Report on Discussions

Multi-hazard Engineering Collaboratory for Hybrid Simulation: Breaking Barriers & Building Capacity

Workshop held December 12-13, 2017
at the University of California, San Diego

Summary

Hybrid simulation is a powerful technique used to examine the behavior of structural systems that may be too large or complex to test in the laboratory. Physical specimens are coupled with computational models, enabling the physical subsystem to be examined under realistic conditions. Hybrid simulation methods have traditionally been used for earthquake engineering, but a new generation of methods is also being developed for tackling wind and coastal engineering problems. Additionally, technical challenges have hindered the application of real-time hybrid simulation for more complex problems. The Multi-Hazard Collaboratory on Hybrid Simulation, (MECHS), has been formed to support a community that can address these needs and challenges, while breaking down barriers that have hindered the use of these methods.

The MECHS Research Coordination Network aims to facilitate the scientific advances needed to establish the theory of and expand the capacity for hybrid simulation as it applies to multi-hazard engineering.

The 1st MECHS Workshop "Breaking Barriers and Building Capacity" was held on December 12-13, 2017 at the University of California, San Diego. A group of 40 researchers participated, including multi-hazard engineering researchers, graduate students, international partners and interdisciplinary collaborators. This report provides a summary of those discussions aiming to identify specific research needs and priorities for this community, as well as capacity building activities that will broaden the community and the types of experimentation possible through the class of hybrid simulation methods.

See the MECHS page for more activities and resources: http://mechs.designsafe-ci.org

The Research Coordination Network in Hybrid Simulation for Multi-hazard Engineering is supported by a grant from the National Science Foundation (CMMI#1661621).

Introduction

The 1st MECHS Workshop titled “Breaking Barriers and Building Capacity” was held on December 12-13, 2017 at the University of California, San Diego. During this 1.5 day workshop we aimed to: bring together a diverse group of researchers to discuss challenges and the opportunities; identify directions that will break through barriers that have hindered new applications of these methods; engage researchers that may be new to hybrid simulation, while leveraging the expertise of researchers working in hybrid simulation; consider ways to effectively build capacity and enable hybrid simulation at more laboratories; and develop a research agenda for hybrid simulation.

A group of 40 researchers participated, including multi-hazard engineering researchers, graduate students, international partners and interdisciplinary collaborators. After a brief introduction to the MECHS community and the workshop goals and agenda, each researcher gave a short presentation to introduce themselves, their background and interests, and their interests in the workshop. These short presentations delivered by each participant are collected and are available on the MECHS DesignSafe site. Then three breakout sessions were formed, two focused on Breaking Barriers and one focused on Building Capacity. Two co-leaders and one recorder in each group were charged with leading the discussions and documenting those for this report. The full agenda for the workshop is documented in the Appendix of this report.

The discussions at the workshop spanned the several classes of hybrid simulation methods that are being used and developed for various problems and applications. Traditional *hybrid simulation* (HS) is conducted at an extended time scale, typically uses higher-order computational models, and is applied when rate-dependence is not present or not significant in the physical subsystem. *Real-time hybrid simulation* (RTHS) is needed when rate dependence plays a significant role in the dynamics of the physical subsystem, although it requires both high-fidelity control of the actuation system and real-time execution of the computational models and associated supervisory tasks. Furthermore, *geographically-distributed hybrid simulation* and *geographically-distributed real-time hybrid simulation* have been demonstrated in isolated cases to further expand the range of possible experiments by coupling multiple laboratories. Each of these classes of methods was discussed across the breakout groups.

Each of the groups also considered what methods may be most effective to Build Capacity across the multi-hazard community and beyond. That is, they considered how more researchers and more labs could gain access to these experimental techniques. Learning materials, illustrative examples/codes, shared digital artifacts, and testbeds/benchmarks were considered to be all effective methods for engaging a broad audience in the fundamentals and challenges in HS/RTHS methods. These types of valuable information will continue to be made available on the MECHS DesignSafe site.

The main points of each working group’s discussions are provided in the next sections of this report, followed by a summary of the research needs and action items regarding the needs of the community for continued progress.

Group 1— Breaking Barriers: Problems & Algorithms

Co-Chairs: James Ricles (*Lehigh University*)
Oh-Sung Kwon (*University of Toronto*)
Recorder: Amin Maghareh (*Purdue University*)
Participants/Affiliations:
Yunbyeong Chae (*Old Dominion University*)
Pei-Ching Chen (*National Taiwan University of Science and Technology, Taiwan*)
Jose Alberto Escobar Sanchez (*Universidad Nacional Autónoma de México, Mexico*)
James Gibert (*Purdue University*)
Chris Gill (*Washington University in Saint Louis*)
Gaston Fermandois (*University of Illinois at Urbana-Champaign*)
Narutoshi Nakata (*Tokushima University, Japan*)
Manuel Vega (*University of California, San Diego*)
Tao Wang (*Institute of Engineering Mechanics, China*)
Bin Wu (*Harbin Institute of Technology, China*)
Jian Zhang (*University of California, Los Angeles*)

The objectives of this working group were to identify barriers/problems for issues that have hindered both hybrid simulation (HS) and real-time hybrid simulation (RTHS) users from tackling more challenging problems and discuss potential solutions to deal with barriers/problems. This group focused on the questions: *What are technical barriers that prevent us from tackling more complex problems? How might we overcome those? How can this be adapted to solve new problems in the Wind and Coastal Engineering area? Are there other engineering fields that could benefit from hybrid simulation methods*?

Main Points of Discussion

HS and RTHS are cyber-physical, time-efficient and cost-effective techniques that integrate physical testing (experimental substructure) with computational simulation (numerical substructure) to offer powerful methods to investigate behavior of structural systems subject to dynamic loading. Until recently, HS and RTHS have been primarily used to investigate the response of structures to seismic hazards.

New Applications and Domains

Participants in Working Group 1 discussed several new applications/domains in which HS and RTHS may be useful:

- Biomedical field
- Wind and Coastal Engineering
- Fluid-structure interaction
- Soil structure interaction
- Progressive collapse of structural systems
- Aerospace and mechanical engineering field

Currently, there is a need to identify meaningful problems/examples in these domains through the communication between the HS/RTHS community and these researchers. In addition, a number of barriers related to the implementation of HS and RTHS in these domains were identified. The most significant barriers discussed in Working Group 1 are summarized as follows.

- <u>Computational resources:</u> High-fidelity computational substructures and need for real-time high-performance computing capabilities
- <u>Frequency range:</u> Frequency ranges of interest in these applications are different from seismic applications (e.g., in aerospace and mechanical applications, it can exceed 100 Hz)

- Time scale: Need to consider time-scaling issues in some of these applications
- Algorithms and techniques: Need to modify/revise existing algorithms to accommodate these ranges of frequencies (e.g., control, actuation and integration) and time-scaling issues
- Boundary conditions: Highly coupled multi-actuators and need to develop more sophisticated control strategies

The discussions that took place during the breakout sessions for Working Group 1 included addressing these barriers. The discussions are presented below.

Challenges in the Computational Substructure/Integrators

Several issues/challenges regarding the computational substructure in RTHS were discussed. A number of computational bottlenecks towards the implementation of highly accurate RTHS were identified. One of the most significant bottlenecks at this time is the execution of high-fidelity computational substructures with real-time guarantees. In RTHS, researchers need to justify the choice of a numerical substructure which meets the user requirements, is accurate, and the uncertainty can be quantified. Several group members indicated the need for real-time high-performance computing platforms in RTHS considering cache effects to effectively use multi-core processing and decomposition of the numerical substructure to use the cores and parallelism more effectively. Opportunities are being missed in the community due to a lack of plug-and-play real-time high-performance computing platform. A real-time high-performance computing platform will offer immediate and significant advances in the fidelity of numerical substructures and implementation of complex multi-directional actuation system controllers. In addition, it will enable an integrated platform for multi-rate computational domain: dimensioning, coordination and allocation of computational resources.

On the computational side of RTHS, currently researchers use various numerical modeling alternatives, such as the finite element method (FEM), convolution integral (CI) and multi-rate methods. FEM subdivides a large computational problem (here, the numerical substructure) into smaller, simpler parts, called finite elements. CI method is developed to specifically address the challenges of the size and convergence of high-frequency behavior of the numerical substructure. In addition, multi-rate methods are developed to enable the use of more complex computational models executed at real-time via employing different time-steps in computational and physical substructures. Several researchers indicated that for the use of RTHS in new applications, where other numerical substructure methods are used such as discrete element method (DEM). DEM is one effective method of addressing engineering problems in granular and discontinuous materials, especially in granular flows, soil and rock mechanics.

The need for rigorous assessment and investigation of the effectiveness of different integration algorithms for linear and nonlinear computational substructures was discussed. Currently, there are two classes of integrators being used in the community: explicit and implicit (predictor-corrector). Explicit integrators are more suitable for RTHS but stability needs to be considered and they can generate high frequency noise in nonlinear systems. On the other hand, implicit integrators are more computationally intensive due to iterations involved. Several researchers indicated that a new generation of integrators should be developed based on effective use of energy norms for assessment of stability, considering energy balance and need for controlled numerical damping.

Challenges in the Experimental Domain, Sensing and Actuation Systems

A number of challenges to implementation of RTHS in new applications (e.g., wind and coastal) were identified. One of the most significant challenges is the need to accommodate different time scales for some of these applications. To overcome this challenge, some researchers indicated two approaches, real-time high-performance computing and normalized time stepping methods (multiple domains with different time stepping). Other challenges identified by researchers in Working Group 1 were the scale effects of the experimental substructure (manufacturing, device behavior, etc.) and the impact of new sensor dynamics (noise, time delay and lag) on the global accuracy of experiments.

Toward facilitating the implementation of more complex experiments, the need for developing model-based self-adaptive robust actuation system controllers would be an appropriate approach. Due to the interaction effects between physical substructure(s) and actuation systems (a.k.a., control-structure interaction), dynamics of test fixtures and oil-column resonance, experimental substructure need to be attached to actuation system for pre-test tuning of controllers and accurate boundary condition enforcement. In traditional approaches, actuation system control is manually tuned which could damage the experimental substructure. Thus, a number of researchers indicated the need for the development of a new generation of model-based self-adaptive robust actuation system controllers. In addition, from a tracking control perspective, there are two types of coupling between actuation system and physical substructure, soft and rigid. The former coupling type is usually not a challenging control problem. However, the latter coupling type is a significant stability concern in RTHS. One possible solution for boundary conditions of stiff specimens is the use of compliant elements in the test setup.

A number of barriers and limitations to effective implementation of boundary conditions in RTHS were identified. Usually researchers avoid the implementation of realistic boundary condition through simplifications and assumptions. In the lab, there are restrictions in terms of applying boundary conditions, such as space, logistics, sensors, etc. In some problems, researchers need to apply surface load instead of discrete load. Some participants of Working Group 1 indicated the most significant technical barriers that currently prevent researchers from tackling more complex problems include:

- Rotational boundary conditions
- Kinematic transformation and coordination of multi-degree-of-freedom boundaries
- Nonlinear geometry and redundancy problem (more actuators than the DOF)
- Highly nonlinear problems / computationally expensive

Action Items and Future Research Needs

- A rigorous assessment of integration algorithms for application of RTHS
- Development of integration schemes considering energy balance
- Development of benchmark problems
- Development of real-time high-performance computing platforms
- Education
    - Recommended course curriculum for students
    - EOC: Educational/outreach, equipment requirements
- Multi-rate computational domain for application to high-fidelity RTHS
- Assessment of different computational modeling alternatives (e.g., FEM, CI method and DEM) in terms of accuracy and resource requirements
- Development of self-adaptive actuation system control algorithms
    - Model-based control strategy due to interaction effects between physical substructure and actuation systems

Group 2— Building Capacity: Testbeds, Workflows, Benchmarks, Community, and other Resources

Co-Chairs: Gilberto Mosqueda (*University of California San Diego*) and
Andreas Schellenberg (*University of California, Berkeley*)
Recorder: Johnny Condori (*Purdue University*)
Participants/Affiliations:
Hector Guerrero Bobadilla (*Universidad Nacional Autónoma de México, Mexico*)
Humberto Caudana (*University of California, San Diego*)
Shirley Dyke (*Purdue University*)
David Ferry (*St. Louis University*)
Bahareh Forouzan (*Clarkson University*)
Mateo Gonzales Hurtado (*Universidad del Valle, Colombia*)
Igor Lanese (*EU Centre, Italy*)
Ge (Gaby) Ou (*The University of Utah*)
Wei Song (*The University of Alabama*)
Manuel Vega (*University of California, San Diego*)

The main objectives of this group were to discuss and brainstorm ideas on how to expand the user base and applications of hybrid simulation and how to collect and curate resources for new, intermediate, and advanced users of hybrid simulation. This group focused on strategizing about how to establish HS and RTHS capabilities in more laboratories, including: presentations to the NHERI community, documentation of experiments, curricular development, webinars, how to integrate into proposals, how to share through the MECHS webpage, how to advertise these abilities, common materials that can be used by the community, etc.

Main Points of Discussion

Based on an extensive discussion between experts and novices in Hybrid Simulation, this group has developed a strategy based on *development, documentation,* and *sharing* of key resources that will ensure that essential and emergent Hybrid Simulation theory and technologies will be delivered effectively to users with different levels of expertise. This tripartite plan is developed and explained below.

Resources to develop and implement:

Provide a library of modules to conduct a hybrid test: Build and make available simulation cases in which the controller, model of the plant and the numerical substructure are provided in Simulink or another standard platform. These libraries should include relevant modules such as compensators, algorithms, and integration methods using common syntax and language. They should allow flexibility to use different modules and control schemes. It is suggested that a collection of validation case studies comparing HS and shake table test results (develop testbed cases) is assembled. For example, EUCENTRE and other labs have done extensive experimentation with large bearing devices using Simulink. Data can be made available to validate numerical models of actuators and improve the understanding of actuator dynamics (tracking and delays).

Development of learning material for HS and RTHS at different levels of expertise. There is an urgent need for users to find reliable and comprehensive learning material, and in order to provide them, the Working Group 2 has discussed the question “How to educate grad students to have a general knowledge of HS/RTHS in addition to shake table testing and quasi-static testing?” One effective method could be to provide different media including documents and videos, and develop course modules on experimental methods such as those by Profs. Bozidar Stojadinovic and Andrei Reinhorn.

Additionally, students and researchers interested in learning the fundamentals should take advantage of this *list of recommended classes* for understanding HS/RTHS outside and within earthquake/wind/hazard engineering:

Inside a typical Civil Engineering curriculum	**Not typically in a Civil Engineering curriculum**
Structural Dynamics	Digital Signal Processing
Finite Element Methods	Classical Control Theory
Experimental Methods	Modern Control Theory
Earthquake Engineering	Multivariable Robust Control,
Wind Engineering	Nonlinear Control

Testbeds: Availability of small and large integrated environments for experimentation are of paramount importance. A large scale frame that will allow individuals to test different types of protective devices, isolators, dampers, or other systems such as frames, walls, different configurations at full scale, in which we can use different simulation tools (Simulink, OpenFresco, OpenSees) and controllers. On the other hand, smaller testbeds will serve for educational or development purposes. However, before conducting HS and RTHS in a laboratory setting, virtual (purely computational) testbeds are of substantial importance since they can be used to test and debug control features and DAQ systems.

Assessment measures. Usually, once a HS/RTHS experiment is successfully conducted, data has to be analyzed and researchers must evaluate whether or not their results are close enough to the real dynamic system behavior. Thus, discussion of acceptance criteria is important, building upon past reports and discussing benefits to available procedures.

Documentation of resources:

According to experience, conducting HS/RTHS can be very challenging, especially for those new to this type of testing. Identifying a mistake in the hardware or debugging the software may take a great deal of time. Therefore, sharing experiences, not only successful, but also unsuccessful cases by collecting data, identifying, and documenting challenges and lessons learned (a trouble shooting manual) will be great help when dealing with instabilities during testing or inconsistencies in the resulting data. It is suggested that this information be stored in a “Wiki” site through MECHS.

The Slack platform could prove useful for short answers, but the creation of a Forum on HS/RTHS would likely be more useful for rapid interaction between people for dedicated and more technical discussions. A mailing list is an alternative (research gate) approach that was mentioned. However, volunteers are needed to curate data/contributions. Also, a decision needs to be made on whether it should be done in partnership with NHERI resources.

Feedback from participants revealed that the “Hybrid Simulation Primer and Dictionary” document is a helpful resource to start with HS/RTHS. However, later when implementing the method, fundamental questions tend to arise, in which case, a second generation of Primers (Primer 2.0, for instance) for intermediate users would be desirable.

Current papers on HS/RTHS are not useful for novice users and researchers because they do not describe the basic steps with enough detail. But, it is known that there exist past reports and papers where essential procedures were described in detail and many of these reports discuss the basics of hybrid testing. It is suggested that these reports are identified in order to generate a basic source of information and to provide an explanation on how HS/RTHS has evolved over time. An initial list of past reports was discussed, and that list can be expanded as time goes on.

Share, disseminate and advertise:

All the resources to be developed and gathered for conducting HS/RTHS will be shared with the community in a gradual and smooth fashion. These resources will be demo versions of virtual testbeds first, then resources for experimentation in small scale will be made available; large scale would be the next step. For instance, one integral example could be the development of a tracking problem using a hydraulic actuator due to its usefulness to understand the impact of the control approach. We must keep in mind that people new to HS/RTHS need information available in one place (guidelines). However, creating documentation requires funding and should be part of broader impacts in NSF proposals.

Workflow: Identify key steps to hybrid simulation and potential for standardization of modules that can be interchangeable.

Get more involved in industry-centered conferences. Include discussion with people in code committees for a potential adoption in practice. How can the technology be transferred to industry applications? Recent application of HS/RTHS to Nuclear Power Plants with support from the International Atomic Energy Association (IAEA).

Communication: How do we keep this discussion going?

Actions Items

- Organize and prepare a series of lectures (~30 min video) in which a knowledgeable researcher/practitioner contributes in his/her area of expertise to make an integral course in HS/RTHS.
- HS101 webinars to provide basics for beginners.
- Collect simple template configurations/models to get started with running HS/RTHS. Start with compensators (benchmark problems).
- Extend the (NEES) Primer on HS to a Primer 2.0.
- Collect list of fundamental references. Organize them so that a user can transition smoothly from basics to more advanced topics. They will be made available through the MECHS website under Resources.
- Recover HS/RTHS material and data from old NEES experimental sites. Look for dissertations, reports (more detailed), other workshops.
- Contact DesignSafe about setting up a HS Wiki.
- Contact Profs. Bozidar Stojadinovic and Andrei Reinhorn for access and posting of experimental methods course material.

Resolution

We all agree to contribute and share data and documents, and sample code that will help the community to build capacity in HS and foster collaboration.

Group 3— Breaking Barriers: Expanding to Wind and Coastal Engineering

Co-Chairs: Forrest Masters (*University of Florida*) and
Arindam Chowdhury (*Florida International University*)
Recorder: Brian Phillips (*University of Maryland*)
Participants/Affiliations:
Sungmoon Jung (*Florida A&M University*)
Richard Christenson (*University of Connecticut*)
Mohamed Moustafa (*University of Nevada, Reno*)
Xiaoyun Shao (*University of Western Michigan*)
Pedro Lomonaco (*Oregon State University*)
Arturo Schultz (*University of Minnesota*)
Ho-Kyung Kim (*Seoul National, South Korea*)
Roberto Gomez (*Universidad Nacional Autónoma de México, Mexico*)
Cheng Chen (*San Francisco State University*)
Denis Istratii (*University of Nevada, Reno*)

This group focused on identifying the characteristics of problems in wind and coastal engineering that can/should be tackled with HS/RTHS, for example: fluid-structure interaction, more realistic component evaluations, etc. To introduce some initial discussion items, Brian Phillips presented on the automated optimal design of a structure under wind loads. The approach uses boundary-layer wind tunnel (BLWT) testing to evaluate candidate designs created using a mechatronic specimen. The exploration of candidate designs is controlled through numerical heuristic search algorithms. A proof-of-concept study was demonstrated for a low-rise building with adjustable parapet wall for both single and multi-objective optimization. Then Richard Christenson presented on the RTHS of a tall building. The building envelope was represented as a rigid model in a BLWT and the across-wind dynamics were controlled through an actuator below the specimen. Pressure measurements on the model were fed to a dynamic numerical model and the expected deflection was produced in the BLWT using the actuator.

Main Points of Discussion

The case for HS/RTHS

- We are trending toward fully numerical analyses. HS/RTHS is a step toward this future. We need to think about how things will be designed in the future
- Current approach – spring models for boundary conditions of section models. Replace spring with actuator – more accurate boundary conditions
- Section model tests can be used to extract parameters. HS can provide freedom to validate aero-elastic and hydro-elastic models. First step – validate current practice.
- Convenience of wind tunnel test, and reliability of the test.
- Process and use data immediately

Problems in wind engineering that cannot be solved now.

- Computational fluid dynamics (CFD) – problems with CFD simulating separating flows, wakes, vortices
- Problem with CFD – Moving grid in CFD to model flow of fluid for tsunami
- Numerical instabilities which can cause problems in hybrid simulation, e.g. extended time scale HS
- Lack of an adaptive BLWT scheme
- Nonlinearities (details later)

What type of hybrid simulation do we want to do?

- Couple two facilities (a.k.a. geographically distributed hybrid simulation); couple two simulations; couple one facility to simulation
- Suggestions from the group include: to keep numerical side as structural, to keep experimental side as wind or tsunami loads (faster than CFD)
- Validate CFD before it is brought into HS
- Improve speed of CFD before it can be used in RTHS. Slow speed HS coupled with CFD is currently feasible
- Force based and displacement based approaches should be examined

Utilizing existing technologies to advance HS
- To use high performance computing (HPC) and take advantage of multiple cores, we need to discretize or parallelize the problem
- Most of the time, HPC runs using a job-based approach. Can one run a daemon to receive and process data on the fly?
- Work on using a local HPC with multiple cores underway for RTHS in Shirley Dyke/Chris Gill collaboration
- Different data collection methods or techniques could eliminate pressure tap delays
- Pressure measurements from Scanivalve sent over UDP. Intercept stream and process in real time

Practical concerns
- Complexity means different things in EQ and wind/coastal. Need to be aware of complexities before choosing HS. Boundary conditions are a significant challenge in earthquake HS. Likely the same is true in wind/coastal HS
- Actuators in close proximity to water is a problem for coastal engineering. Can use water or air actuators. Order of magnitude in cost increase. Can use mechanical solutions to transfer forces from hydraulic oil actuators.
- External actuators and sensors can distort the fluid flow

Research Questions

Development areas
Many of the standard algorithms for seismic RTHS should work for wind/coastal engineering. Loop rates are nominally the same. Seismic and wind are around the same frequency after scaling. [Challenges may arise if having experimental substructure with material nonlinearities]. Additional algorithm development required for:
- Mechatronic models (e.g., spine) for HS (model in the loop) or optimization (loop in the model)
- Reduced DOF model specimen (idealization) and validation. How does this differ in wind/coastal versus seismic?
- Transfer learning: use experimental results to validate numerical models. Use numerical models to train neural networks or other learning techniques. Integrate into HS.
- We want to process data immediately (e.g., RTHS). Rather than post-processing. Need intelligent systems to process and use the data. Artificial and General Intelligence (AGI).
- Use deep learning to automatically adapt the testing protocol based on collected data.
- Develop new sensors and signal processing techniques as needed for HS applications (e.g., pressure measurements under vibrating models).

General applications of HS
- Optimization of civil infrastructure and lifelines for strength and serviceability
- Advancing computational wind/coastal engineering
- Nonlinear response to wind/water action
- Simulation of structural degradation

- Simulation of aeroelastic and hydroelastic behavior accounting for multiple DOFs

Hazard scenarios / coupling

- Can we combine WOW with Oregon State?
- General design procedure that works for wind and earthquake – calibrated for location. [Joel Conte]
- How hazard-specific wind/coastal/earthquake mitigation techniques influence responses under other hazards (e.g., base isolation, TMD)
- Concurrent/simultaneous multi-hazard, e.g., wind and surge.
- Sequential multi-hazard, e.g., tsunami following an earthquake
- Wind driven rain: In the current approach, a water coefficient distribution is used in combination with breach models to estimate losses. HS can enhance this modeling technique.

Structure-specific applications

- Can HS be applied to continuous systems such as dams and tunnels?
- Design of LS bridges. Aeroelastic testing in BLWT is the most expensive approach. IT is hard to match natural frequencies in model. Models are for final check. HS can potentially replace current approach.

Unique approaches to HS

- In seismic HS/RTHS, building is substructured into numerical and experimental components. Go beyond substructuring/partitioning and explore other approaches for wind/coastal.

Nonlinearities

- Still can't explain sudden failure under winds – roof failures and other abrupt failure mechanisms. This is especially a problem for tornadoes.
- Nonlinearities can be used to develop fragility curves. Current experimental and CFD approaches are insufficient. HS can possibly provide this information.
- To define damage states you need a nonlinear model.
- To create nonlinearities:
    - Can create a BLWT model that can reproduce nonlinearities. Difficulty in achieving accurate material nonlinearities such as concrete at 1:50 scaling or so, so need equivalent mechanisms.
    - Can couple BLWT model with a numerical model that captures material nonlinearities.
    - Can couple BLWT model with a large scale experimental model. Creates a time scale mismatch that needs to be explored further.
- Success has been achieved for scaled nonlinear modeling for centrifuge tests in EQ.
- Couple numerical with a large scale models capturing the failure mechanism (such as transmission towers).
- Aerodynamic damping effects can be captured through HS if large deformations can be applied in experiment

Action Items

- Create wind/coastal engineering 101 resources or assemble existing resources (e.g., free online courses).
    - Approaches to learn about wind/coastal: contact NHERI sites and work with them to develop NSF and other proposals
- Disseminate a list of grand challenges in wind/coastal engineering.
- Develop testbeds at OSU, FIU, UF for demonstration and dissemination. Include Lehigh, Sim Center, and Data Center.
    - Can be used to validate HS.
    - Can be used to validate CFD for eventual integration with HS.

  - Many databases of experimental results are available for CFD – identify benchmark potential. Develop databases for fluid-structure interaction.
- Identify acceptability criteria for HS results in wind/coastal engineering.

Resolutions

Encourage the RCN to continue these collaborative activities, and to:

- Facilitate relationship development around these topics
- Identify other stakeholders and agencies who could support HS

APPENDIX: DETAILED AGENDA

DAY 1: 8:30am – 8:00pm	
8:15-8:30am 8:30-8:40am 8:40am-12:00pm 12:00-1:00 pm 1:00-3:00pm 3:00-3:30pm 3:30-5:30pm 6:00-8:00pm	Check in. Introduction & Goals (15 min). Explanation of the research agenda All give 3 minute presentations on research needs (see email) Coffee break included. Buffet Lunch and Begin Break Out Discussions Break out sessions "A" Break Break out sessions "B" Dinner on the Terrace
DAY 2: 8:30am – 1:00pm + tour	
8:30-10:00am 10:30am-12:00pm 12:00-12:45pm 12:45-3:45pm	Break out sessions "C" Summary / reports & research agenda, survey completion Box Lunch and Discussion of Next Steps Tour of the UCSD Shake Table & NHERI Facility

BREAKOUTS by Topic:

Time	**Group 1** **(Room ?)**	**Group 2** **(Room ?)**	**Group 3** **(Room ?)**
BO sessions A **1:00-3:00**	Breaking Barriers: Problems & Algorithms	Building Capacity: Testbeds, Workflows, Benchmarks, and other Training Resources	Breaking Barriers: Wind/Coastal
BO sessions B **3:30-5:30**	Breaking Barriers: Problems & Algorithms	Building Capacity: Testbeds, Workflows, Benchmarks, and other Training Resources	Breaking Barriers: Wind/Coastal
BO sessions C **10:00**	Wrap-up on Research Agenda	Wrap-up on Research Agenda	Wrap-up on Research Agenda