Design of a National Full-Scale Testing Infrastructure for Community Hardening in Extreme Wind, Surge, and Wave Events (NICHE)

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ABSTRACT

A major interdisciplinary effort to design a new multi-university facility was recently funded through the National Science Foundation's Mid-Scale Research Infrastructure (MsRI) program. The program is led by a consortium of nine universities and a wind tunnel design consultancy firm and will be leveraging field observations, computational modeling, and physical experimentation to design a *National Full-Scale Testing Infrastructure for Community Hardening in Extreme Wind, Surge, and Wave Events* (NICHE).

The centerpiece of the project is an integrated design testbed (IDT) that couples computational fluid dynamics (CFD) modeling and field data with experiments conducted in a physical design testbed (PDT) that leverages capabilities distributed across multiple experimental facilities to answer specific research questions. PDT experimental data will then be leveraged by the IDT for the design of the full-scale NICHE by [a] addressing fundamental questions on similitude requirements, [b] innovating new experimental capabilities, and [c] minimizing experimental uncertainties.

1. Introduction

Extreme windstorm events (e.g., hurricanes, downbursts, tornadoes, derechos) occur annually causing damage to civil infrastructure, resulting in population dislocation, economic losses, and community disruption (National Academies of Sciences, Engineering, and Medicine, 2019). Increasing hazard exposure and sea level rise due to anthropogenic warming are escalating the risk to society and its assets, especially civil infrastructure, e.g., homes, buildings, bridges, and lifelines. To help protect the coastal communities in the United States and across the globe against losses from extreme windstorm events, a multi-disciplinary team with demonstrated excellence in their respective disciplines and methodologies, as well as at the interfaces between them, will design a National Full-Scale Testing Infrastructure for Community Hardening in Extreme Wind, Surge, and Wave Events (NICHE). NICHE responds to this pressing national imperative to promote more resilient and sustainable communities by reducing losses, population displacement, and outmigration due to climate-driven hazards.

NICHE will provide a unique, national, multi-user facility to evaluate the impact of extreme winds combined with storm surge and wave actions on different types of civil infrastructure, including full-scale low-rise structures, large-scale infrastructure systems, and communities as scaled models. The design of the NICHE was recently funded through the National Science Foundation's (NSF's) Mid-Scale Research Infrastructure (MsRI) program. The NICHE design process will be led by a team drawn from nine universities and one industry partner: Florida International University, Colorado State University, Georgia Institute of Technology, Oregon State University, Stanford University, University of Florida, University of Illinois at Urbana-Champaign, University of Notre Dame, Wayne State University, and Aerolab LLC. This project will be a component of the NSF-supported Natural Hazards Engineering Research Infrastructure (NHERI) program and will deepen NSF's contributions to the National Windstorm Impact Reduction Program (NWIRP).

2. Scientific Objectives

Currently, there is no experimental facility in the world with full-scale (or near full-scale) combined wind-wave-surge simulation capabilities to support novel investigations of the impact of climate hazards on our society. Moreover, (i) most existing facilities are able to simulate only one of the aforementioned natural hazards independently, and (ii) in those facilities where these hazards can be simulated simultaneously, the facility dimensions and, therefore, the scale, are significantly reduced and simplified. Hence, the design of NICHE requires a unique combination of state-of-the-art techniques to ensure its functionality and develop the ability to answer the fundamental and applied scientific questions regarding multi-hazard events.

The convergent process to design NICHE will be led by a team of multidisciplinary experts with demonstrated excellence in their respective disciplines and methodologies, as well as at the interfaces between them. The team will demonstrate proof-of-concept using an **integrated design testbed (IDT)** that brings experiments, computational simulations and field observations together to design NICHE from the ground up. The IDT will enable a combined cyber-physical design process, essential to minimize the risk in NICHE's future implementation, providing a critical proving ground to (1) validate the computational modeling of the interacting hazards that can then be scaled up with confidence to inform the design of the full-scale NICHE, (2) reconcile several scientific and practical challenges associated with achieving similitude for simultaneous application of wind and water hazards in a single research infrastructure, and (3) explore design trade-offs to provide the greatest scientific return on investment. The proposed approach includes the use of a physical design testbed (PDT) that enables experimental simulation of single-phase and multi-phase combinations of wind, waves, storm surge and/or currents. The design approach also includes a complex computational fluid dynamics (CFD) component. Some of the fundamental closure and/or empirical models within the CFD component, particularly those related to the wind-wave interactions, have not been fully validated and calibrated under the conditions required at full-scale NICHE. Therefore, the design supported by CFD requires validation of some of those closure models. The PDT will take advantage of experiments at multiple existing facilities to produce experimental data needed to validate the CFD models, addressing the lack of experience and of previous validation for this type of complex coupled simulation. The validated CFD models will be upscaled to create a design for a full-scale national NICHE.

The IDT will also aid the design of non-physical aspects of NICHE: the infrastructure enabling convergence research, workforce development and stakeholder engagement. This will result in a multi-faceted design process with the following scientific objectives:

- **Objective 1: Integrative Design and Assessment:** use the integrated design testbed (IDT) to create a **Project Execution Plan (PEP)** and **implementation-ready design** for a full-scale NICHE facility with sufficient scope and capacity to simulate the effects of interacting coastal and wind hazards (for either synoptic or non-synoptic wind hazards) and demonstrate the facility's operational feasibility and technical readiness for future implementation;

- **Objective 2: Research Capacity Development:** develop a **convergent research capacity framework** and demonstrate example testbed communities to showcase how the full-scale NICHE can integrate physical testing, computational simulation, and field observations to foster breakthroughs in climate-adaptive design and mitigation to inform policy;

- **Objective 3: Workforce Development:** create training modules for students, post-doctoral researchers, facility operators, project managers, and faculty, and pilot test these modules to facilitate the **development of a next-generation workforce** trained in a convergent approach to address societal challenges associated with climate-driven hazards;

- **Objective 4: Stakeholder Engagement:** use policy learning tool kit and engagement protocols to develop a **stakeholder engagement plan** that integrates institutional and community stakeholders to create a mechanism (of) for translating future research discoveries into policy and practice.

3. Methodology

The team will use a robust design process that positions NICHE to converge traditionally siloed disciplines and methodologies for the delivery of novel research, workforce development, and research translation capabilities. This will be accomplished by operationalizing multiple dimensions of strategic integration depicted in Figure 1:

● Disciplinary Convergence: understanding that seminal discovery operates at the intersection of engineering, behavioral, social, and economic sciences;

● Methodological Convergence: optimally leveraging the strengths of computational simulations, physical testing, and field observations;

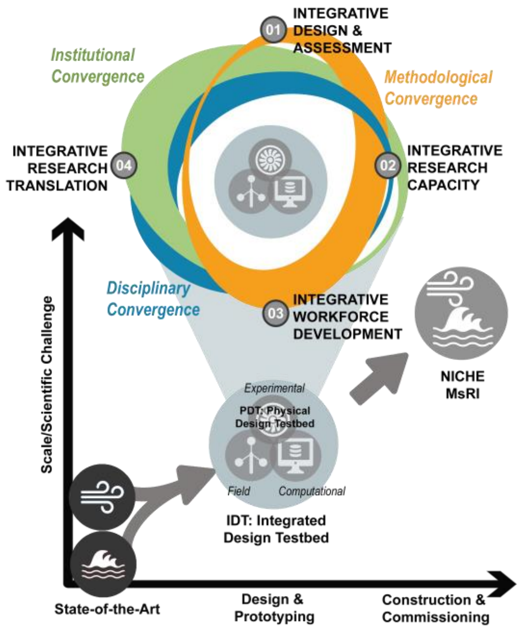

Figure 1. NICHE's evolution over time

● Institutional Convergence: contextualizing research within disaster-affected communities to accelerate impacts on policy and practice.

4. Distributed Physical Design Testbed (PDT)

The current MsRI-1 project will develop and test prototype NICHE functionality by experimenting at (and, if needed, upgrading) four existing facilities (at UCSD, OSU, UM, and UF) and a new wind-only facility to be built at FIU. The PDT experiments will be conducted by personnel associated with the tasks related to such experiments. The PDT will also serve as a physical prototype for certain novel components at full scale which will be included in the full-scale NICHE facility. These novel components include the fans and flow control devices to be used for simulation of non-synoptic wind conditions.

The wind-only PDT needs to be configured with a dual-mode capability to support operations in both open circuit and close circuit modes. The dual-mode capability will enable experiments to quantify the relative attributes of the configurations in their relationship to non-synoptic wind flow control, maximum wind speeds, flow stability, and destructive testing capabilities (including debris management) which in turn will inform the design of the final configuration for the full-scale NICHE.

During the initial phase of the project, the NICHE team focused on the selection of the distributed PDT that will provide the necessary data to validate the CFD simulations and inform the design of the full-scale NICHE. Central to this process was the formulation of a number of outstanding **scientific and technical questions** that should be answered based on PDT experiments and CFD to design the full-scale NICHE:

Q1. How do we generate correctly scaled wind/wave interaction?
- Q1.1 How do we mitigate unintended effects of wave generation on wind?
- Q1.2 What design options can generate realistic wind/wave flow with limited fetch?
- Q1.3 How does the beach shape affect the wind/wave flow and required fetch?
- Q1.4 How do we scale sea spray effects? Volume fraction and sizing of droplets; droplet spatial distribution and effect on turbulence?

Q2. What is the effect of seawater vs freshwater?

Q3. How can we generate non-synoptic wind?
- Q3.1 Can we generate realistic ranges of parameters of non-synoptic winds important to wind loading?
- Q3.2 Can we represent non-synoptic flow features as specialized simulation facilities?

Q4. What is the technical feasibility of the full-scale NICHE facility?
- Q4.1 What is the efficiency and durability of equipment (e.g., fans, motors, switch gears) and components to (e.g., high-frequency louver systems for flow controls)
- Q4.2 What are the efficiency factors and possible flow instability issues while running the system in an open circuit versus closed circuit mode (e.g., in terms of power consumption, flow controls, debris management, etc.) to balance performance, power consumption, and efficiency.

5. Programmatic Elements

The current design process is also prototyping various programmatic elements of the future NICHE facility. This includes developing a workforce that can effectively engage this research infrastructure to address grand challenges of escalating climate-driven hazards. Thus NICHE's workforce development program will develop the requisite convergence skillsets and mindsets through training that strategically targets multiple points in the workforce development pipeline. The IDT will be used to design a sequence of five training modules that will serve as a kernel for this program and scaled up and across different audiences in NICHE's future implementation. Each module centres on the cross-cutting themes of convergence to cultivate essential technical skillsets and establishes the foundation for effective research translation. More importantly, this training will impart the skills necessary for "interacting hazards modelling," thus fostering a workforce of next-generation leaders in convergence approaches and an eventual diverse user base for the future NICHE MsRI. The tailored content will be delivered as pilots offered to the graduate students and postdoctoral associates supporting the MsRI design process, with the potential to expand the pilot undergraduate students through a future Research Experiences for Undergraduates (REU) supplement. Lessons learned from these pilots will guide updates to these tailored offerings and the underlying kernel, to form the basis of the workforce development programming at the future NICHE facility. The NICHE design phase will also include planning and development for stakeholder engagement. Candidate stakeholders of the NICHE include individuals from government, industry and academia. Developing a plan and toolkit for engaging stakeholders will facilitate the cross-cutting impacts of NICHE's design on long-term resilience.

6. Scientific and Broader Societal Impacts

6.1 Scientific Impacts

Direct losses, perhaps the simplest (though non-comprehensive) indicator of vulnerability, demonstrate that the current methods for developing the coastal built environment are not sustainable given the escalating risks from climate-driven hazards. To date, the research community has been unable to answer a number of high-priority scientific questions arising from the need to respond to this threat. The failure to resolve these questions stems from: (1) the inability to physically simulate coupled climate-driven hazards at the scales required to faithfully reproduce vulnerabilities in our built environment; and (2) the sole use of such experiments without engaging computational simulations or field observations required to overcome their limitations.

Historically, investigations of windstorm impacts on civil infrastructure have engaged a trio of methodological approaches: physical experimentation, computational simulations, and field observations. While considerable advances have been made in each, none has been able to adequately capture the complex physics of structures subjected to interacting wind and coastal hazards. Existing experimental facilities (such as those under NHERI) can simulate the impacts of coastal and wind hazards on civil infrastructure independently in different facilities and at different scales, missing opportunities to advance and validate computational models for coupled hazards. These facilities further lack the physical scale and intensity to authentically recreate the catastrophic failures observed in practice and assess the efficacy of potential mitigation solutions.

The design produced by this MsRI project is for a NICHE facility that can physically simulate coupled climate-driven hazards at the scales required to faithfully reproduce realistic vulnerabilities in the built environment and link these experiments with field observations and computational simulation for a truly comprehensive research platform to study the impact of extreme winds combined with storm surge, waves, and currents on different types of civil infrastructure, including full-scale low-rise buildings, large-scale infrastructure systems, and scaled community models. Thus, the anticipated NICHE facility will enable the wind and coastal engineering research community to address high-priority scientific questions arising from the impact of increasing storm risks on civil infrastructure through high-fidelity investigations of the three dimensions of the problem space: wind hazards (synoptic and non-synoptic), coastal hazards (waves and storm surge), and the built environment (e.g., from structures to community scale).

6.2 Broader Impacts

NICHE will directly respond to one of the biggest societally-driven challenges of the 21st Century: achieving more resilient, sustainable, and climate adaptive communities (National Research Council, 2012, Applied Technology Council, 2016; National Institute of Building Sciences, Multi-Hazard Mitigation Council,2019; ASCE's Policy Statement, 2021). NICHE's design initiates the essential convergence of previously siloed research and stakeholder communities,delivering critical thought leadership, new lines of inquiry, and the intellectual capacity for new dimensions of transdisciplinary collaboration. The adopted convergence approach ensures that the resulting technical breakthroughs ultimately reach affected communities to reduce future losses, strengthen economic and national security, and promote societal well-being. This is achieved through research translation, workforce development, and stakeholder engagement. NICHE's approach to Research translation fosters the exchange of scientific knowledge, technical recommendations, and policy opportunities with practitioners and policymakers. Meanwhile, NICHE's integrated workforce development maintains a competitive advantage for the US in hazards research. It further cultivates the next-generation's capacity, including early career faculty, to continue the advancement of convergence research that is anchored within affected community contexts, engaging underrepresented populations disproportionately vulnerable to climate-driven hazards. In addition, NICHE's stakeholder engagement focuses on integrating research, academic, industry and government in planning the translation of facility research to practical policy lessons and applications. Finally, NICHE uses two of NSF's 10 Big Ideas to expand the agency's leadership not only in the National Windstorm Impact Reduction Program but also in the Nation's climate-responsive infrastructure priorities, while capitalizing on past NSF investments by more intently integrating their data and capacities into the proposed research infrastructure.

Acknowledgment

The authors would like to acknowledge the National Science Foundation's (NSF's) financial support for Award # 2131961 (Mid-scale RI-1 (M1:DP): National Full-Scale Testing Infrastructure for Community Hardening in Extreme Wind, Surge, and Wave Events (NICHE)). The views and opinions expressed in this paper are those of the authors and do not necessarily reflect the position of NSF or their respective institutions.

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