scenario-based analysis, and work across disciplinary boundaries. Stronger **collaboration** among climate scientists, materials researchers, structural engineers, and standards development committees is essential. Workshops, pilot studies, coordinated research programs, and educational initiatives are necessary to build the shared language and technical capacity required for next-generation design.

In short, the shift toward future-informed codes is both feasible and necessary. With strategic investment in reliable hazard data, time-dependent reliability analysis methods, degradation modeling, adaptive design frameworks, and modernized standards processes, the engineering community can better align practice with evolving hazards and long-term resilience goals. These recommendations provide a foundation for the forward-looking joint work of researchers, practitioners, and standards-developing organizations. The findings emphasize the need for coordinated technical progress, adaptable frameworks, and clear pathways for implementation. Ongoing collaboration among all stakeholders will be key to creating forward-looking codes and standards that are technically sound and support public safety.

4. Acronyms and Abbreviations

Acronyms and abbreviations included in this final report are provided for clarity.

AI	Artificial Intelligence
ALARP	As Low as Reasonably Practicable
ASCE	American Society of Civil Engineers
CMIP	Couple Model Intercomparison Project
CO2	Carbon Dioxide
DMDU	Decision-Making under Deep Uncertainty
GWL	Global Warming Level
ML	Machine Learning
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
PBD	Performance-Based Design
RAM	Reliability–Availability–Maintainability
SEI	Structural Engineering Institute
SLR	Sea-Level Rise
VoI	Value of Information

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6. Appendix

Research needs identified during each workshop are included in the specific workshop reports. This appendix provides those research needs organized according to the six themes identified and described in Section 3.

Appendix A. Future Hazard Data and Information

Table A-1 lists research needs to support the theme of fFuture Hazard Data and Information identified during Workshops 1–4.

Table A-1. Future Hazard Data and Information

WS#	**Topic**
WS1	Develop more efficient ways to identify fit-for-purpose, site-specific hazard data, models, and design criteria.
WS1	Standardize methodologies for national, transparent, open-source models to develop and archive hazard data and maps for present-day and future conditions; develop framework(s) for processing data and a centralized repository for data.
WS1	Develop machine learning/engineering software to fill gaps in uncertainty, downscaling, treatment of observable data, impacts on design reliability, and perhaps in implementing a process.
WS1	Improve planning-level data with novel statistics.
WS1	Make good/better use of the data sources and methodologies currently used within actionable time scales.
WS1	Develop a suite of multidecadal regional and/or global climate model simulations that are run at convection-permitting spatial resolution (4 km or finer) with variables relevant to engineering standards stored at temporal and spatial resolutions appropriate for the design of projects.
WS1	Clarify how uncertainty could be considered in future conditions decisions for engineering approaches.
WS1	Improve understanding about “extremes” from a climate science perspective.
WS1	Develop a database of concurrent/compounding hazards for creation of improved load combinations and for site-specific hazard analysis.
WS1	Align understanding of the way global warming level is calculated by the climate science community and how engineering handles GWL as the target future condition.
WS2	Develop multiple high-resolution (km-scale) simulations for historical and future severe convective storms, bounded by observations, to reduce or better quantify uncertainty.
WS2	Develop observational data that have 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 Next Generation Weather Radar.
WS2	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.
WS4	Improve and standardize the characterization of current and projected hazard levels, including metrics and indicators for implementing adaptive strategies over time.
WS1	Develop methods to combine observational data and models; improve measurement science and processing approaches for uniform determination of historical hazard data.

WS1	Quantify how future changes to the built environment affect hazards.
WS1	Improve communication to engineers and design teams on what the hazard is, climate model results, metrics, and stats used to quantify it and how they are computed.
WS1	Use hazard data to support a life-cycle cost evaluation.
WS1	Understand the minimum requirements for spatial/temporal resolution, length (past and future), and continuousness of the projections by hazard types.
WS2	Assess wind load design assumptions for the range of wind types to determine adequacy for historical and future wind loads.
WS2	Improve current definitions (boundary conditions) and models of various flood characteristics and better understand their associated uncertainties.
WS2	Investigate ice loads that are not covered now, including hail and its effects on buildings and rime icing and its effects on power transmission.
WS3	Develop an open-source database including in situ material characteristics and structural system behavior to calibrate performance models under hazard events. For example, information gathered during post-hazard assessments or upon demolition.
WS3	Collect future-oriented hazard and load data. Practitioners need up-to-date, scientifically credible, fit-for-purpose datasets (e.g., precipitation, wind, flood) that reflect future conditions rather than outdated baselines like NOAA Atlas 14. Scalable methods (e.g., simple adjustment factors, ensembles) could provide usable interim tools until full datasets are refreshed.
WS4	Establish standardized, geographically targeted datasets that are consistent with design standards and codes for use in resilience modeling and performance-based designs.

Appendix B. Future Load Effects and Infrastructure Conditions

Table B-1 lists research needs to support Future Load Effects and Infrastructure Conditions identified during Workshops 1–4.

Table B-1. Future Load Effects and Infrastructure Conditions

WS#	**Topic**
WS1	Quantify how future changes to the built environment affect hazards.
WS1	Improve communication to engineers and design teams what the hazard is, climate model results, metrics, and stats used to quantify it and how they are computed.
WS2	Develop methods and design criteria to capture effects associated with damage due to wind-driven rain, to ensure continued functionality.
WS2	As a near-term approach until standardized, universal future conditions flood hazard data products are developed, 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.
WS2	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.
WS2	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, data sources for localized design.
WS2	Research is needed to relate ground snow to roof and drifting loads, the processes that are involved, and how to incorporate climate effects. The goal is to better understand regional differences in how snow moves and accumulates and how this will change in the future.
WS2	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.
WS2	Investigate ice loads that are not covered now, including hail and its effects on buildings and rime icing and its effects on power transmission.
WS2	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.

WS2	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.
WS2	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.
WS2	Validate deterioration models using advanced numerical tools and real-time and accelerated laboratory and field testing.
WS2	Improve understanding of localized deterioration and its impact on component and system performance.
WS3	Develop data-driven life-cycle models. Need degradation models that are well validated. Also need models that can be updated with structural monitoring data. Need to understand where, when, why degradation happens in structures to improve effectiveness of retrofits, designs, and reliability assessments. Need data from existing structures and full-scale experimental testing to validate life-cycle models.
WS3	Evaluate durability characteristics of structural materials (e.g., concrete, steel, wood) and nonstructural materials (e.g., coatings, sealants) with a focus on anticipated future effects and relating accelerated lab testing to real-world long-term behavior.
WS3	Better understanding of "micro to macro": how materials degradation impacts components and how this affects behavior of the structural system. For example, developing system reliability in lieu of, or in addition to, member reliability incorporating degradation to the components.
WS3	Characterize effects due to concurrent or compounding material degradation modes that reflect real-world behavior.
WS3	Monitoring, materials, and degradation research. More research is needed on long-term performance of structures under future conditions, covering new materials, degradation mechanisms, and sensor-based monitoring of public and private infrastructure. Standardized protocols for instrumentation and data-sharing could make real-world data more accessible for codes and practice (and to ensure that data are used for good, no liability from providing entities further down the line).
WS3	Research on assessing the effects of uncertainty in climate scenarios and associated uncertainties in the damaging effects of different hazards.
WS3	Future-oriented hazard and load data. Practitioners need up-to-date, scientifically credible, fit-for-purpose datasets (e.g., precipitation, wind, flood) that reflect future conditions rather than outdated baselines like NOAA Atlas 14. Scalable methods (e.g., simple adjustment factors, ensembles) could provide usable interim tools until full datasets are refreshed.
WS4	Establish standardized, geographically targeted datasets that are consistent with design standards and codes for use in resilience modeling and performance-based designs.
WS4	Research to identify and reduce uncertainties to better define future hazard levels for design.

WS1	Standardize methodologies for national, transparent, open-source models to develop and archive hazard data and maps for present-day and future conditions; develop framework(s) for processing data and a centralized repository for data.
WS1	Determine how to detect nonstationarity and transition between stationary and nonstationary hazards for reliability analysis; adapt the design criteria to nonstationarity.
WS1	Develop machine learning/engineering software to fill gaps in uncertainty, downscaling, treatment of observable data, impacts on design reliability, and perhaps in implementing a process.
WS1	Make good/better use of the data sources and methodologies currently used within actionable time scales.
WS1	Clarify how uncertainty could be considered in future conditions decisions for engineering approaches.
WS1	Develop a database of concurrent/compounding hazards for creation of improved load combinations and for site-specific hazard analysis.
WS1	Develop data and design methods for hazards not fully addressed now that are projected to increase, including wind-driven rain and hail, and for future conditions needed for foundation design, including frost depth and permafrost, groundwater elevations, and saltwater intrusion into groundwater.
WS2	Assess wind load design assumptions for the range of wind types to determine adequacy for historical and future wind loads.
WS2	Multiple high-resolution (km-scale) simulations for historical and future severe convective storms, bounded by observations, are needed to reduce or better quantify uncertainty.
WS2	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.
WS2	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.
WS2	Improve current definitions (boundary conditions) and models of various flood characteristics and better understand their associated uncertainties.
WS2	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.
WS2	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.

WS2	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.
WS3	Develop an open-source database including in situ material characteristics and structural system behavior to calibrate performance models under hazard events. For example, information gathered during post-hazard assessments or upon demolition.
WS4	Research associated with developing methodologies for adaptive pathway designs, including multihazards, fragility curves, system degradation, and implementation in performance-based design.
WS4	Develop a database of actual building performance (failures and successes) under extreme events including cost-benefit analysis.

Appendix C. Design Guidelines, Criteria, and Tools

Table C-1 lists research needs to support the theme of Design Guidelines, Criteria, and Tools identified during Workshops 1–4.

Table C-1. Design Guidelines, Criteria, and Tools

WS#	**Topic**
WS1	Develop methods to combine observational data and models; improve measurement science and processing approaches for uniform determination of historical hazard data.
WS1	Determine how to detect nonstationarity and transition between stationary and nonstationary hazards for reliability analysis; adapt the design criteria to nonstationarity.
WS1	Understand the minimum requirements for spatial/temporal resolution, length (past and future), and continuousness of the projections by hazard types.
WS1	Determine the service life window of future hazard data to extend service life beyond 50 years.
WS1	Develop data and design methods for hazards not fully addressed now that are projected to increase, including wind-driven rain and hail, and for future conditions needed for foundation design, including frost depth and permafrost, groundwater elevations, and saltwater intrusion into groundwater.
WS2	Assess wind load design assumptions for the range of wind types to determine adequacy for historical and future wind loads.
WS2	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.
WS2	Improve current definitions (boundary conditions) and models of various flood characteristics and better understand their associated uncertainties.
WS2	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, improve understanding of hydrological models that translate precipitation into flood characteristics.
WS2	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.

WS2	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.
WS2	Build reliability models accounting for uncertainties in capacity degradation and apply those to calibrate load combination factors; generate data-driven, site-specific capacity reduction factors.
WS2	Provide requirements for monitoring and inspection requirements for evaluating capacity and future performance under climate impacts.
WS3	Optimal, effective monitoring to assess new vs. existing structures. Inexpensive tools for monitoring degradation, such as corrosion or delamination. Technology for nondestructive remote monitoring, including below surface; adapt existing technologies used by other disciplines (bridges, geotechnical, etc.). Need models to identify optimal monitoring frequency and locations based on degradation type, load paths and failure modes, spatial variability, and uncertainty.
WS3	Develop an open-source database including in situ material characteristics and structural system behavior to calibrate performance models under hazard events. For example, information gathered during post-hazard assessments or upon demolition.
WS3	Uncertainty, reliability, and threshold criteria. Engineers require clearer ways to handle uncertainty in climate projections and structural degradation. Establishing benchmark thresholds, reliability criteria (for research, e.g., number of papers or consensus of percentage increase), and peer-reviewed vetting processes would help ensure that updates are scientifically defensible and practical for design.
WS3	Research on the applicability of current methodology used for stationary conditions to the design of structures in nonstationary conditions.
WS4	Develop, update, and calibrate data and models for incorporating functional recovery of facilities, infrastructure networks, and communities and their interactions into resilience-informed design standards and tools.
WS4	Develop a database of actual building performance (failures and successes) under extreme events including cost-benefit analysis.
WS4	Leverage existing hazards and building performance data to inform performance-based design and incorporate better translation of existing research into design practice.
WS1	Develop more efficient ways to identify fit-for-purpose, site-specific hazard data, models, and design criteria.

WS1	Improve communication to engineers and design teams on what the hazard is, climate model results, metrics, and stats used to quantify it and how they are computed.
WS1	Develop machine learning/engineering software to fill gaps in uncertainty, downscaling, treatment of observable data, impacts on design reliability, and perhaps in implementing a process.
WS1	Improve planning-level data with novel statistics.
WS1	Develop a suite of multidecadal regional and/or global climate model simulations that are run at convection-permitting spatial resolution (4 km or finer) with variables relevant to engineering standards stored at temporal and spatial resolutions appropriate for the design of projects.
WS1	Improve understanding about "extremes" from the climate science perspective.
WS1	Align understanding of the way global warming level is calculated by climate science community and how engineering handles GWL as the target future condition.
WS2	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 sources should make use of existing, new, and emerging data sources, including wind measurement stations, satellite data, and Next Generation Weather Radar.
WS2	Develop methods and design criteria to capture effects associated with damage due to wind-driven rain, to ensure continued functionality.
WS2	Develop methods for improved tornado wind modeling and to 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.
WS2	As a near-term approach until standardized, universal future conditions flood hazard data products are developed, 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.
WS2	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.
WS2	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, data sources for localized design.

WS2	Research is needed to relate ground snow to roof and drifting loads, the processes that are involved, and how to incorporate climate effects. The goal is to better understand regional differences in how snow moves and accumulates and how this will change in the future.
WS2	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.
WS2	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.
WS2	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.
WS2	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.
WS2	Validate deterioration models using advanced numerical tools and real-time and accelerated laboratory and field testing.
WS2	Improve understanding of localized deterioration and its impact on component and system performance.
WS3	Codes and standards that address capacity degradation. Codes need to address frequent events that affect degradation as well as extreme events. This could be implanted through maps (e.g., ASCE hazard tool) of future environmental conditions (e.g., temperature, humidity, CO2 concentration) and associated reduction factors for degradation in structural design and evaluation.
WS3	Adaptive design methods. For DMDU approach, identify selection basis for scenarios, models, and stress tests for design that maintains an acceptable level of risk. Need thresholds values and time intervals for decision support and a strong foundation for such thresholds. Develop societal requirements for structural design and expected performance and life cycle based on an economic model of cradle-to-cradle life-cycle costs to deliver long service lives for critical structures.
WS3	Assessment of changing conditions and future hazards. Develop improved characterization of compounding (sequential) hazards and time-varying structural conditions. Study of relative impacts of future conditions, including extreme and frequent events, and their impact on structural capacity/degradation over time. Develop plausible scenarios for regions that designers might consider.

WS3	Data-driven life-cycle models. Need degradation models that are well validated. Also need models that can be updated with structural monitoring data. Need to understand where, when, and why degradation happens in structures to improve effectiveness of retrofits, designs, and reliability assessments. Need data from existing structures and full-scale experimental testing to validate life-cycle models.
WS3	Evaluate durability characteristics of structural materials (e.g., concrete, steel, wood) and nonstructural materials (e.g., coatings, sealants) with a focus on anticipated future effects and relating accelerated lab testing to real-world long-term behavior.
WS3	Better understanding of "micro to macro": how materials degradation impacts components and how this affects the behavior of the structural system. For example, developing system reliability in lieu of, or in addition to, member reliability incorporating degradation to the components.
WS3	Characterize effects due to concurrent or compounding material degradation modes that reflect real-world behavior.
WS3	Monitoring, materials, and degradation research. More research is needed on long-term performance of structures under future conditions, covering new materials, degradation mechanisms, and sensor-based monitoring of public and private infrastructure. Standardized protocols for instrumentation and data-sharing could make real-world data more accessible for codes and practice (and to ensure that data are used for good, no liability from providing entities further down the line).
WS3	Research on assessing the effects of uncertainty in climate scenarios and associated uncertainties in the damaging effects of different hazards.
WS3	Future-oriented hazard and load data. Practitioners need up-to-date, scientifically credible, fit-for-purpose datasets (e.g., precipitation, wind, flood) that reflect future conditions rather than outdated baselines like NOAA Atlas 14. Scalable methods (e.g., simple adjustment factors, ensembles) could provide usable interim tools until full datasets are refreshed.
WS4	Investigate how financial, behavioral, and policy-based incentives can effectively motivate infrastructure owners to invest in resilience that aligns with community needs and long-term value.
WS4	Create design approaches for adaptation—leading to decision-support tools, design guidelines, standards, and codes—that integrate resilience into infrastructure planning across diverse stakeholders.
WS4	Research to identify and reduce uncertainties to better define future hazard levels for design.
WS4	Research associated with developing methodologies for adaptive pathway designs including multihazards, fragility curves, system degradation, and implementation in performance-based design.

WS4	Extend functional recovery research for current and future hazards for new building design and existing buildings.
WS4	Support broad-based research to inform adaptive design for wildfire.
WS4	Improve understanding of the legal, political, and policy challenges and barriers to implementation of adaptive strategies over time.
WS4	Integrate time-dependent structural capacity degradation with nonstationary load effect.
WS4	Develop performance-based design approaches where appropriate for hazards such as fire and flood that are not already addressed, while maintaining flexibility for minimum design code on smaller projects.

Appendix D. Resilience and Adaptation

Table D-1 lists research needs to support the theme of Resilience and Adaptation identified during Workshops 1–4.

Table D-1. Resilience and Adaptation

WS#	**Topic**
WS2	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/performance during frequent floods.
WS2	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.
WS3	Performance-based and future conditions design frameworks. Demand is strong for performance-based approaches (e.g., for flooding) and methods to overlay current and future hazard conditions at the site level. These frameworks would allow codes and standards to evolve beyond prescriptive rules, enabling adaptation to compounding hazards and long-term climate shifts.
WS3	Develop guidelines for monitoring existing structures and for determining appropriate criteria and thresholds for adapting existing assets to future conditions and to evaluate the performance of adaptive designs over time.
WS3	Updates between code and standard cycles might be promoted by applying performance-based design. A need exists to develop guidelines and standards for data validation for interim updates including guidelines for assessing existing structures for future conditions and procedures explaining how we to review and update established criteria in codes and standards.
WS4	Investigate how financial, behavioral, and policy-based incentives can effectively motivate infrastructure owners to invest in resilience that aligns with community needs and long-term value.
WS4	Create design approaches for adaptation—leading to decision-support tools, design guidelines, standards, and codes—that integrate resilience into infrastructure planning across diverse stakeholders.
WS4	Identify, quantify, and measure the factors influencing community resilience outcomes and use measurement science to establish trends and develop evidence-based guidelines.
WS4	Research associated with developing methodologies for adaptive pathway designs including multihazards, fragility curves, system degradation, and implementation in performance-based design.
WS4	Develop simplified tools based on common framework and data accessible to define future hazard risks and provide design values to practitioners and building owners for implementation on projects.

WS4	Extend functional recovery research for current and future hazards for new building design and existing buildings.
WS4	Improve understanding of how preferences around risk and resilience scale from the individual to the community and the implications for practical engineering design at the project scale.
WS4	Investigate the conditions under which prescriptive or nonprescriptive approaches are preferred, their relative benefits, and trade-offs for adaptive building design.
WS4	Support broad-based research to inform adaptive design for wildfire.
WS4	Improve understanding of the legal, political, and policy challenges and barriers to implementation of adaptive strategies over time.
WS4	Integrate time-dependent structural capacity degradation with nonstationarity load effect.
WS4	Develop performance-based design approaches where appropriate for hazards such as fire and flood that are not already addressed, while maintaining flexibility for minimum design code on smaller projects.
WS4	Foster multidisciplinary collaboration and integration that include community-driven risks and priorities.
WS4	Understanding the benefits of resilience to improve likelihood of adoption into codes so that it can be incorporated into standard development up front.
WS1	Determine the service-life window of future hazard data to extend service life beyond 50 years.
WS3	Adaptive design methods. For DMDU approach, identify selection basis for scenarios, models, and stress-tests for design that maintain an acceptable level of risk. Need thresholds values and time intervals for decision support and a strong foundation for such thresholds. Develop societal requirements for structural design and expected performance and life cycle based on an economic model of cradle-to-cradle life-cycle costs to deliver long service lives for critical structures.
WS3	Develop guidelines to incorporate uncertainty in future structural capacity when evaluating designs for acceptable reasonable risk. For example, using decision-making under uncertainty.
WS3	Uncertainty, reliability, and threshold criteria. Engineers require clearer ways to handle uncertainty in climate projections and structural degradation. Establishing benchmark thresholds, reliability criteria (for research, e.g., number of papers or consensus of percentage increase), and peer-reviewed vetting processes would help ensure that updates are scientifically defensible and practical for design.
WS3	Research on implementation of adaptative design and whether the current risk categories are applicable for all types of hazards and asset size and number of users. Future requirements should include adaptation/adaptative capacity rating categories to extend the current four risk categories.
WS4	Establish standardized, geographically targeted datasets that are consistent with design standards and codes for use in resilience modeling and performance-based designs.

WS4	Develop, update, and calibrate data and models for incorporating functional recovery of facilities, infrastructure networks, and communities and their interactions into resilience-informed design standards and tools.
WS4	Improve and standardize the characterization of current and projected hazard levels, including metrics and indicators for implementing adaptive strategies over time.
WS4	Incorporate risk and resilience metrics in current design frameworks to enable consideration of exposure and vulnerability and assessment of the economic impacts of failure.
WS4	Leverage existing hazards and building performance data to inform performance-based design and incorporate better translation of existing research into design practice.

Appendix E. Planning and Design Frameworks

Table E-1 lists research needs to support the theme of planning and design frameworks identified during Workshops 1–4.

Table E-1. Planning and Design Frameworks

WS#	**Topic**
WS1	Use hazard data to support a life-cycle cost evaluation.
WS1	Clarify how uncertainty could be considered in future conditions decisions for engineering approaches.
WS3	Adaptive design methods. For DMDU approach, identify selection basis for scenarios, models, and stress-tests for design that maintains an acceptable level of risk. Need thresholds values and time intervals for decision support and a strong foundation for such thresholds. Develop societal requirements for structural design and expected performance and life cycle based on an economic model of cradle-to-cradle life-cycle costs to deliver long service lives for critical structures.
WS3	Research on implementation of adaptative design and whether the current risk categories are applicable for all types of hazards and asset size and number of users. Future requirements should include adaptation/adaptative capacity rating categories to extend the current four risk categories.
WS3	Timely and flexible code updates. The current 3- to 6-year cycles for codes and standards are often too long to incorporate rapidly evolving climate science and engineering research. Mechanisms are needed to publish vetted interim requirements or supplements without confusing practitioners or undermining the authority of codes. Also, provide requirments for nontraditional entities that regulate development through local land-use ordinances.
WS3	Research funding, governance, and dissemination pathways. The development of next-generation codes and standards requires clarity on how research is funded, coordinated, and translated into practice. Industry groups, insurers, standards bodies, and government agencies play roles in shaping research priorities, publishing new standards, and influencing updates—yet stronger mechanisms are needed to ensure consistent dissemination of requirements not only to engineers but also to planners, policymakers, and other decision-makers who shape the built environment.
WS4	Incorporate risk and resilience metrics in current design frameworks to enable consideration of exposure and vulnerability and assessment of the economic impacts of failure.

WS2	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.
WS2	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.
WS2	Incorporate decision analytic frameworks into design and provide requirements 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/performance during frequent floods.
WS2	Provide requirements for monitoring and inspection requirements for evaluating capacity and future performance under climate impacts.
WS3	Performance-based and future conditions design frameworks. Demand is strong for performance-based approaches (e.g., for flooding) and methods to overlay current and future hazard conditions at the site level. These frameworks would allow codes and standards to evolve beyond prescriptive rules, enabling adaptation to compounding hazards and long-term climate shifts.
WS3	Develop guidelines for monitoring existing structures and for determining appropriate criteria and thresholds for adapting existing assets to future conditions and to evaluate the performance of adaptative designs over time.
WS3	Updates between code and standard cycles might be promoted by applying performance-based design. A need exists to develop guidelines and standards for data validation for interim updates, including guidelines for assessing existing structures for future conditions and procedures explaining how to review and update established criteria in codes and standards.
WS3	Research on the applicability of current methodology used for stationary conditions to the design of structures in nonstationary conditions.
WS4	Identify, quantify, and measure the factors influencing community resilience outcomes and use measurement science to establish trends and develop evidence-based guidelines.

WS4	Develop simplified tools based on a common framework and accessible data to define future hazard risks and provide design values to practitioners and building owners for implementation on projects.
WS4	Improve understanding of how preferences around risk and resilience scale from the individual to the community and the implications for practical engineering design at the project scale.
WS4	Investigate the conditions under which prescriptive or nonprescriptive approaches are preferred, their relative benefits, and trade-offs for adaptive building design.
WS4	Foster multidisciplinary collaboration and integration that includes community-driven risks and priorities.
WS4	Understand the benefits of resilience to improve likelihood of adoption into codes so that it can be incorporated into standard development up front.
WS1	Determine how to detect nonstationarity and transition between stationary and nonstationary hazards for reliability analysis; adapt the design criteria to nonstationarity
WS3	Assessment of changing conditions and future hazards. Develop improved characterization of compounding (sequential) hazards and time-varying structural conditions. Study of relative impacts of future conditions, including extreme and frequent events, and their impact on structural capacity/degradation over time. Develop plausible scenarios for regions that designers might consider.
WS3	Develop guidelines to incorporate uncertainty in future structural capacity when evaluating designs for acceptable reasonable risk. For example, using decision-making under uncertainty.
WS3	Better understanding of “micro to macro”: how materials degradation impacts components and how this affects behavior of the structural system. For example, developing system reliability in lieu of, or in addition to, member reliability incorporating degradation into the components.
WS4	Improve understanding of the legal, political, and policy challenges and barriers to implementation of adaptive strategies over time.
WS4	Integrate time-dependent structural capacity degradation with nonstationarity load effect.
WS4	Develop performance-based design approaches where appropriate for hazards such as fire and flood that are not already addressed, while maintaining flexibility for minimum design code on smaller projects.

Appendix F. Codes and Standards

Table F-1 lists research needs to support the theme of Codes and Standards identified during Workshops 1–4.

Table F-1. Codes and Standards

WS#	**Topic**
WS2	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.
WS2	Provide requirements for monitoring and inspection requirements for evaluating capacity and future performance under climate impacts.
WS3	Timely and flexible code updates. The current 3- to 6-year cycles for codes and standards are often too long to incorporate rapidly evolving climate science and engineering research. Mechanisms are needed to publish vetted interim requirements or supplements without confusing practitioners or undermining the authority of codes. Provide requirements for nontraditional entities that regulate development through local land-use ordinances.
WS3	Research funding, governance, and dissemination pathways. The development of next-generation codes and standards requires clarity on how research is funded, coordinated, and translated into practice. Industry groups, insurers, standards bodies, and government agencies play roles in shaping research priorities, publishing new standards, and influencing updates—yet stronger mechanisms are needed to ensure consistent dissemination of requirements not only to engineers but also to planners, policymakers, and other decision-makers who shape the built environment.
WS1	Standardize methodologies for national, transparent, open-source models to develop and archive hazard data and maps for present-day and future conditions; develop framework(s) for processing data and a centralized repository for data.
WS3	Develop codes and standards that address capacity degradation. Codes need to address frequent events that affect degradation as well as extreme events. This could be implanted through maps (e.g., ASCE hazard tool) of future environmental conditions (e.g., temperature, humidity, CO2 concentration) and associated reduction factors for degradation in structural design and evaluation.
WS3	Performance-based and future conditions design frameworks. Demand is strong for performance-based approaches (e.g., for flooding) and methods to overlay current and future hazard conditions at the site level. These frameworks would allow codes and standards to evolve beyond prescriptive rules, enabling adaptation to compounding hazards and long-term climate shifts.

WS3	Monitoring, materials, and degradation research. More research is needed on long-term performance of structures under future conditions, covering new materials, degradation mechanisms, and sensor-based monitoring of public and private infrastructure. Standardized protocols for instrumentation and data-sharing could make real-world data more accessible for codes and practice (and to ensure that data are used for good, no liability from providing entities further down the line).
WS3	Updates between code and standard cycles might be promoted by applying performance-based design. A need exists to develop guidelines and standards for data validation for interim updates, including guidelines for assessing existing structures for future conditions and procedures explaining how to review and update established criteria in codes and standards.
WS4	Establish standardized, geographically targeted datasets that are consistent with design standards and codes for use in resilience modeling and performance-based designs.
WS4	Develop, update, and calibrate data and models for incorporating functional recovery of facilities, infrastructure networks, and communities and their interactions into resilience-informed design standards and tools.
WS4	Understand the benefits of resilience to improve likelihood of adoption into codes so that it can be incorporated into standard development up front.