A Research Coordination Network (RCN):
Multi-hazard Engineering
Collaboratory in Hybrid Simulation

Breaking Barriers & Building Capacity

1st Workshop, December 12-13, 2017
Univ. California, San Diego

Supported by the
US National Science Foundation

A Research Coordination Network (RCN):

Multi-hazard Engineering Collaboratory in Hybrid Simulation

This 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.

MECHS Steering Committee:

Shirley Dyke	Oh-Sung Kwon
Cheryl Ann Blain	Gilberto Mosqueda
Roberto Gomez	Narutoshi Nakata

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Research Agenda

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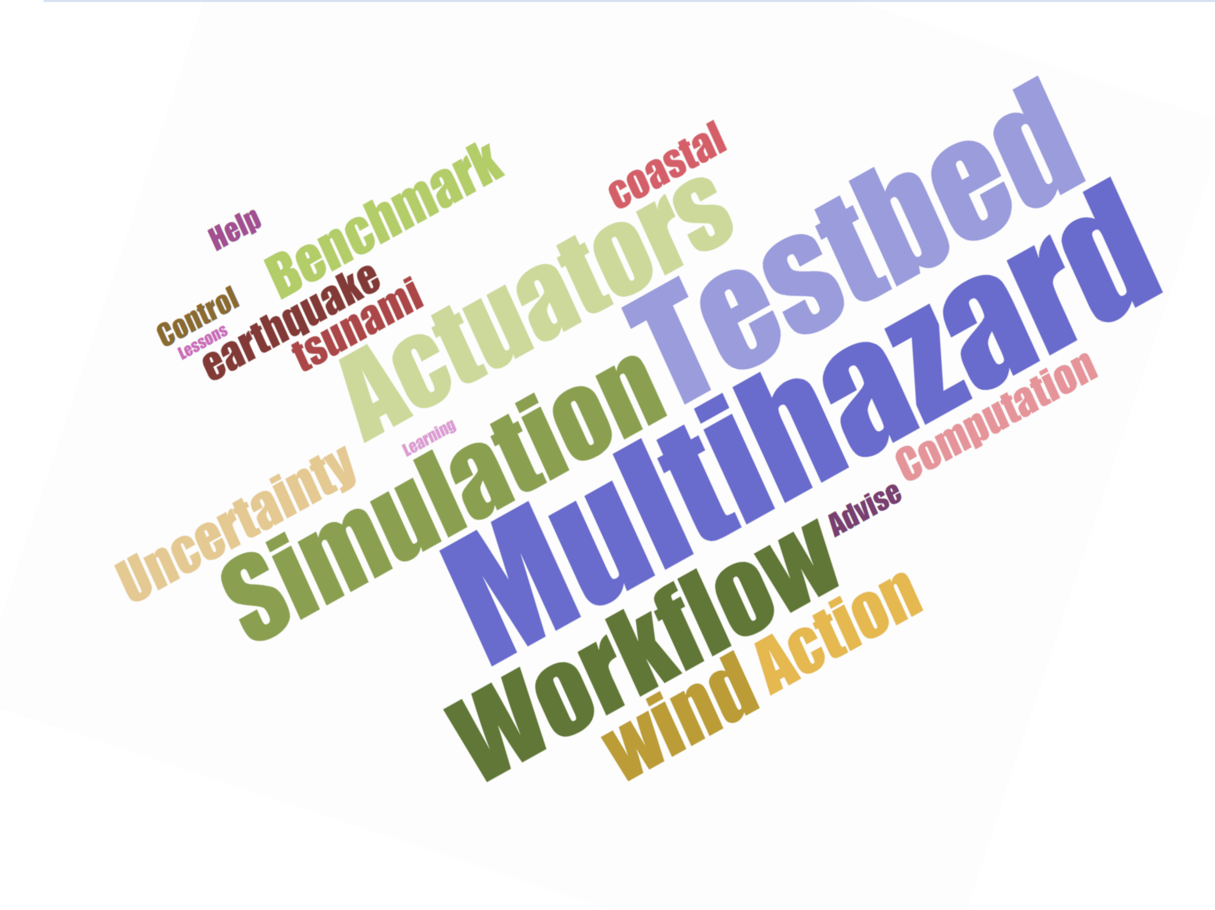

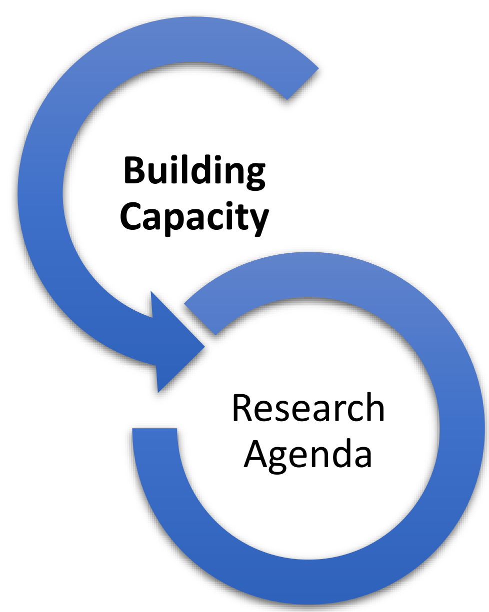

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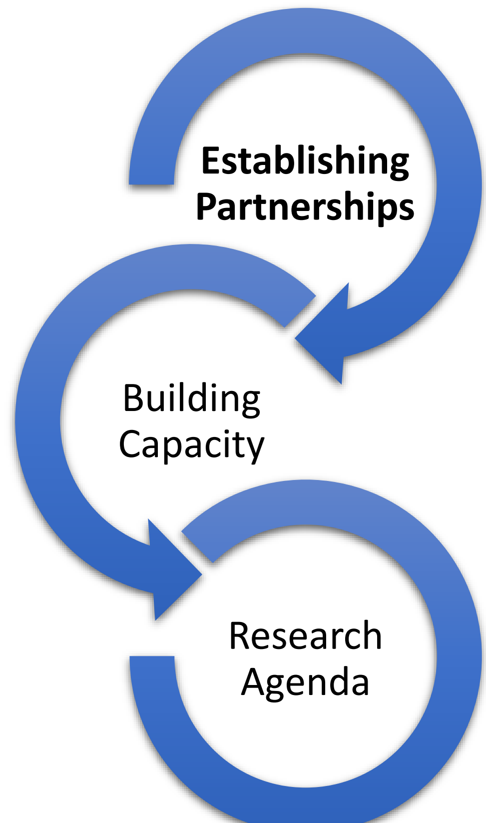
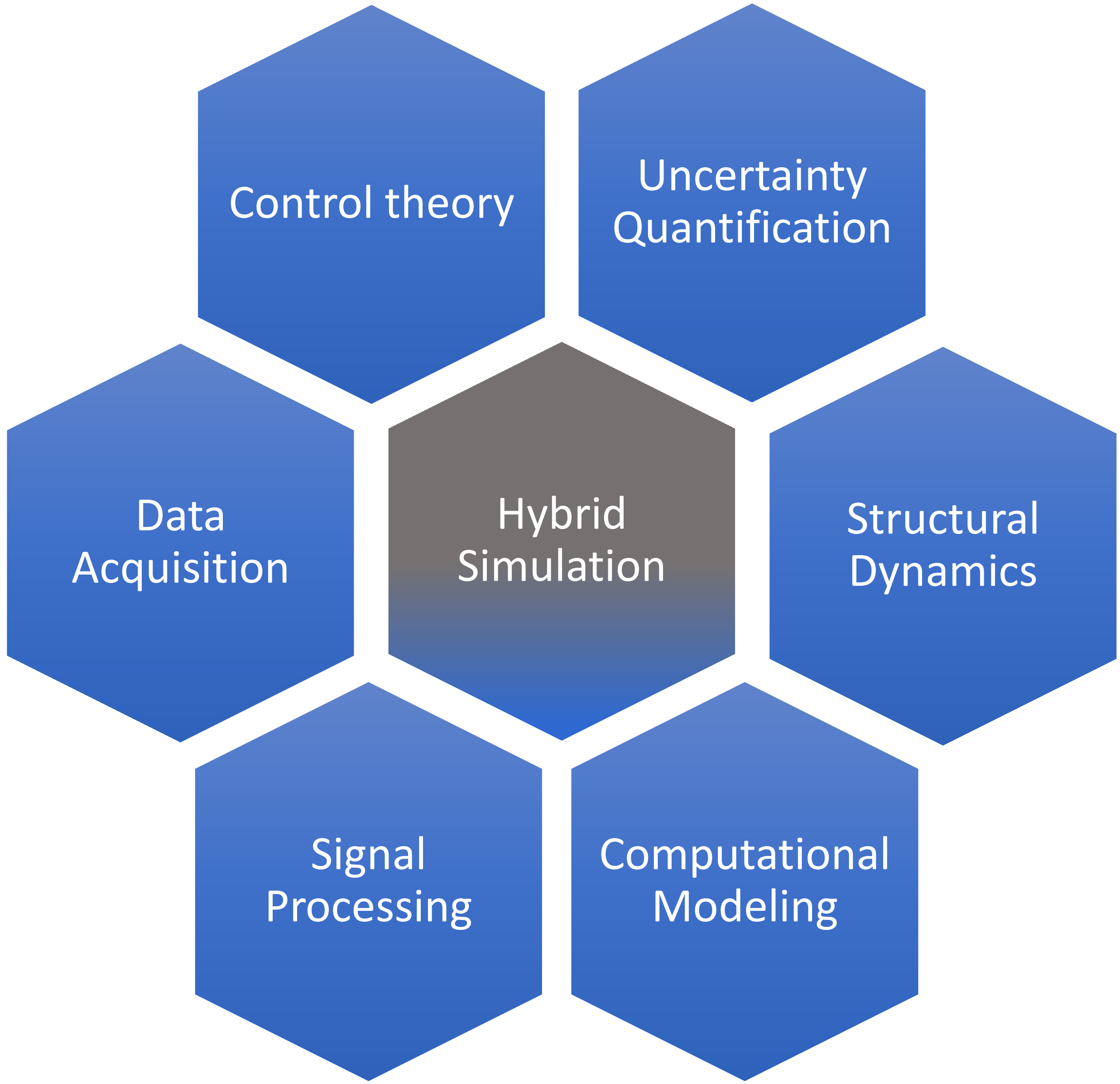


Multi-disciplinary



Online Resources, Community

DESIGNSAFE-CI

NHERI: A NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE

MULTIHAZARD ENGINEERING COLLABORATORY ON HYBRID SIMULATION

A RESEARCH COORDINATION NETWORK

DESIGNSAFE-CI
A NATURAL HAZARDS ENGINEERING COMMUNITY

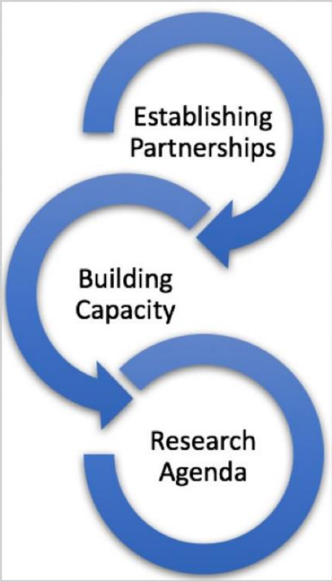
MECHS OVERVIEW

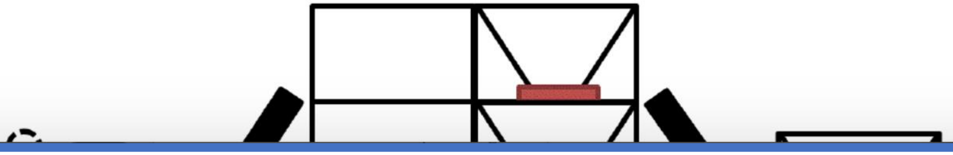
Hybrid Simulation is a cyber-physical technique used to examine the behavior of structural systems that may be too large or complex to test in the laboratory. Physical specimens are linked with computational models. A challenge is to ensure that this combined system is tested under realistic conditions. Thus, boundary conditions at the interface between the physical and computational portions must be enforced, and hydraulic actuators are frequently used (see figure below).

AIM: 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 main objectives are to:

- Diversify the community of researchers using hybrid simulation
- Build capacity for hybrid simulation in existing laboratories
- Develop a research agenda for hybrid simulation
- Foster peer-to-peer and institute-to-institute partnerships
- Share relevant resources and digital artifacts
- Cultivate international collaborations





“Breaking Barriers” & “Building Capacity”

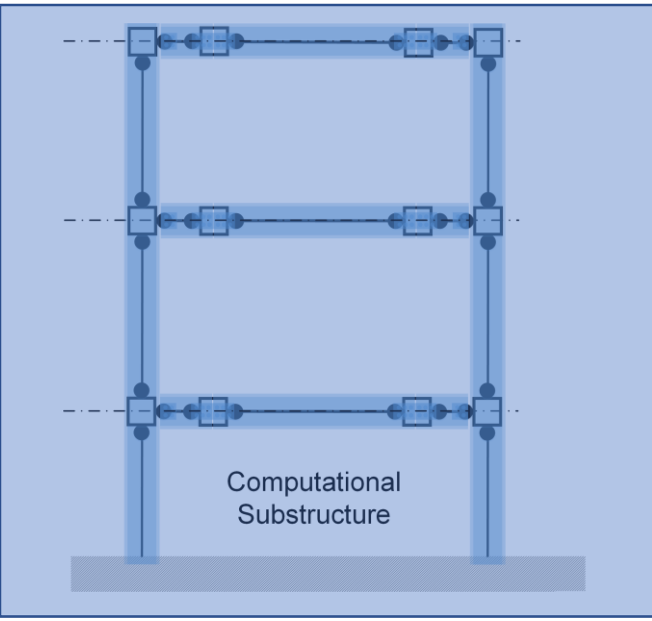
8:40am-12:00pm	All give 3 minute presentations on research needs (see email) Coffee break included.
12:00-1:00 pm	Buffet Lunch and Begin Break Out Discussions
1:00-3:00pm	Break out sessions “A”
3:00-3:30pm	Break
3:30-5:30pm	Break out sessions “B”
6:00-8:00pm	Dinner on the Terrace

DAY 2: 8:30am – 1:00pm + tour	
8:30-10:00am	Break out sessions “C”
10:30am-12:00pm	Summary / reports & research agenda, survey completion
12:00-12:45pm	Box Lunch and Discussion of Next Steps
12:45-3:45pm	Tour of the UCSD Shake Table & NHERI Facility (by shuttle bus)

(Multihazard) Problems & Algorithms

Co-leads: Oh-Sung Kwon and James Ricles
Recorder: Amin Maghareh
Focused on identifying problems and possible solutions for issues that hold us back.

Numerical Substructure



Numerical Simulation Data

Experimental Techniques
Control theory
Hydraulics
Signal Processing
Data Acquisition

Computational Modeling
Numerical Methods
Structural Dynamics
Embedded Systems
Uncertainty Quantification

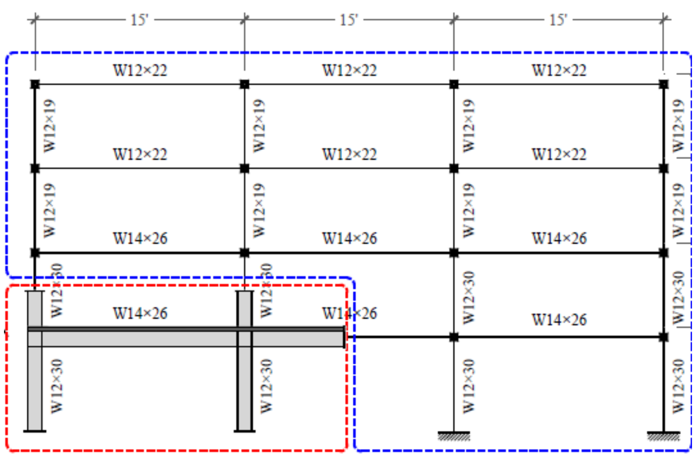
Physical Response Data

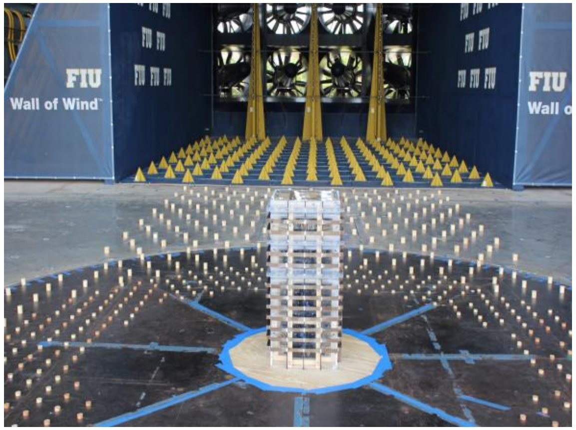
Physical Substructure

Testbeds, Workflows, Community

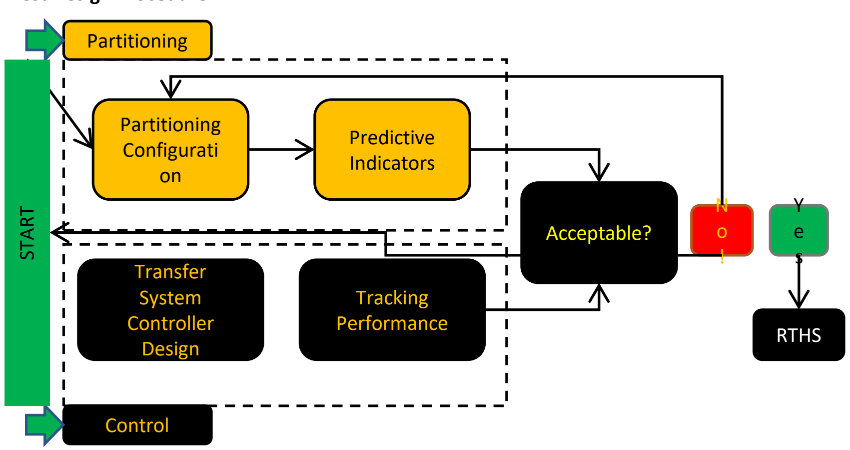
Co-leads: Gilberto Mosqueda and Andreas Schellenberg
Recorder: Johnny Condori
Strategize on building capacity and broadening participation through access to resources and partnerships.

Hybrid Model of Moment-Resisting Frame





Test Design Procedure:

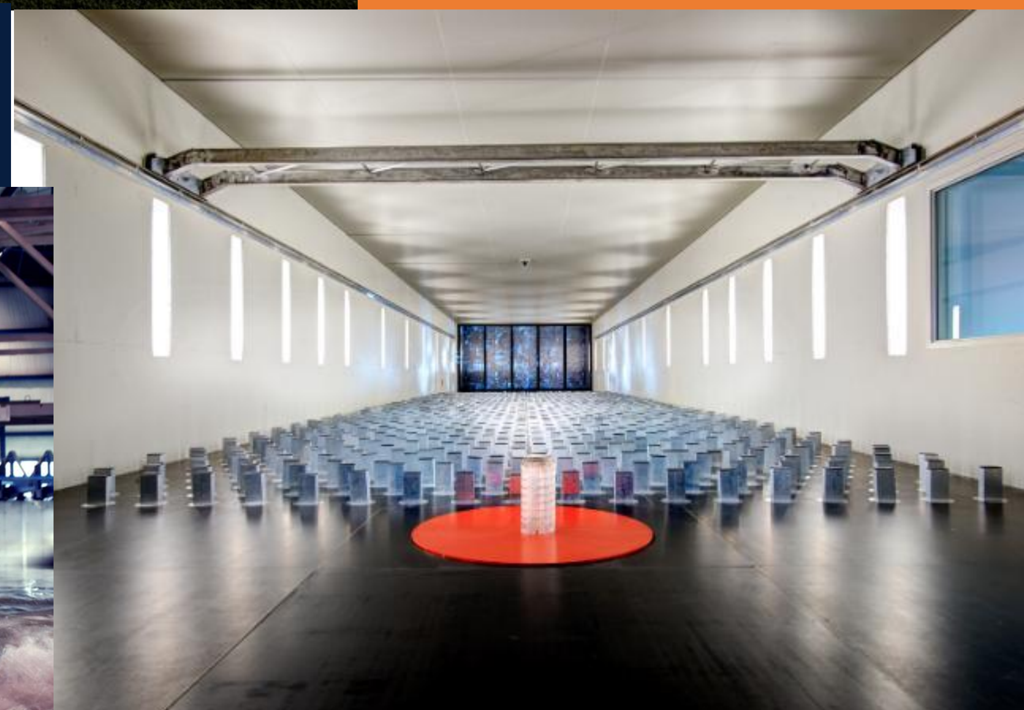


Expanding to Wind/Coastal

UF | UNIVERSITY of FLORIDA

FIU | Wall of Wind

NHERI Experimental Facility



Oregon State University

Questions posed

- How does this meet the needs/goals expressed in the NHERI Science Plan?
- How can the community (collectively) leverage data/projects from the past?
- What kind of testbeds/benchmarks would be helpful for building capacity and breaking barriers?
- What barriers exist for users new to hybrid simulation methods? If you are not using it, why?
- What are technical barriers that prevent us from tackling more complex problems?
- And how might we overcome those?
- How can this be adapted to solve new problems in the WIND/COASTAL engineering?
- Are there any problems in other engineering areas that could benefit from hybrid simulation methods?

DATA

How can we learn from the data generated in past experiments?

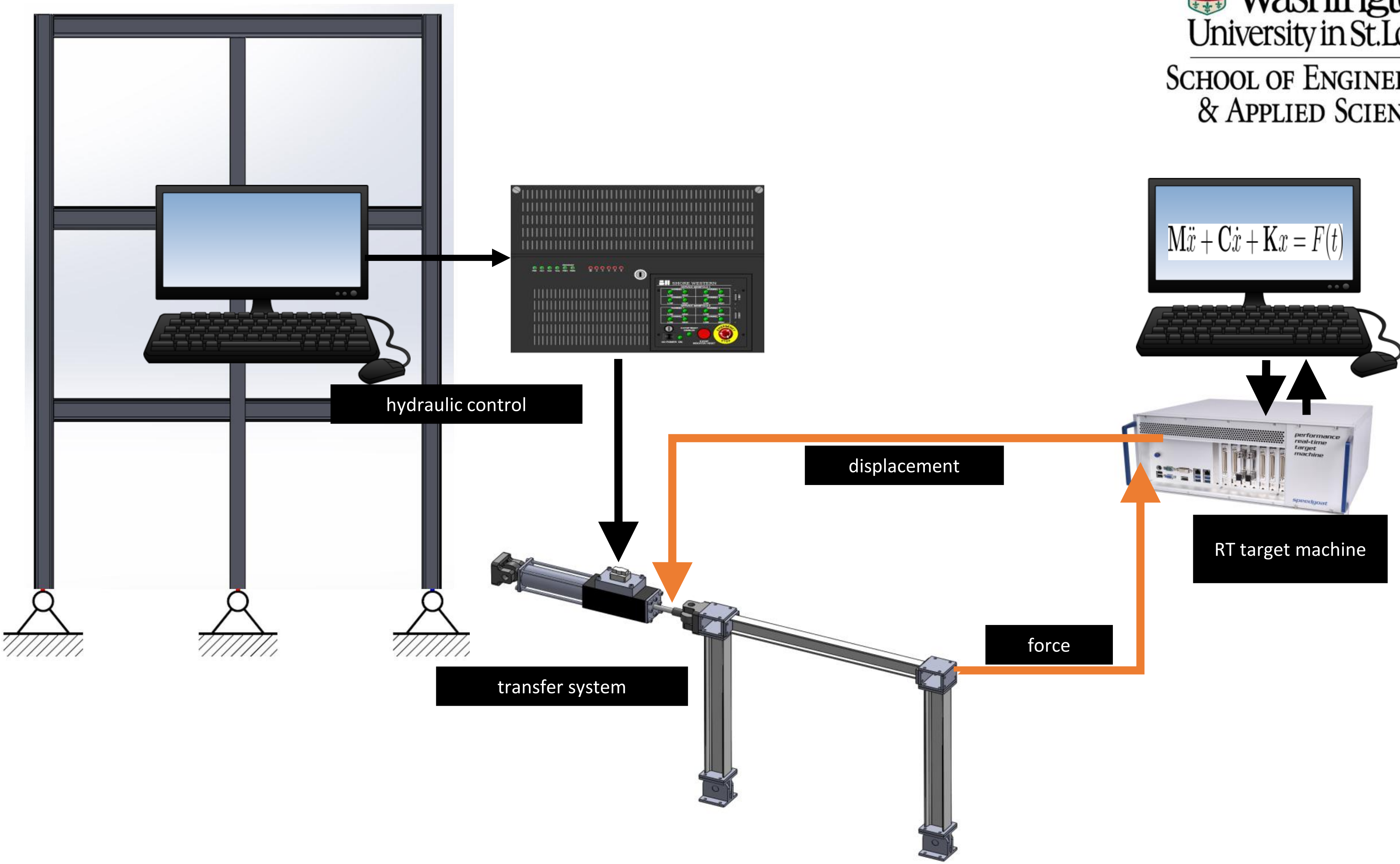
- Quantifying uncertainties
- Building confidence
- Improving modeling
- Engaging practitioners
- Acceptance criteria

moonshots

What complex tests could be performed with ?

- Progressive collapse
- ?

Benchmark RTHS



Thank you

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

Mariant Gutierrez

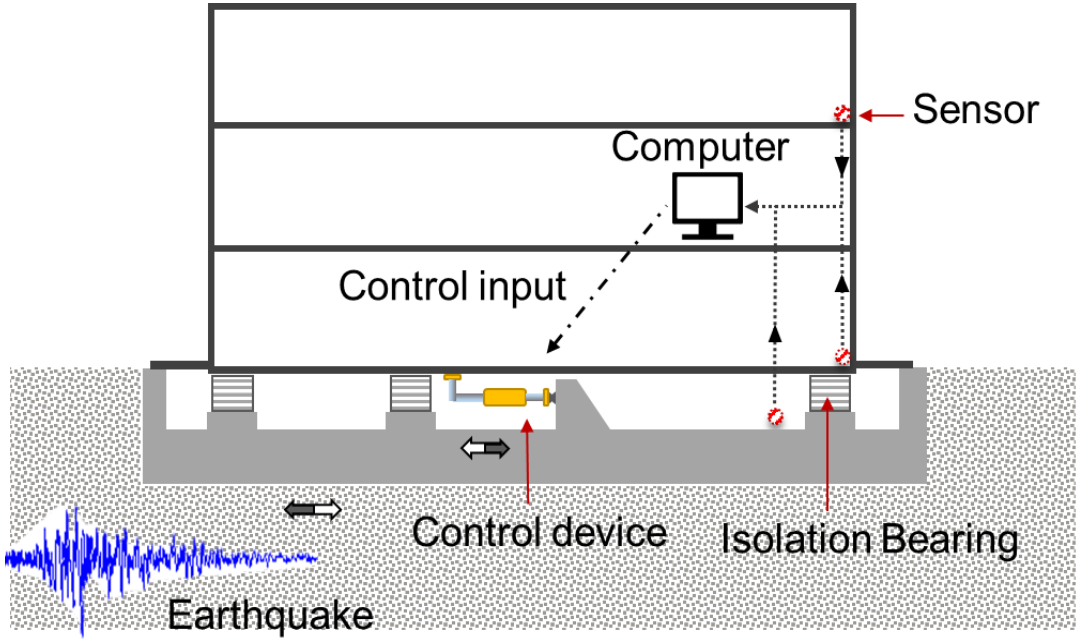
University of Kentucky

Mariantonieta 'Mariant' Gutierrez Soto, PhD

Assistant Professor, University of Kentucky

Research Areas:

- Structural vibration control
- Soft-computing optimization



NHERI database: Structural benchmark problems addressed using HS or RTHS (training using AR, VR?)

DATAHUB DATA COMMUNITY ABOUT LOGIN ›

Home › NEES Database: Structural Control and Monitoring Benchmark Problems

NEES Database: Structural Control and Monitoring Benchmark Problems

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Show 10 entries First Previous 1 2 Next Last Search:

ID	Title	Authors	Citation	Specimen	Video	Problem Statement	Matlab Zip File
ID	Title	Authors	Citation	Specimen	Video	Problem Statement	Matlab Zip File
1	Linear Active Mass Driver Control Problem	B.F. Spencer Jr., S.J. Dyke, H.S. Deoskar	B.F. Spencer, Jr., S.J. Dyke, and H.S...		-	Report on the Linear Active Mass Driver Control Benchmark Problem	MATLAB_BLDG_AMD1
2	Linear Active Tendon Control Problem	B.F. Spencer Jr., S.J. Dyke, H.S. Deoskar	B.F. Spencer, Jr., S.J. Dyke, and H.S...		-	Report on the Linear Active Tendon Control Problem	MATLAB_BLDG_Tendon1
3	Linear Full Scale Building Control Problem	B.F. Spencer Jr., R.E. Christenson, S.J. Dyke	B.F. Spencer, Jr., R.E. Christenson ...		-	Report on the Linear Full Scale Building Control Problem	MATLAB_BLDG_Full2
4	Nonlinear Full Scale Building Control Problem	Y. Ohtori, R.E. Christenson, B.F. Spencer,	Y. Ohtori, R.E. Christenson, B.F. S...		-	Report on the Nonlinear Full Scale Building Control	MATLAB_BLDG_Full3

New to HS:

- Integration of HS in complex structures instrumented with advanced damping devices subjected to multi-hazards

- Real-time capability for geographical distributed HS (instrumentation using IoT and cloud systems)

- Computational power to complete large scale projects

- Overall project’s timing to obtain results using HS or RTHS

- How does NHERI program relates to other NSF programs (proposal writing)

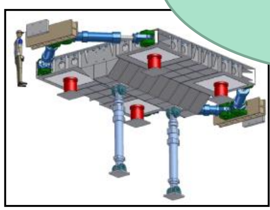
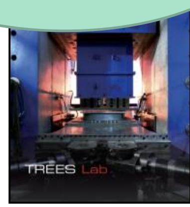
Igor Lanese

EUCENTRE

EUCENTRE Foundation – Pavia, Italy

European Centre for Training and Research in Earthquake Engineering


EXPERIMENTAL TESTING

STRUCTURAL MONITORING

INTERNATIONAL COOPERATION

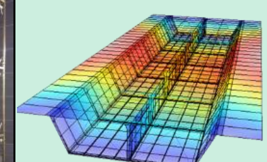
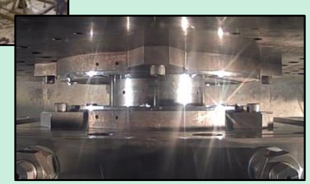
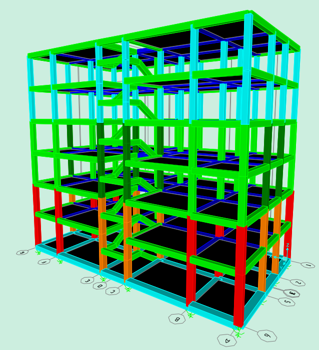
RESEARCH & DISSEMINATION

TRAINING, MsC, PhD

Aerospace Geotechnical EE Masonry Structures Multi-risk Assessment Non-structural Elements Risk Governance Structural Analysis, ...


EMERGENCY RESPONSE


Hybrid Simulation of seismic isolated structures


Open questions…

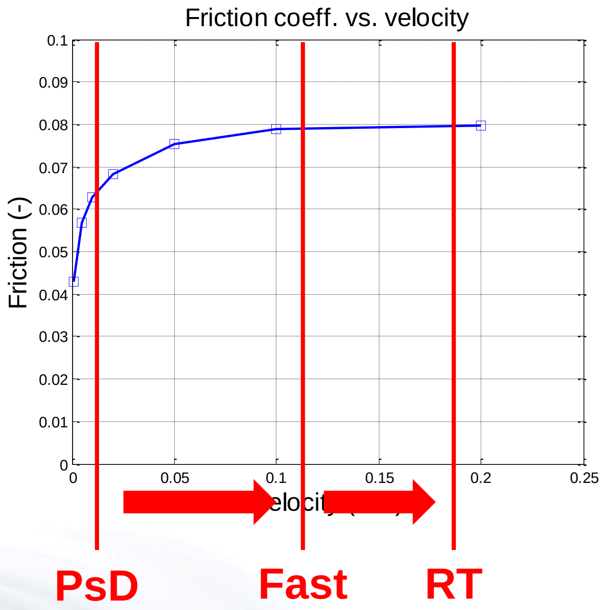
- **Barriers for new HS method users:**
  - Standard and guidelines on HW & SW are partially missing → exp. campaigns complex and onerous to be implemented, so other testing methods are considered (and trusted);
  - Sponsors like in automotive field would really help

- **Tackling more complex problems:**
  - Matlab environment: hard to define K,M,C, state variables, …;
  - OpenSees (or similar) environment: Implementation not trivial, bug fix can be hard as well

Future trend of Hybrid Simulation and applications

• Rate-dependency - optimal time scale selection

Friction pendulum sliding material (graded PTFE with carbon)



No PsD, but <u>a “Fast” execution will give more accurate results than real-time</u>

• Dissemination

NOT only in the special Hybrid Simulation special sessions!

(unless talking about algorithm & peculiar aspects)

Mateo Gonzales

Universidad del Valle

Peter Thomson
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Universidad del Valle

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Email
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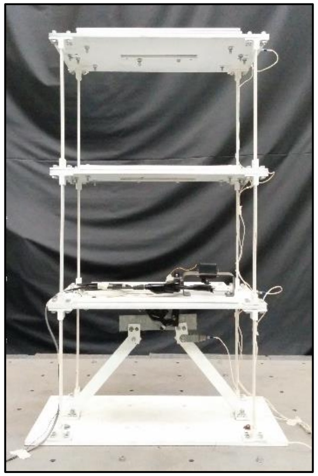
Some Research Areas

- Structural Dynamics and Control.
- Structural Health Monitoring.
- Seismic Engineering.
- Eolic Engineering.
- Soil Mechanics.
- Rocks Mechanics.
- Computational Mechanics.

Previous and current projects



- Technological Development of Structural Control Systems Using Low-Cost Seismic Isolators and Semi-Active Dampers.
- Seismic Response of Structures Using Real-Time Hybrid Simulations.
- Development of Low Cost Seismic Isolators.

Other universities in Colombia also interested in Hybrid Simulations:

- New building (under construction) for Research and Laboratories of the Faculty of Engineering, Pontifical Javeriana University.
  Source: ingenieria.javeriana.edu.co.

Challenges

- Characterization of the seismic behavior of thin RC walls using RTHS.

- Soil-Structure Interaction.

- Human-Structure Interaction.

9th Colombian Conference on Earthquake Engineering

(… and International Workshop on Hybrid Simulation?)

SANTIAGO DE CALI, 2019
IX CONGRESO NACIONAL DE INGENIERÍA SÍSMICA
http://eicg.univalle.edu.co/ixcongresosismica

ORGANIZAN

Universidad del Valle

EICG
ESCUELA DE INGENIERÍA CIVIL Y GEOMÁTICA

ais Asociación Colombiana de Ingeniería Sísmica

Pei-Ching Chen

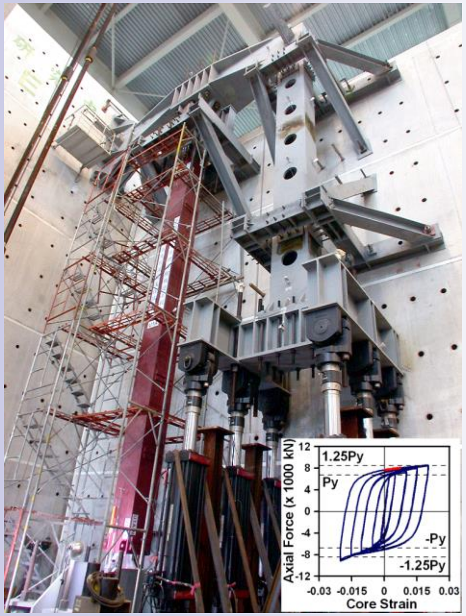
National Taiwan University of Science and Technology

National Center for Research on Earthquake Engineering (NCREE)

Site	Specifications of the earthquake simulator				
	Dimension (m)	Max Stroke (m)	Max Velocity (m/s)	Max Acceleration (g)	Max payload (kN)
Tainan Lab	8 x 8	H±1 V±0.4	H±2 V±1	H±2.5 V±3.0	2500
Taipei Lab	5 x 5	H±0.25 V±0.1	H±1 V±0.5	H±1.5 V±1.0	500

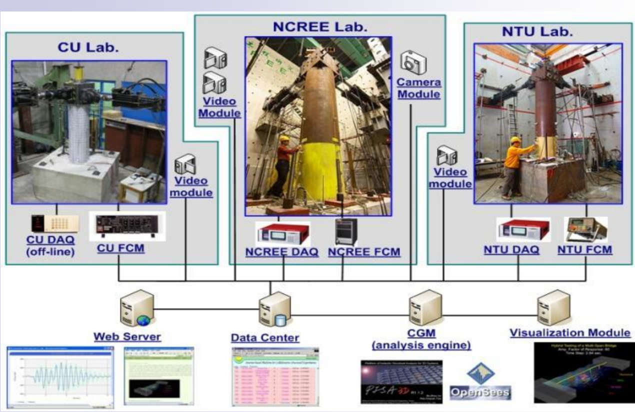
Description	MATS	BATS
Static vertical comp. force (MN)	30	30
Dynamic vertical comp. force (MN)	30	30
Total vertical comp. force (MN)	60	60
Vertical tension force (MN)	4	8
Vertical velocity (+/- m/s)	0.03	0.15
Vertical displacement (+/- m)	0.075	0.075
Longitudinal force (+/- MN)	4	4
Longitudinal velocity (+/- m/s)	0.25	1
Longitudinal displacement (+/- m)	1.2	1.2
Roll, pitch, and yaw (+/- deg)	2	2

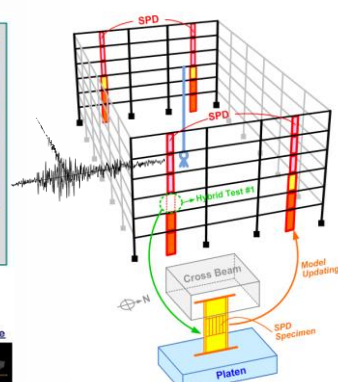
What barriers exist for users new to hybrid simulation methods? If you are not using it, why?



- Users are much more familiar with conventional testing methods
- Hybrid simulation is not promoted aggressively
- Users with different backgrounds are good at diverse analytical software
- Lack of general and flexible testing framework

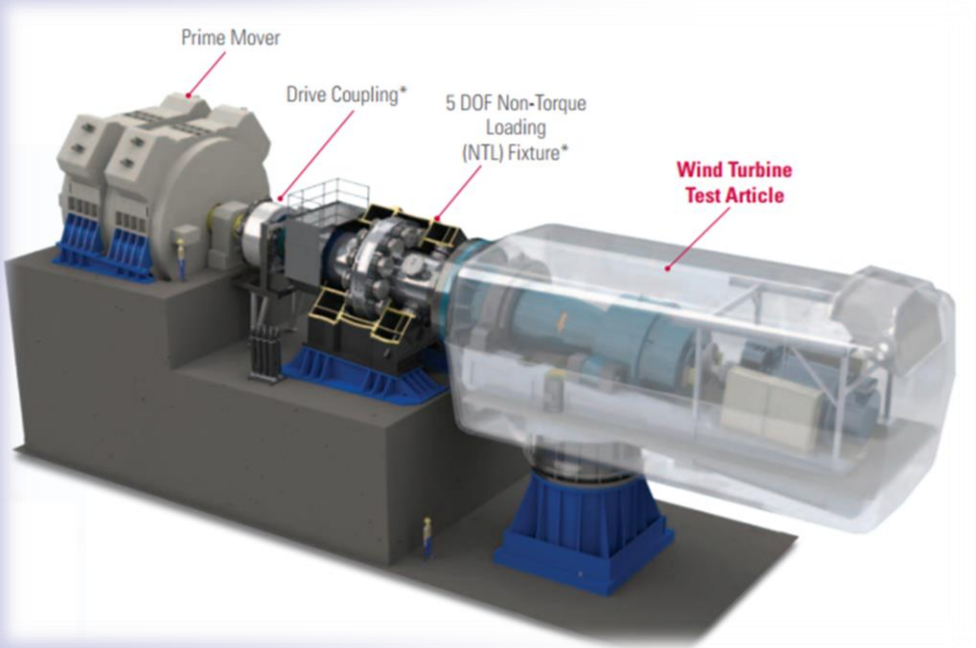
What are technical barriers that prevent us from tackling more complex problems?



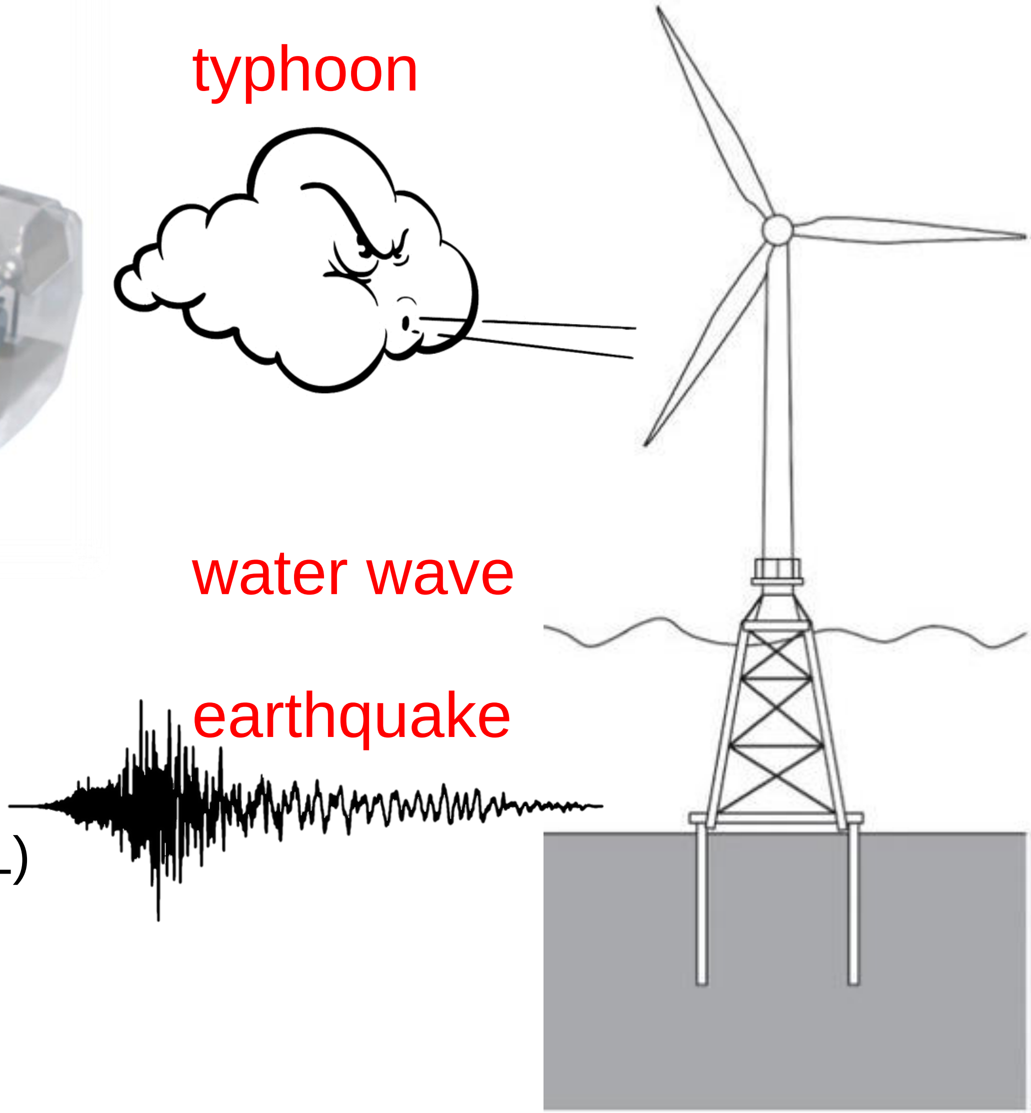


- Limitation of equipment capacity
- Diversity of testing facilities
- Accuracy and efficiency of computation
- Techniques for MDOF real-time control of actuators

Hybrid Simulation of Offshore Wind Turbines subjected to Earthquakes, Water Waves, and Typhoons



MTS Non-Torque Loading (NTL) System



- Wind pressure to loadings of degrees-of-freedom
- HIL testing of generators (NREL)
- Soil-wave-structure interaction
- Hydraulic variable pitch control system

Richard Christenson

University of Connecticut

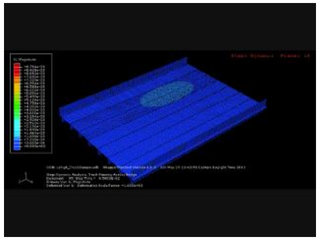
University of Connecticut

Richard Christenson, Professor

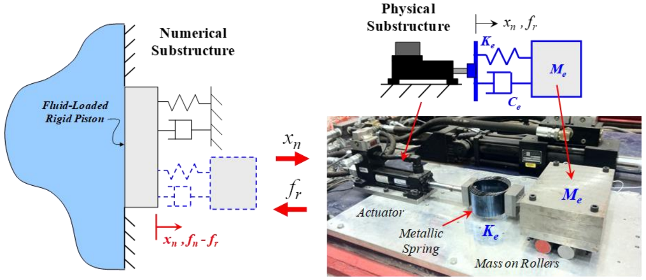
- Real-Time Hybrid Simulation/Substructure (RTHS)
  - Magneto-Rheological Fluid Dampers (CU Boulder & Lehigh NEES facilities)

  - Geographically Distributed RTHS

  - RTHS of large models



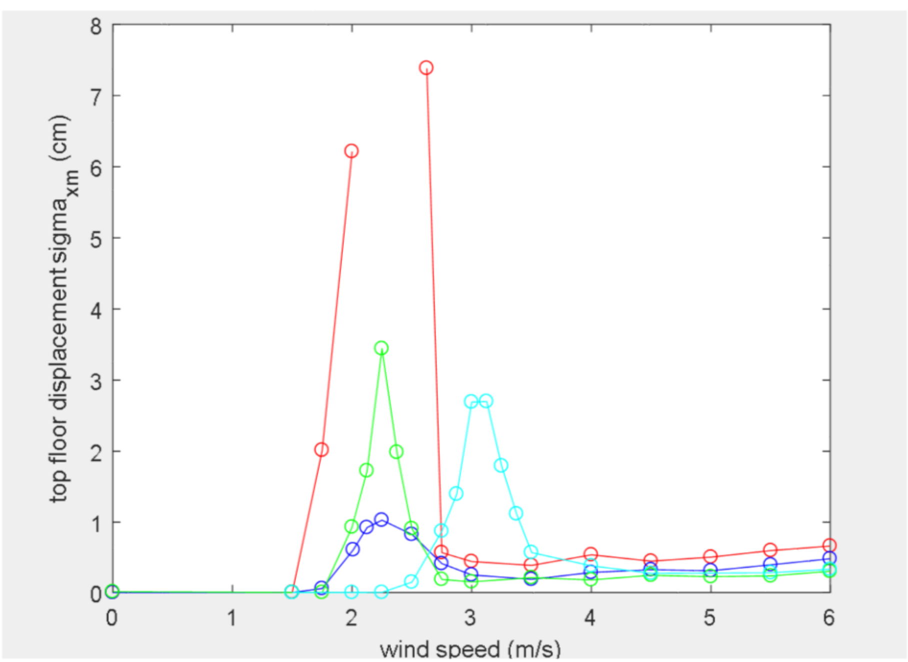
  - RTHS of Marine Structures (fluid loading of pistons, plates & shells)



Advanced Hazards Mitigation Lab
Department of Civil & Environmental Engineering

How can HS be adapted to solve WIND Engineering Problems?

- Solve challenges with scaling mass, stiffness and damping in aeroelastic wind tunnel models
- aeroRTHS conducted with Clarkson University at UF NEHRI BLWT November 2017



HS (RTHS) should be Applied to Aerospace Applications

- **Vibrations are critical in many aspects of aerospace missions: spacecraft – payload vibrations, parachute deployment, …**

(Peter Morenus/UConn Photo)

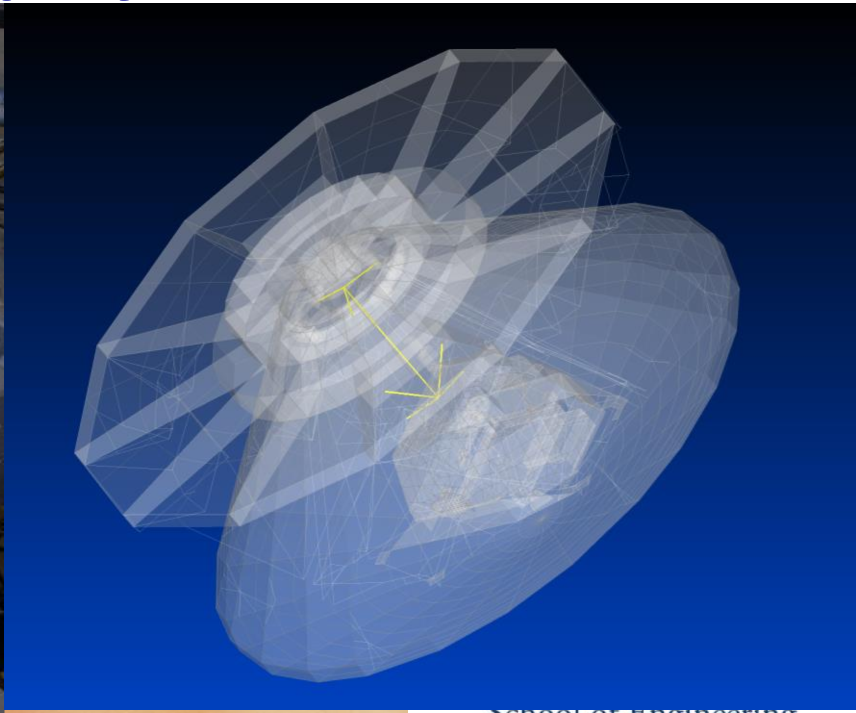


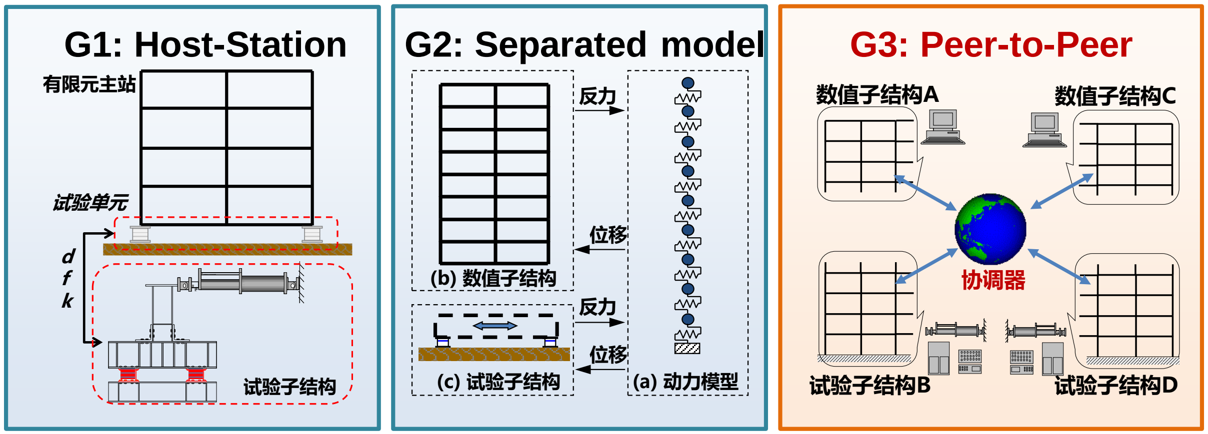
Photo by © CORBIS/Corbis via Getty Images

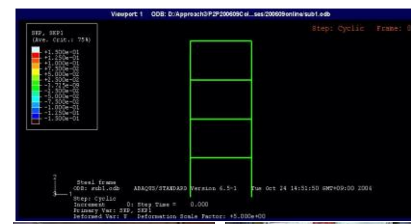
WANG Tao

Institute of Engineering Mechanics

What I Have Done… WANG Tao @ IEM

- WANG Tao, Researcher, Dr. Eng., Vice Head of Huixian Lab on Earthquake Engineering, Institute of Engineering Mechanics, CEA.
- Distributed hybrid test system-Coordinating **Num.** & **Tested** subs
  - **Three** online hybrid test frameworks



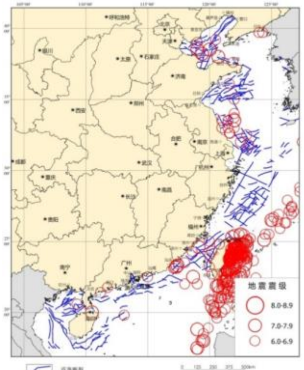


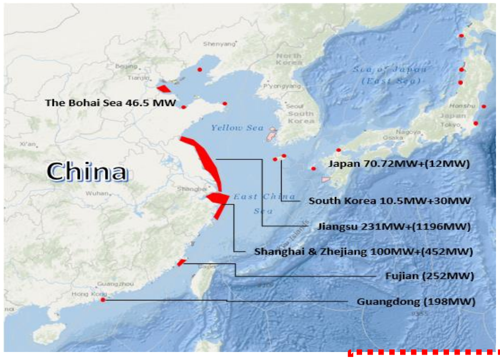
  - More than **10** real applications
- Several facilities in my lab

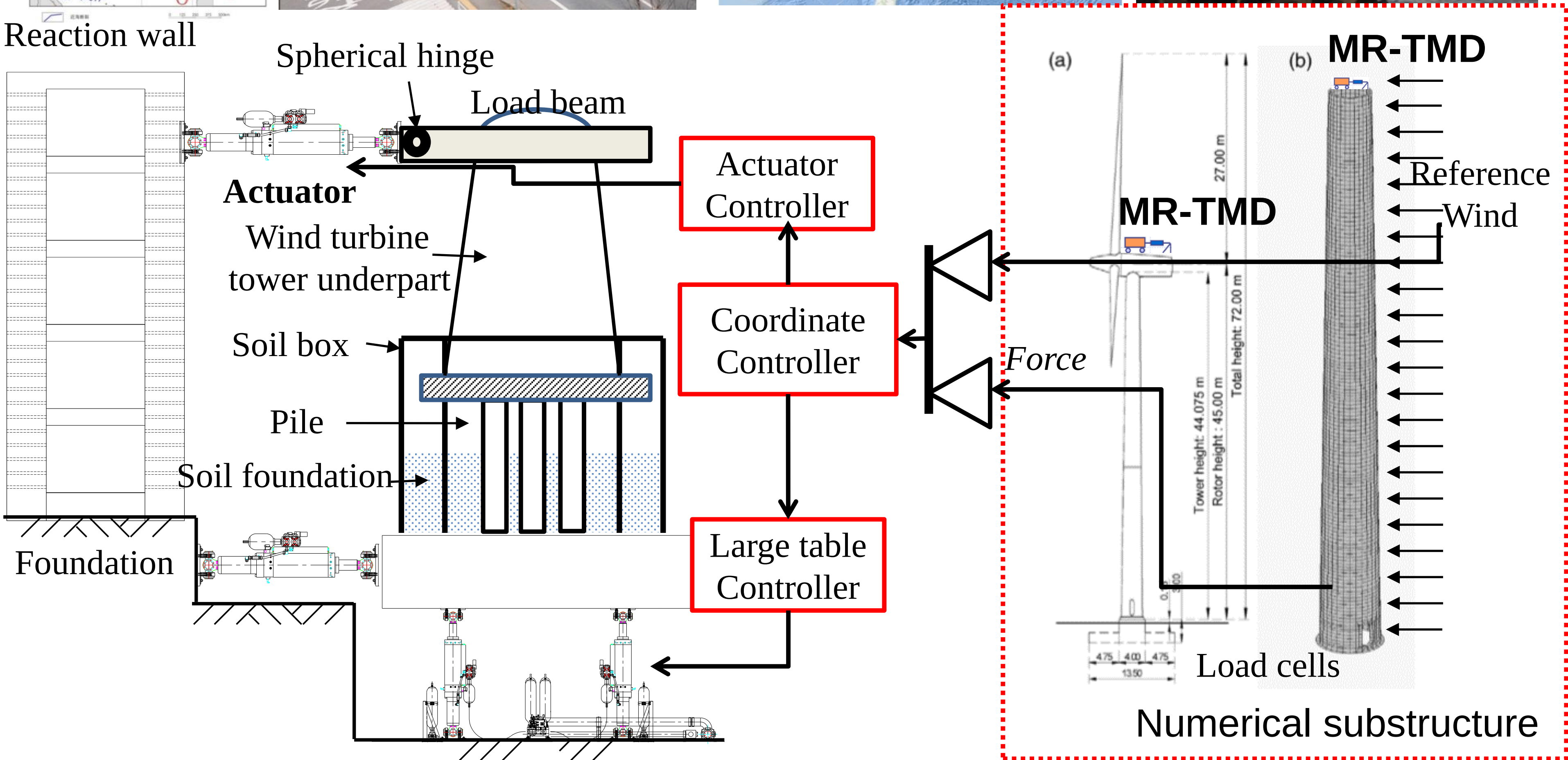
My Understanding of Hybrid Test

- *What barriers exist for users new to hybrid simulation methods?*
  - *Knowledge of multi-disciplinary*
  - *User-friendly software interface*
- *What are technical barriers that prevent us from tackling more complex problems?*
  - *Precise and robust control of modern facilities*
  - *Accuracy of numerical substructures*
  - *Interface realization (physical and numerical)*
  - *Sophisticated FEM adapted to subs with distinct characteristics*
- *And how might we overcome those?*
  - *Integrated system like LBCB to easily realize boundaries*
  - *Model updating for numerical subs*
- *How can this be adapted to solve new problems in the WIND/COASTAL engineering?*
  - *What's the influence of wind and tide…*
  - *I do care about the action to the structure, but not the action to the wind/water*

MR-TMD Offshore Wind Turbine Tower System







Xiaoyun Shao

Western Michigan University

Xiaoyun Shao Ph.D., P.E.

MECHS workshop, La Jolla, CA, Dec. 12-13, 2017

Education:

2007 Ph.D. Structural Engineering, University at Buffalo
Dissertation: *Unified Control Platform for Real-Time Dynamic Hybrid Simulation*

2001 M.S. Structural Engineering, Tongji University, Shanghai, China
Thesis: *Experimental Study on Flexural Behavior of Fiber Reinforced High Performance Concrete Beams*

1999 B.S. Structural Engineering, Tongji University, Shanghai, China

Employment:

08/2008-present Assistant/Associate Professor, Western Michigan University

Major achievements:

- *Established Laboratory of Earthquake and Structural Simulation (LESS)*
- *Lead hybrid simulation development in two NEESR projects*
- *Advancing RTHS in various aspects*

08/2007~08/2008 Adjunct Assistant Professor, North Carolina A&T State University

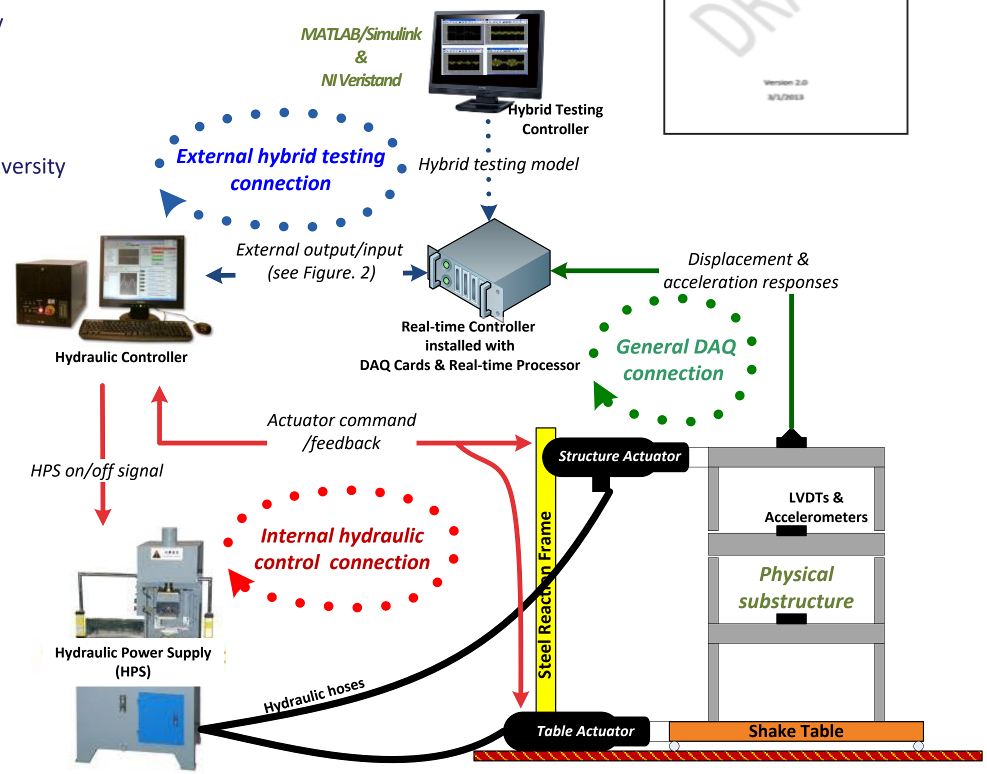
10/2006~07/2007 Postdoctoral Researcher, University at Buffalo

NESS-Soft Project (2010~2014)

NESS-RC Collapse Project (2011~2015)

RTHS development @ LESS:

- Slow / Real-time PSD hybrid simulation platform → **Lab manual**
  - Integration algorithms
  - Delay compensations
  - Distributed RTHS
  - RTHS with online model updating
- Shake table substructure testing



LESS Damage
Laboratory of Earthquake and Structural Simulation

WESTERN MICHIGAN UNIVERSITY
Civil and Construction Engineering

WESTERN MICHIGAN UNIVERSITY 1903

Xiaoyun Shao Ph.D., P.E.

- What barriers exist for users new to hybrid simulation methods?
  - *Lack of interest*
  - *Lack of understanding*
  - *Lack of collaborations*
  - *Lack of confidence*
- *What are technical barriers that prevent us from tackling more complex problems?*
  - *Planning and preparing*
  - *Accuracy/stability (algorithms, controls)*
  - *Complexity of numerical models*
  - *Acceptance and utilization of results*

Q: What problem/issue would you like to see HS applied to?

A: Structural system level response subject to hazard loadings

Structures	Hazard	Loadings	Experimental method
Costal structures (i.e., floating wind turbine)	Hurricane	Simultaneous Wind + Storm surge	Distributed HS combining wind tunnel and wave laboratory
	Tsunami	Sequential Seismic + wave	HS (substructure) in wave laboratory
Wood residential buildings with existing /new features (materials, configurations, construction methods, etc.)	Hurricane	Wind	HS in wind tunnel
	Earthquak e	Seismic	HS/RTHS

Ge (Gaby) Ou

The University of Utah

THE UNIVERSITY OF UTAH

A Multi-hazard Engineering Collaboratory for Hybrid Simulation (MECHS)

Ge (Gaby) Ou
12/12/2017
University of Utah

Introduction

Ge (Gaby) Ou

- Assistant Professor in Civil and Environmental Engineering at University of Utah (2016-)
- Ph.D. from Purdue University (2016), advisor: Dr. Shirley Dyke
- Experiences with Hybrid Simulation
  - Developed control algorithm for actuators in RTHS
  - Investigated and improved numerical integration stability for RTHS with delay and partitioning
  - Investigated and validated the fidelity of hybrid simulation with model updating with comparison to shake table testing

Feedback on the Proposed Questions

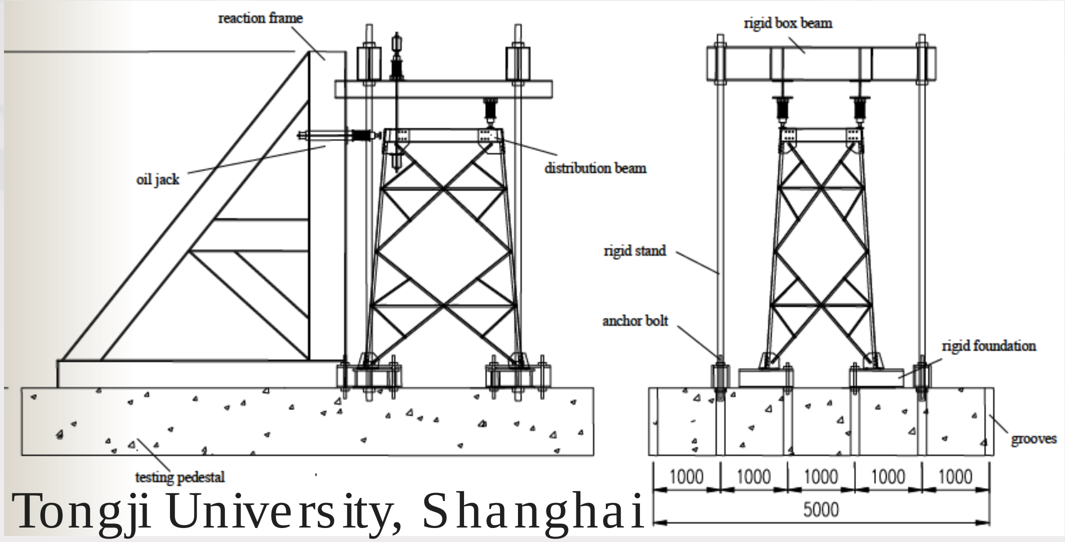
Engage researchers that may be new to hybrid simulation, while leveraging the expertise of researchers working in hybrid simulation; build capacity to enable hybrid simulation tests at more laboratories

- Development of tutorial series (best to be in video format) on:
  1) commonly used software (HS and RTHS)
  2) actuator controller design for RTHS
  3) coordinator setup for HS
  4) integration of experimental hardware and computational software
  5) laboratory demo with real-case experimental procedure (HS and RTHS)

Problem/issue I would like to Pursue

Stability and collapse of transmission tower-wire system under extreme wind

- How to select the experimental substructure?
- How (or if it is necessary) to imply wind load on experimental substructure?
- How to study wire-insulator-tower interaction?
- How to validate the HS results?



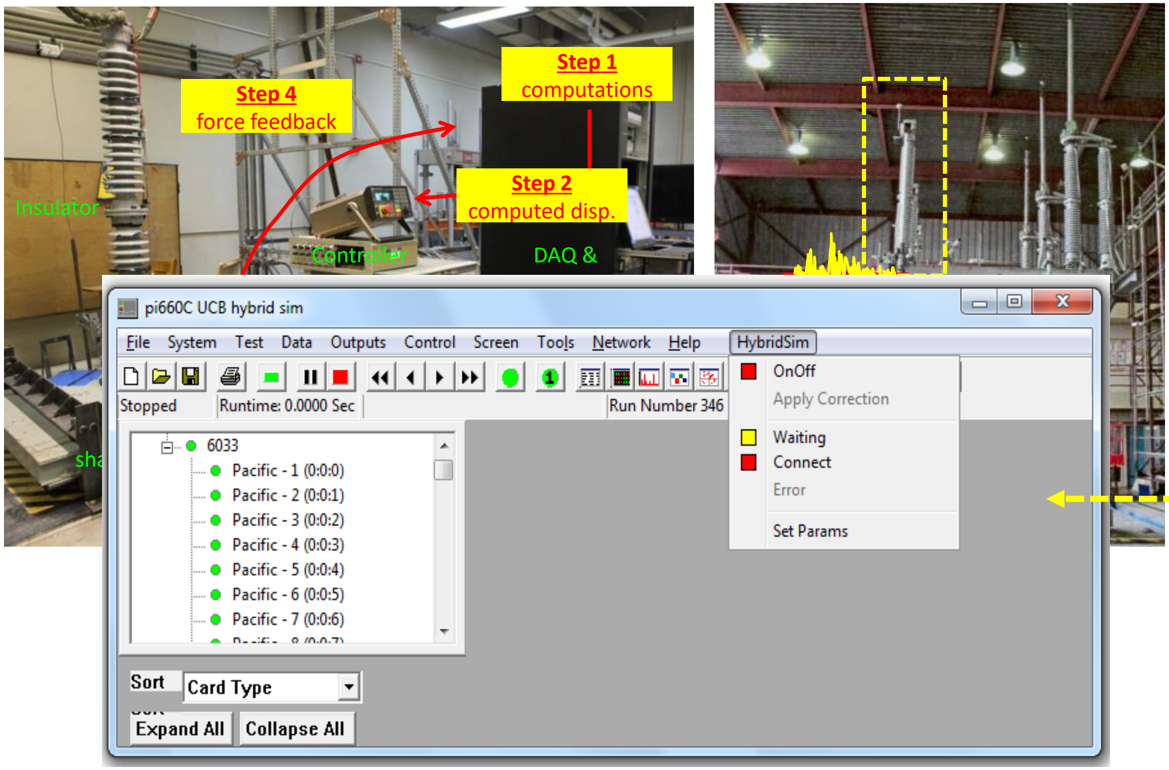
Tongji University, Shanghai

A Research Coordination Network (RCN):
Multi-hazard Engineering
Collaboratory in Hybrid Simulation

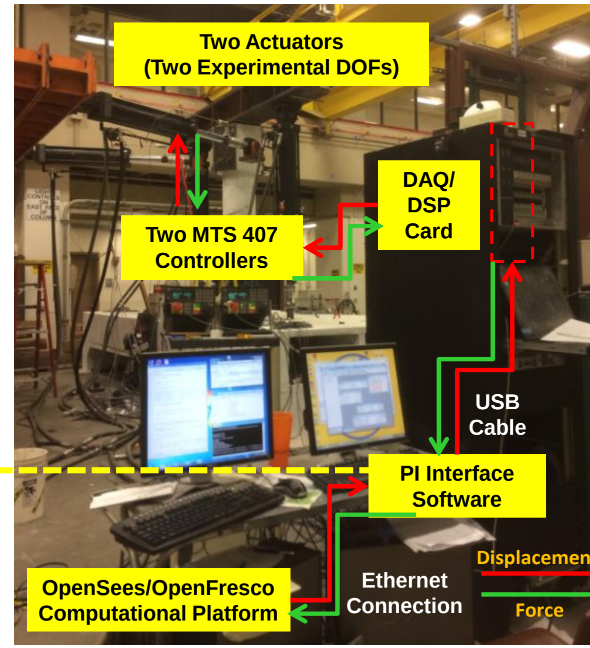
Mohamed Moustafa

University of Nevada, Reno

Background



Large-scale slow HS for RC bridge



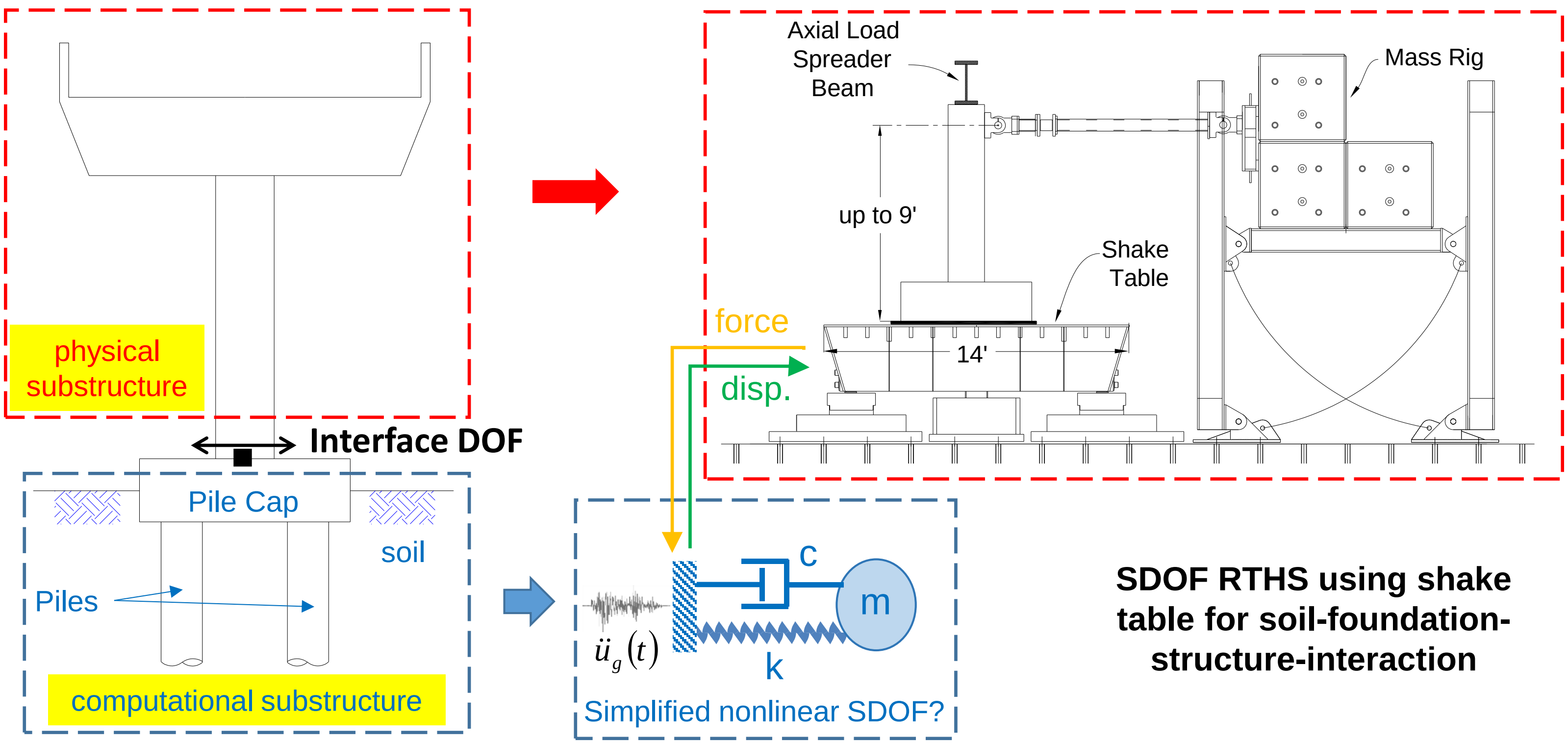
University of Nevada, Reno

RTHS Challenges

1. Technical barriers for more complex problems:

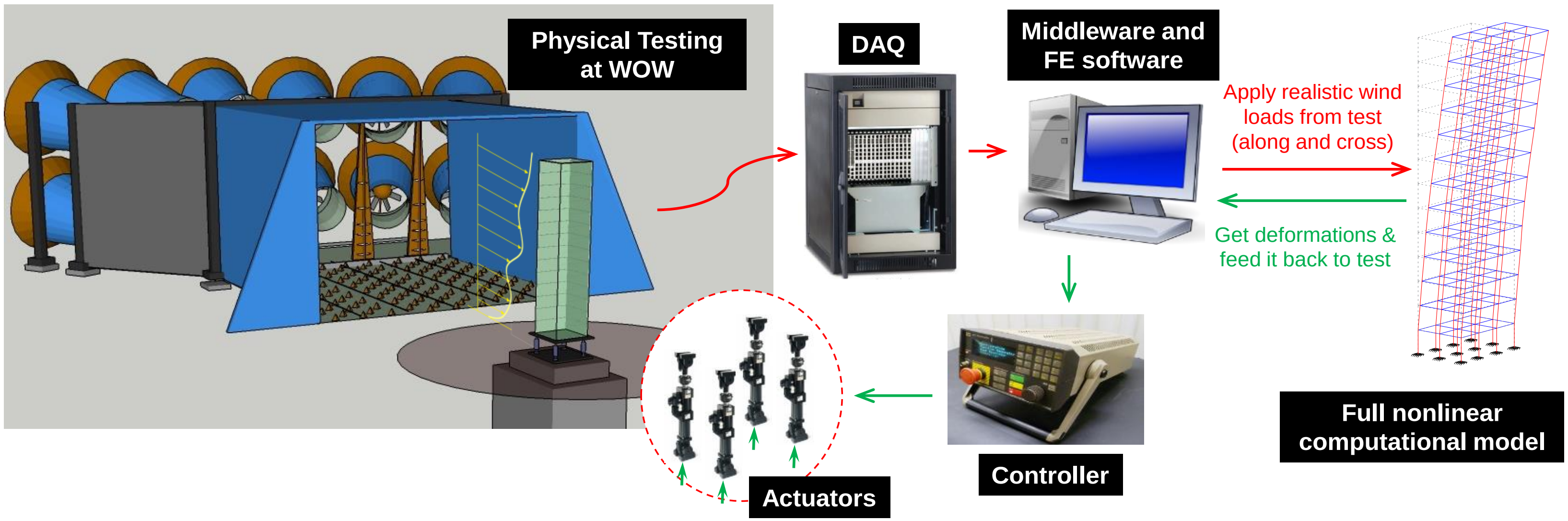
Large nonlinear computational models:

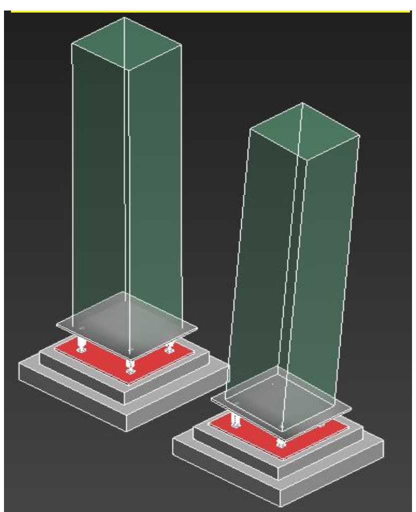
- Computational time?
- Convergence issues?



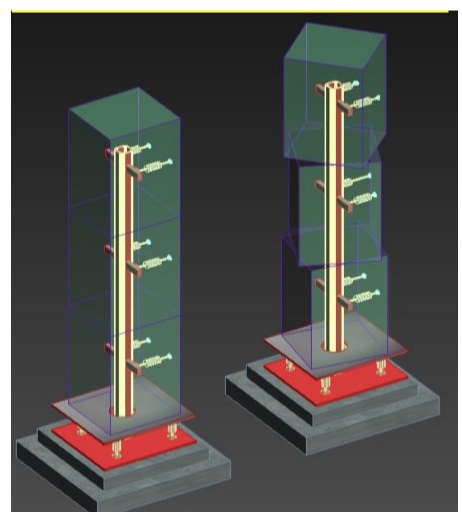
SDOF RTHS using shake table for soil-foundation-structure-interaction

RTHS New Opportunities for Wind Hazards





Rigid model w/ rotational DOFs



Segmental model w/ torsional DOFs

Gaston Fermandois

University of Illinois at Urbana-Champaign

Gaston Fermandois

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Academic Instructor
Santa Maria University
Santiago, Chile

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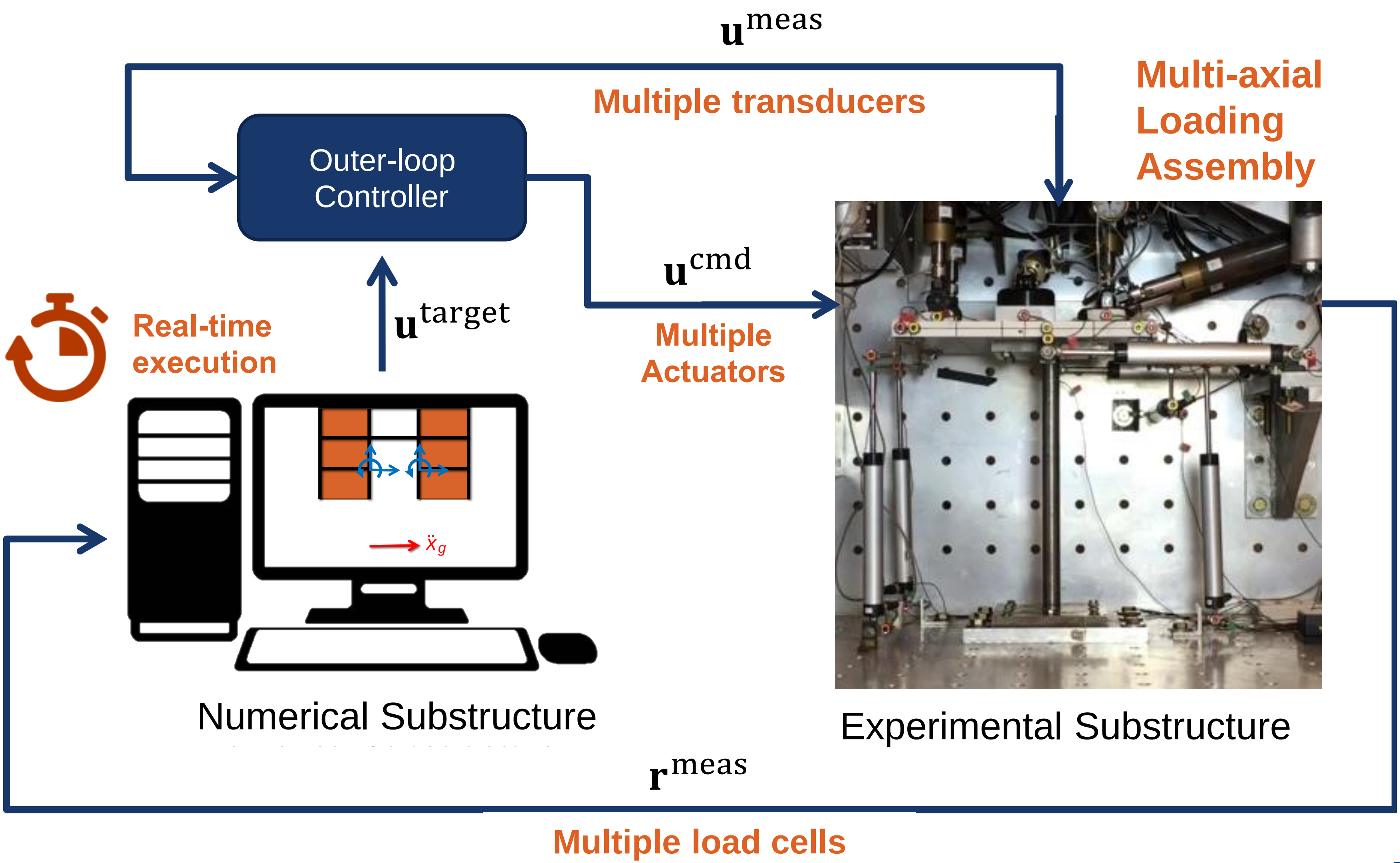
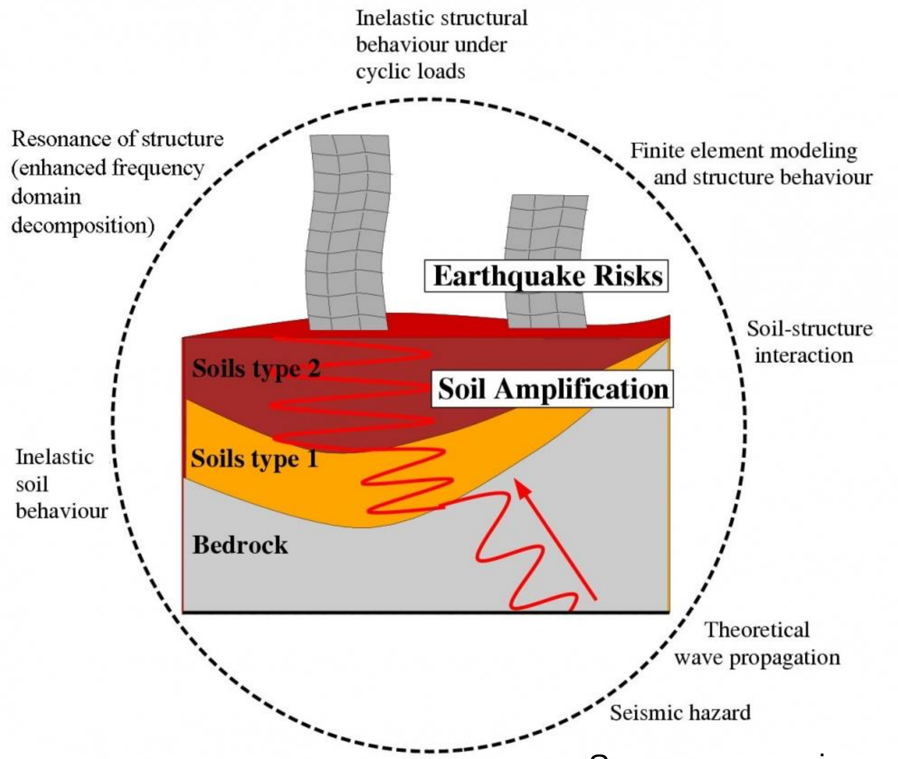
Multi-axial Real-time Hybrid Simulation



What barriers exist for users new to hybrid simulation methods?

- Clear understanding of the advantages of HS methods compared to other experimental methods, in terms of technical capabilities and cost-effectiveness

Source: www.bosai.go.jp/hyogo/ehyogo/



Source: www.ngi.no

Technical barriers?

- Quantification of experimental errors, and its consistent implementation and application in the field
- Computational complexity of the numerical substructure, specially for real-time hybrid simulation

Bahareh Forouzan

Clarkson University

Force-Based Hybrid Simulation for Structural Assessment to Coastal and Wind Hazards

Structural Simulation

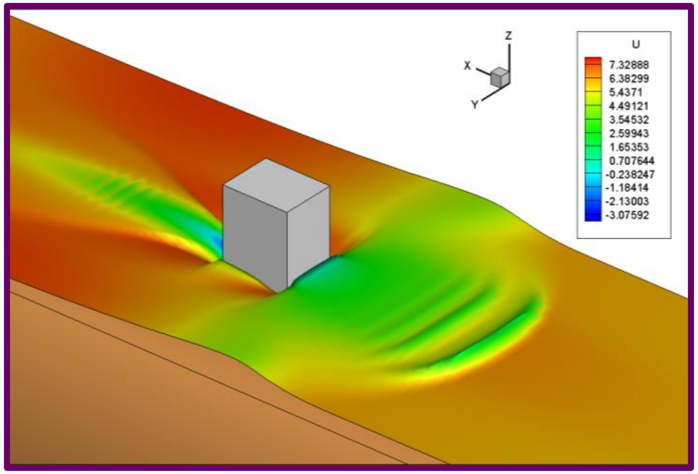
$\mathbf{F}(\mathbf{x}, \mathbf{t})$

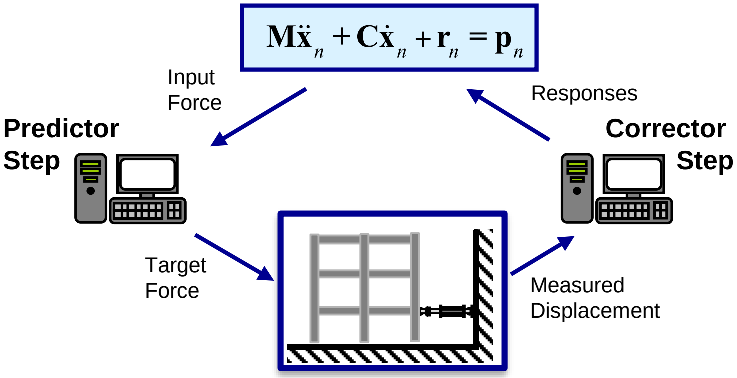
Pressure Force

Deformation

$\mathbf{x}$

Fluid Simulation





Experimental Process

Bahareh Forouzan

Department of civil and Environmental Engineering, Clarkson University

MULTIHAZARD ENGINEERING COLLABORATORY ON HYBRID SIMULATION

Dec 12-13, 2017

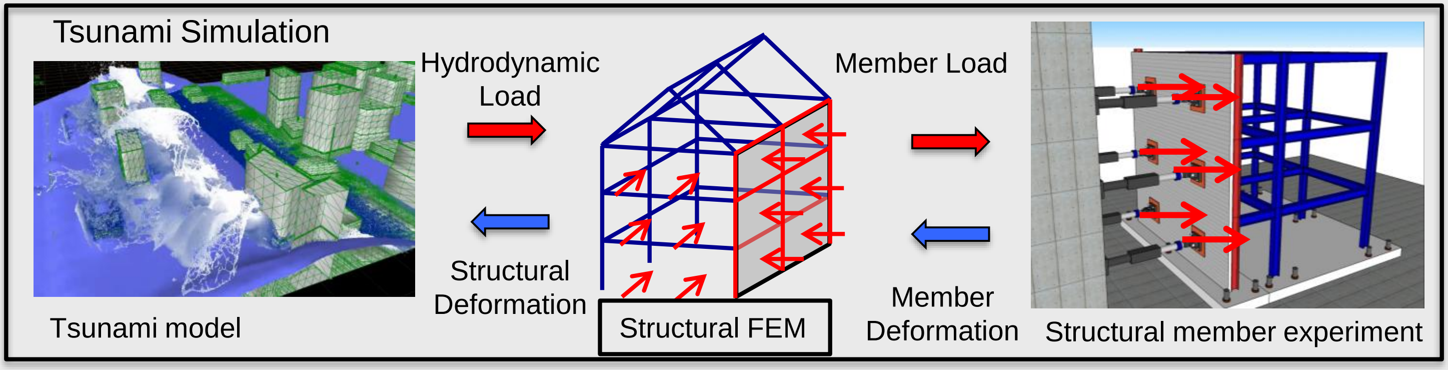
Application of Hybrid Simulation in the Wind/Coastal Engineering

Hybrid Simulation is a potential approach for analyzing structures under dynamics loading such as strong wind, tsunami, and hurricane.

Incorporate advanced modeling techniques for wind and coastal loads into hybrid simulation.

- Nistor et al. (2010), Wei et al. (2015)
- Kareem (1990), Tamura et al. (1999), Tamura et al (2008)

Interaction between the structure and hydrodynamic force



Future direction

- Develop new algorithms where satisfy the force equilibrium and improve force error in the equation of motion at structural node at each time step.

$$\mathbf{e}_{n+1} = \mathbf{M}\ddot{\mathbf{x}}_{n+1} + \mathbf{C}\dot{\mathbf{x}}_{n+1} + \mathbf{r}_{n+1} - \mathbf{f}_{n+1}$$

- Advance real time hybrid simulation for wind loading.

  - Use wind tunnel for incorporating deformation and loading.
  - Calculate target displacement of model from time integration algorithm and impose through actuator.
  - Utilize wind force from wind tunnel at each time step as a new input force in the equation of motion and solve for target displacement.

James Gibert

Purdue University

JAMES GIBERT

ADAMMS LAB

- Ph.D., Clemson University, Mechanical Engineering, Dec., 2009
- Visiting Professor Dept. of Civil Engineering Clemson University, Jan. 2010 to April 2013
- Post Doctoral Researcher Dept. of Mechanical Engineering Clemson University, May 2010- April 2013.
  - **Dynamic Modeling and Testing**-Nonlinear Vibration and Energy Harvesting Lab (NOVEHL)
  - **Manufacturing and Optimization**-Clemson Engineering Design Application and Research (CEDAR)
  - Advanced TWEEL Development Meta-Materials Design, Analysis and Manufacturing Clemson-Michelin: NIST Advanced Technical Program
- Contractor MOOG CSA, April 2013 to Present
- Assistant Professor Clarkson University, August 2013 to 2015
- Assistant Professor Purdue University, August 2015 - Present

Research Area

- Viscoelastic Damping
- Friction Driven Losses/Systems
- Impacting Systems
- General Nonlinear Mechanical Systems

Applications

- Vibration based additive manufacturing
- Dynamics of packaging Systems- Impact response, random vibration response
- Multi-axis vibration testing
- Kinetic energy harvesting
- Topological optimization of nonlinear dynamic structures
- Impact Dampers
- Impacting Logic Gates
- Tribo-electric devices

PURDUE UNIVERSITY

THOUGHTS

New to the field…

Questions on current limitations:

1. Complexity of structures and phenomena to be modeled,
2. Frequency range- DC to ???,
3. Implementation issues-hardware needed, standardize equipment?
4. How are nonlinearities handled, computational efficiency ?

New Areas

1. Defense Applications – scenarios where it may be impossible to test the whole structure
2. Transport Applications – interaction of packaged products and transport system are not considered most assume an enforced motion input, recent research contradicts this.

TAKE-AWAYS

ADAMS LAB

1. **Understanding of the state of the art in the field**

2. **Practical ways that I may implement this type of simulation in my current work**

3. **Network that I can discuss/share new ideas**

Hector Guerrero

Institute of Engineering - UNAM

INSTITUTO DE INGENIERÍA UNAM

HECTOR GUERRERO, *PhD*

hguerrerob@ii.unam.mx

PhD: The University of Manchester, UK

Currently: posdoctoral researcher at UNAM, Mexico

Research interests:

- Hybrid simulation
- Seismic response of structures
- Seismic protection systems
- PBEE, Multihazard Engineering

Experience: quasi-static and dynamic tests of structures equipped with hysteretic dissipation systems, mostly BRBs. Almost new to HS.

Facilities at UNAM

Most of the research on Structural Engineering in Mexico is conducted at UNAM, there we have the following facilities:

- The materials and structures laboratory at the Institute of Engineering
  - ✓ 4 Rexroth hydraulic actuators (2 of 1000 kN and 2 of 500 kN)
  - ✓ 2 MTS hydraulic actuators (1 of 500 kN and 1 of 200 kN)
- The big structures laboratory at the National Center for Natural Disaster Prevention (CENAPRED)
  - ✓ 4 MTS hydraulic actuators of 500 kN
  - ✓ 4 Japanese hydraulic actuators (2 of 1000 kN and 2 of 500 kN)
- The shaking table laboratory (4m x 4m platform, 1 g, up to 200 kN models)
- Wind tunnel laboratory. Boundary layer wind tunnel with closed return. The turbine can generates wind velocities up to 100 m/s.

What barriers exist for users new to hybrid simulation methods? If you are not using it, why?

- It seems a complicated topic.
- The language is not easy to understand.
- Most people is scared about electronics and control.
- More step-by-step implementation guides and probably videos are needed to encourage people to use HS.
- Some courses and workshops on HS are required to show its benefits.
- I am almost new to HS. It has been difficult and expensive to implement it. However, I know it has a great potential and I am sure it will bring great benefits to my career, to my university and to my country.

What do I hope to get from this workshop?

- I hope I can learn more about HS and the state of the art on the topic.
- I hope I can meet experienced people with similar interests.
- I hope we can make collaborative groups to implement HS to tackle several engineering problems.

Thank you!

Hector Guerrero
hguerrerob@ii.unam.mx

Yunbyeong Chae

Old Dominion University

Technical Barriers in RTHS

by Yunbyeong Chae

Assistant Professor
Department of Civil and Environmental Engineering
Old Dominion University

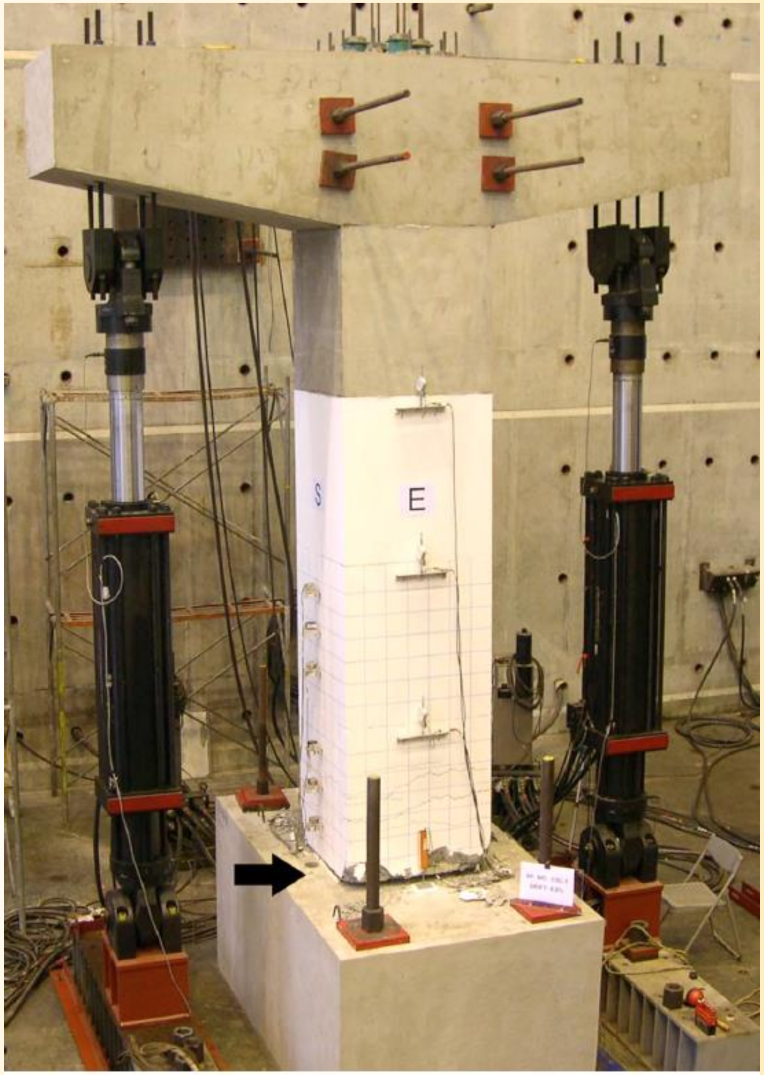
OLD DOMINION UNIVERSITY
IDEA FUSION

- Difficult to satisfy force boundary condition in **REAL-TIME** for *axially stiff members*
  - ➢ A majority of civil infrastructures are axially stiff (columns, beams, walls, base isolators, etc.)
  - ➢ Post-yield response is significantly affected by axial force ➔ important to satisfy axial force boundary condition accurately
  - ➢ The lack of knowledge for real-time force control significantly restricts the implementation of RTHS for axially stiff structures

Existing Large-Scale *Slow* Dynamic Tests

which are challenging to be conducted in real time

Full-scale slow hybrid simulation for an SMRF beam-column connection
Bennier, D.J. (2009). “Hybrid simulation of steel frames with semi-rigid connections.” M.S. Thesis, Department of Civil and Environmental Engineering, University of Illinois, Urbana, IL.

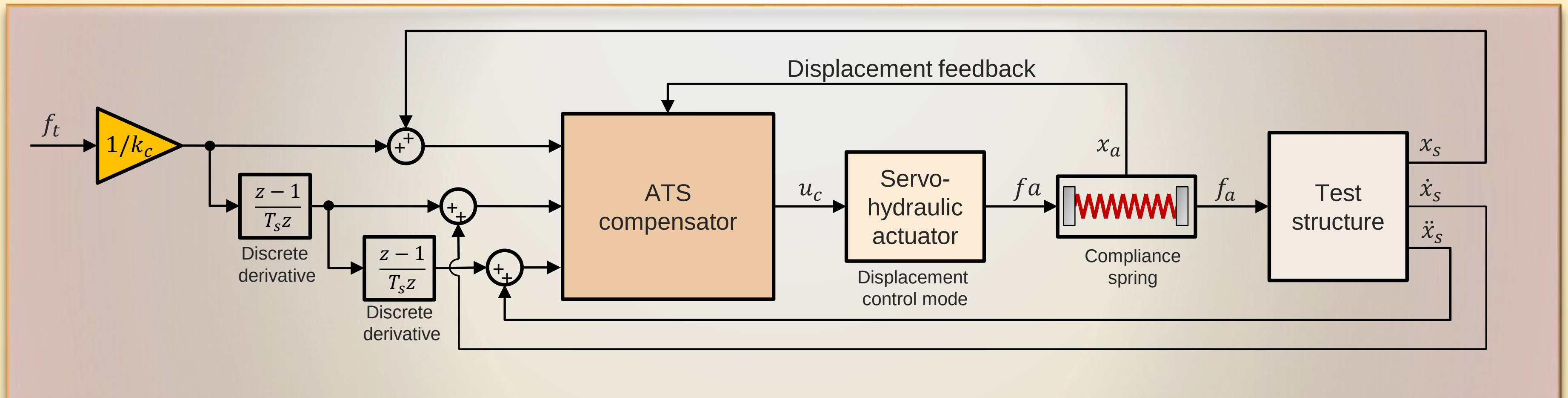


Ou et al. (2010). “**Large-Scale Experimental Study of Precast Segmental Unbonded Posttensioned Concrete Bridge Columns for Seismic Regions**”, Journal of Structural Engineering, 136(3):255-264.

How To Satisfy Force Boundary Condition in Real-Time?

- Need to develop robust real-time force control methods
- Use of Flexible Loading Frame (FLF)

D-ATS force control method*



* Chae, Y., Rabiee, R. Dursun, A., and Kim, C-Y. (2017) "Real-time force control for servo-hydraulic actuator systems using adaptive time series compensator and compliance springs", *Earthquake Engineering and Structural Dynamics*. https://doi.org/10.1002/eqe.2994

Roberto Gomez-Martinez

Institute of Engineering - UNAM

INSTITUTO
DE INGENIERÍA
UNAM

BOUNDARY LAYER WIND TUNNEL

Roberto Gómez-Martínez
Associate Professor
INSTITUTE OF ENGINEERING, UNAM
MEXICO

INSTITUTO DE INGENIERÍA UNAM

Q: Why we are not using HS in Mexico?

- **Lack of knowledge**
- **Instrumentation**
- **Measurement systems**
- **Funds ($$)**

Q: Technical barriers that prevent us from tackling more complex problems?

- **Our lack of knowledge**

Q: What problem/issue would you like to see HS applied to? [New to HS]

- **Develop and improve methods to simulate effects of wind on structures**
- **Improve methods for wind tunnel testing**

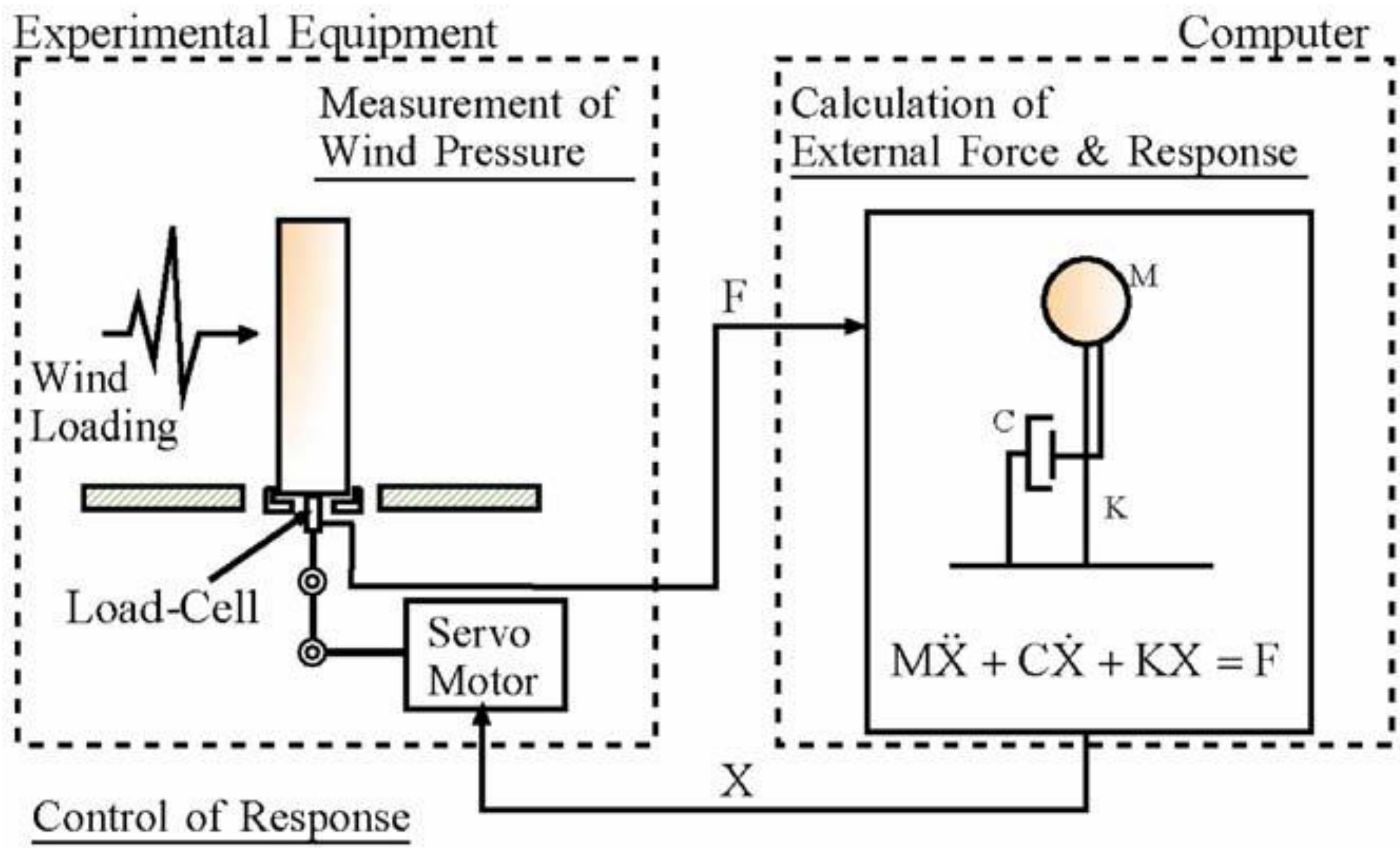
Q: What kind of testbeds/benchmarks would be helpful for building capacity and breaking barriers?

- **Means for verification of results from wind tunnel studies**

Q: What do you hope to get from this HS workshop?

- **Knowledge**
- **Contacts**

HYBRID SIMULATION FOR WIND TUNNEL TESTING



Narutoshi Nakata

Tokushima University

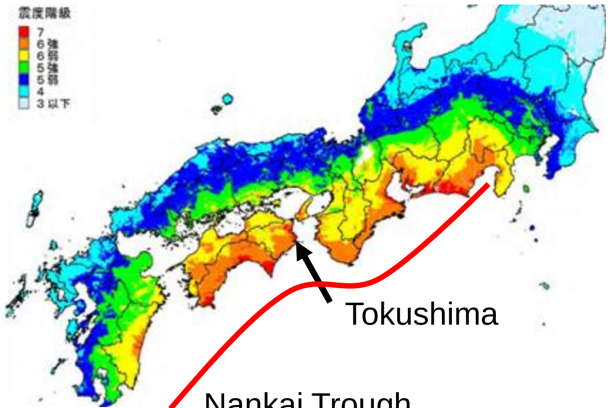
Structural Simulation for Disaster Prevention and Mitigation

Narutoshi Nakata, Ph.D.
Tokushima University, Japan

Faculty of Science and Technology
Tokushima University

Nankai Megathrust Earthquake

➢ Expected Ground Shaking

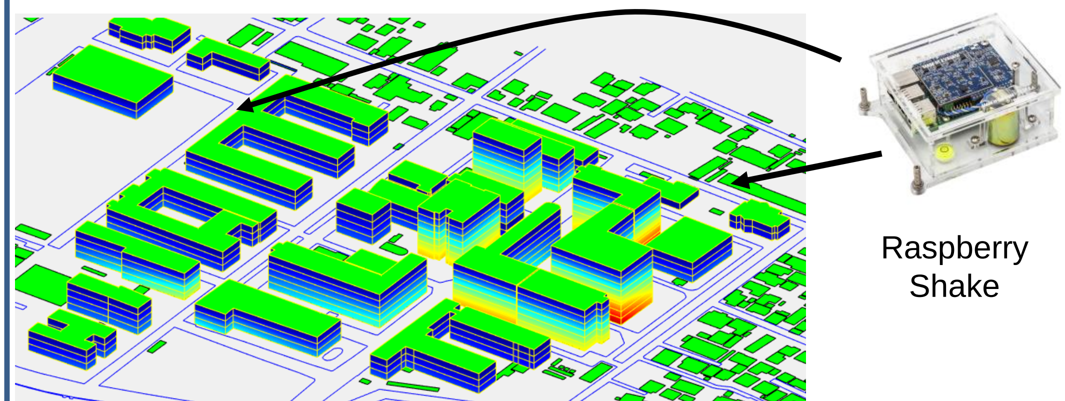


➢ Government Estimates

- Magnitude 8-9
- Death: 320,000
- Collapsed Buildings: 2.4 million
- Power Outage: 2.5 million
- Evacuee: 4.4-9.5 million
- Direct Loss: about $ 2 trillion
- Indirect Loss: $ 600 billion

My Research

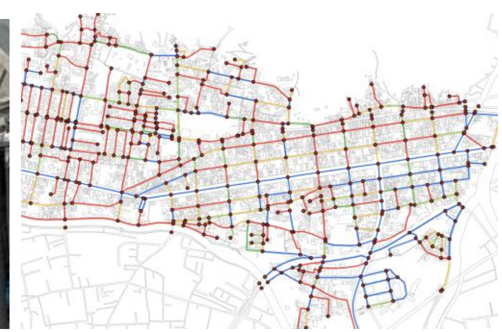
➢ Rapid Estimates of Regional Seismic Damage



Earthquake Simulation（Tokushima University Campus）

- GIS-based structural models
- Highly-dense seismological network

➢ Road Closure Hazard Map for Tsunami Evaluation



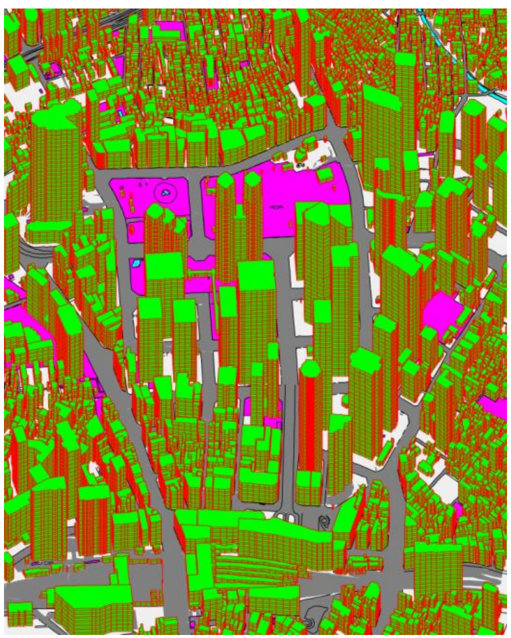
- Collapse Simulation using Extended DEM

Answers to Suggested Questions

- *What barriers exist for users new to hybrid simulation methods?*
  - ✓ *Building HS system/facility takes so much effort. Unless there is a strong application or development need, it is hard for users new to HS to make such an effort. 'How to' documents would be helpful.*
- *What are technical barriers that prevent us from tackling more complex problems? And how might we overcome those?*
  - ✓ *Need of validation*
  - ✓ *We need collection of success in complex problems.*
- *How can this be adapted to solve new problems in the WIND/COASTAL engineering?*
  - ✓ *Identify critical constitutive laws, governing relations, etc. that have to be satisfied in HS with fluids, and develop necessary techniques*
- *How can the community (collectively) leverage data/projects from the past?*
  - ✓ *Examine broader impact of the past projects and learn from the successful ones*
- *What kind of testbeds/benchmarks would be helpful for building capacity and breaking barriers?*
  - ✓ *The ones that include soil-foundation-structure-nonstructure with various EQ scenarios*

Possible directions for HS?

- Hybrid Simulation using Measurement from Existing Structures
- Hybrid Simulation for Regional Earthquake Simulation
- Hybrid Simulation for Soil-Structure Interaction Including Liquefaction
- Hybrid Simulation with Discrete Element Method



Regional Simulation Model (Shinjuku Area with 4000 buildings)

In the highly-clouded area, collapse of one building may cause domino-effect which is difficult to simulate unless

- All of the buildings are modeled
- Collapse is accurately simulated

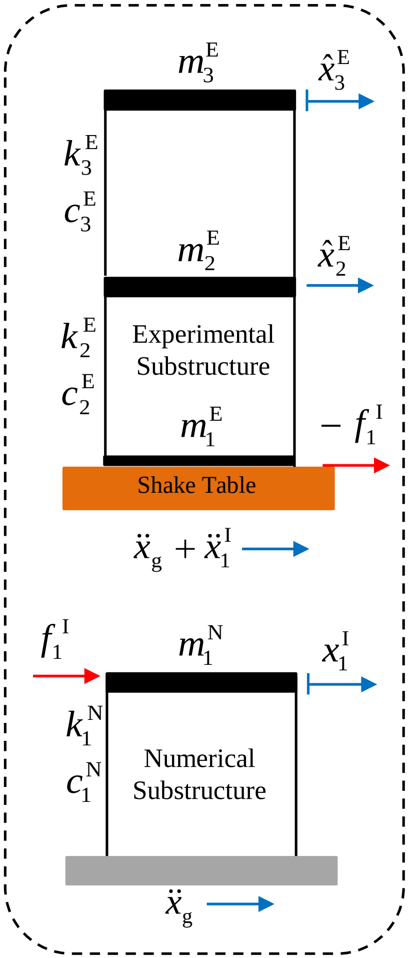
Is HS helpful for such problems?

Brian Phillips

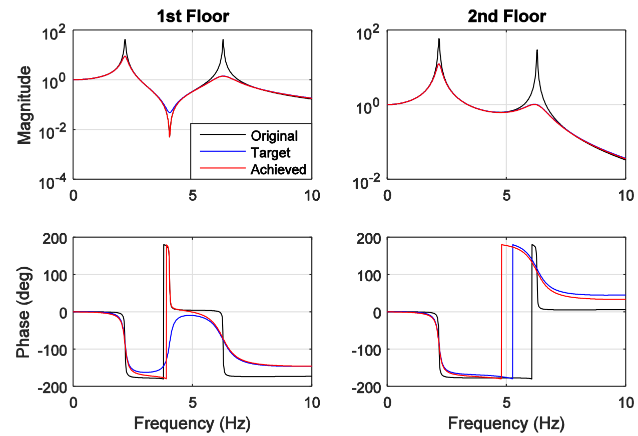
University of Maryland

Brian Phillips – University of Maryland
Recent Research in HS

Substructuring

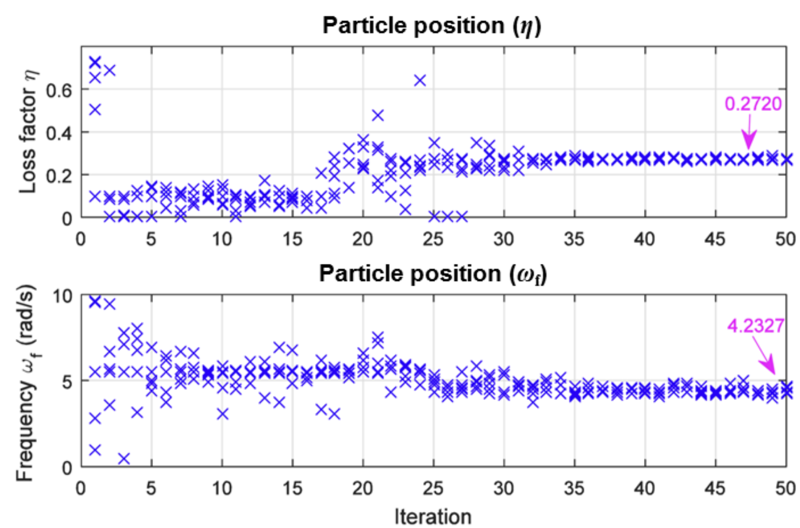


Artificial specimen damping

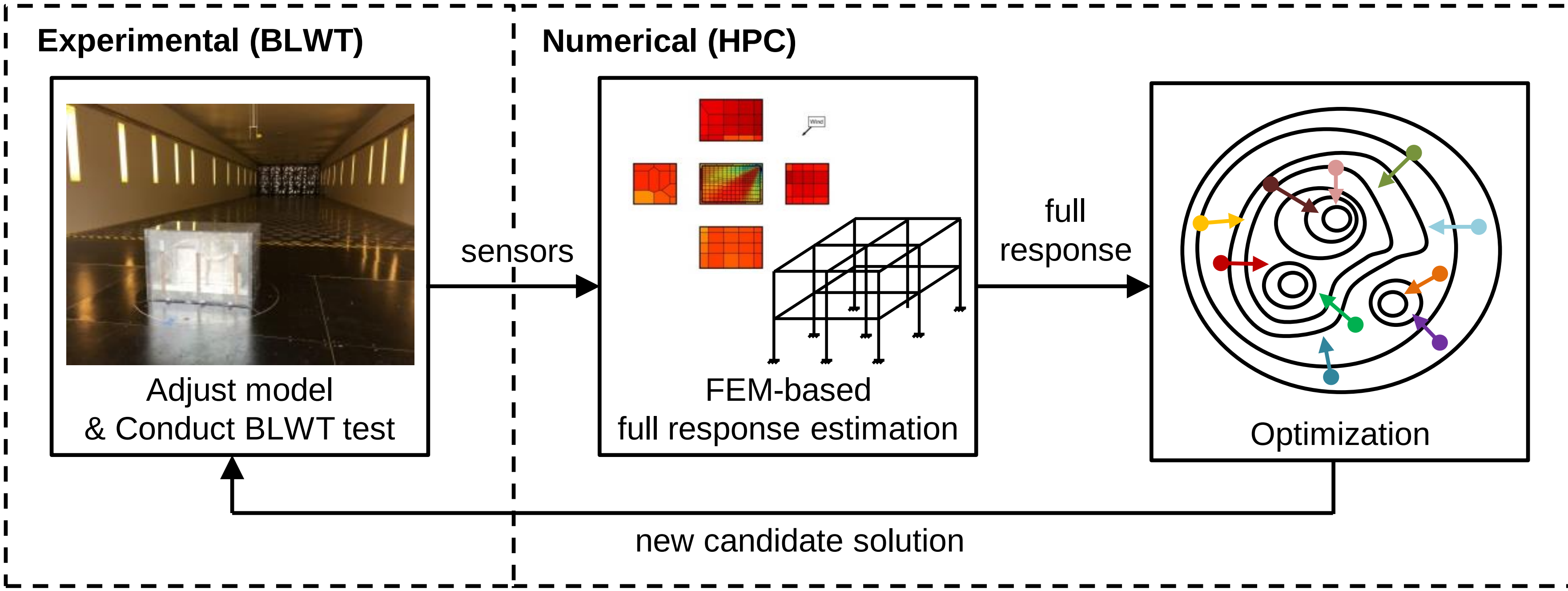


Optimization

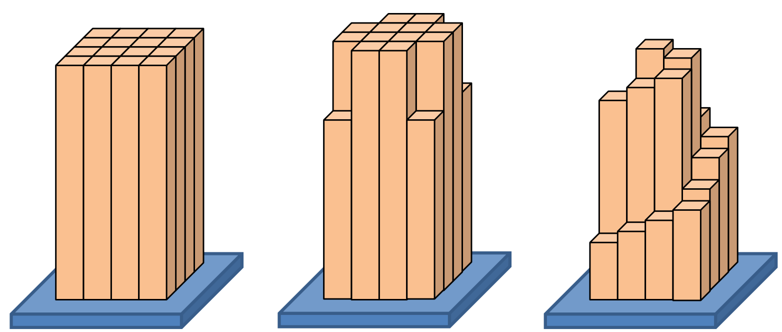
$$F_D(\omega) = k\eta\left(\frac{i\omega - \omega_f}{i\omega + \omega_f}\right)$$



How can HS be adapted to solve new problems in WIND/COASTAL engineering?



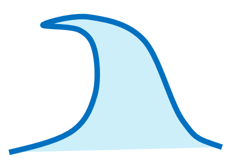
Example morphing structure:



Problems I would like to see HS applied to

- Multi-physics problems
  - Fluid-structure interaction
  - Soil-structure interaction
  - Impact forces
- Substructuring of physical system across multiple labs (e.g., multiple NHERI sites)
  - Model envelope and structure separately
  - Model simultaneous or sequential hazards

Earthquakes



Tsunami

Wind

Storm surge

Bin Wu

Harbin Institute of Technology

Bin Wu, Professor

School of Civil Engineering and Archetecture,
Wuhan University of Technology

School of Civil Engineering,
Harbin Institute of Technology

● Facilities

- **Harbin Institute of Technology**

  Uni-directional reaction wall with seven 1000kN/2000kN actuators

- **Wuhan University of Technology**

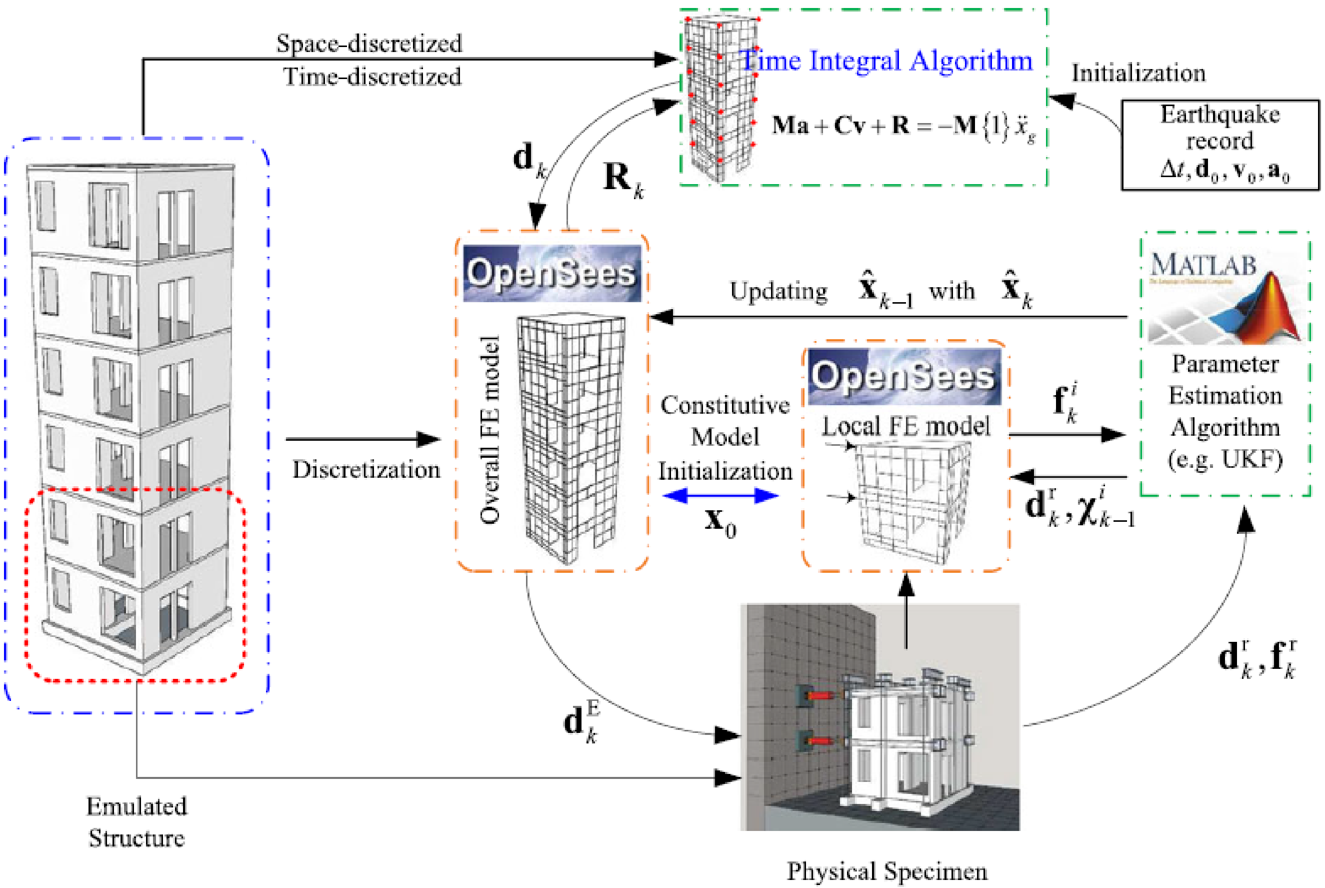
  Bi-directional reaction wall with six 500kN/1000kN actuators

1.What are technical barriers that prevent us from tackling more complex problems?

—Incomplete boundary conditions

2. How might we overcome those?

—Online numerical simulation



What problem/issue would you like to see HS applied to?

- **—More complex problems such as hybrid simulation of bi-directional earthquake response.**
- **— Related issues include redundancy control, geometric nonlinearity, model updating.**

A Research Coordination Network (RCN):
Multi-hazard Engineering
Collaboratory in Hybrid Simulation

James Ricles

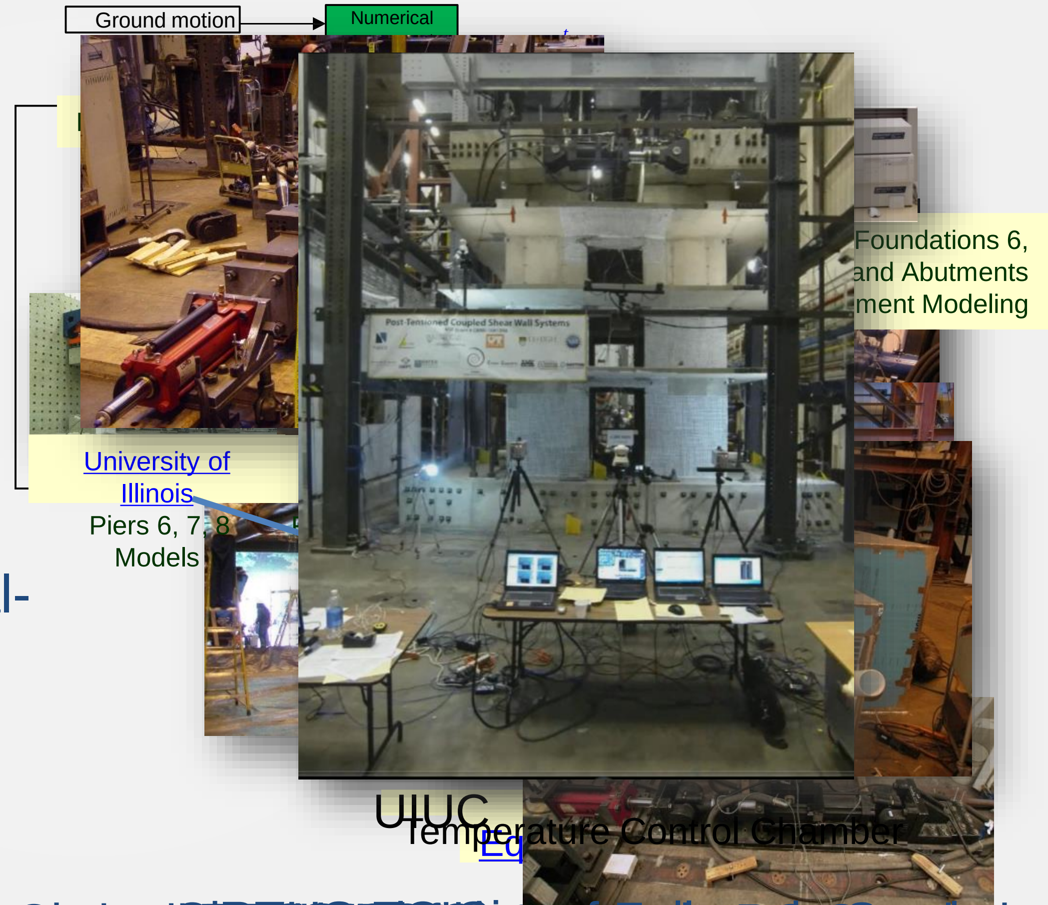
Lehigh University

James Ricles

- Professor, CEE Dept., Lehigh University
- PI and Director: NHERI Experimental Facility with Large-Scale Multi-Directional Hybrid Simulation Testing Capabilities
- Registered Professional Engineer State of California
- Selected Areas of Research and Expertise:
  - Large-scale simulation: numerical; experimental; hybrid
  - Large-scale, multi-directional real-time hybrid simulation
  - Performance-based engineering
  - Development of innovative resilient structural systems for multi-hazard mitigation
  - Computational modeling

NHERI Natural Hazards Engineering Research Lehigh Experimental Facility

- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures
- Geographically Distributed Hybrid Simulation
- Geographically Distributed Real-time Hybrid Simulation
- Predefined load or displacements (Quasi-static testing or characterization testing)
- Dynamic testing



RTHS EQ Simulation of Building with MR Dampers (Kim, Christenson)

Opportunities and Barriers in Hybrid Simulation

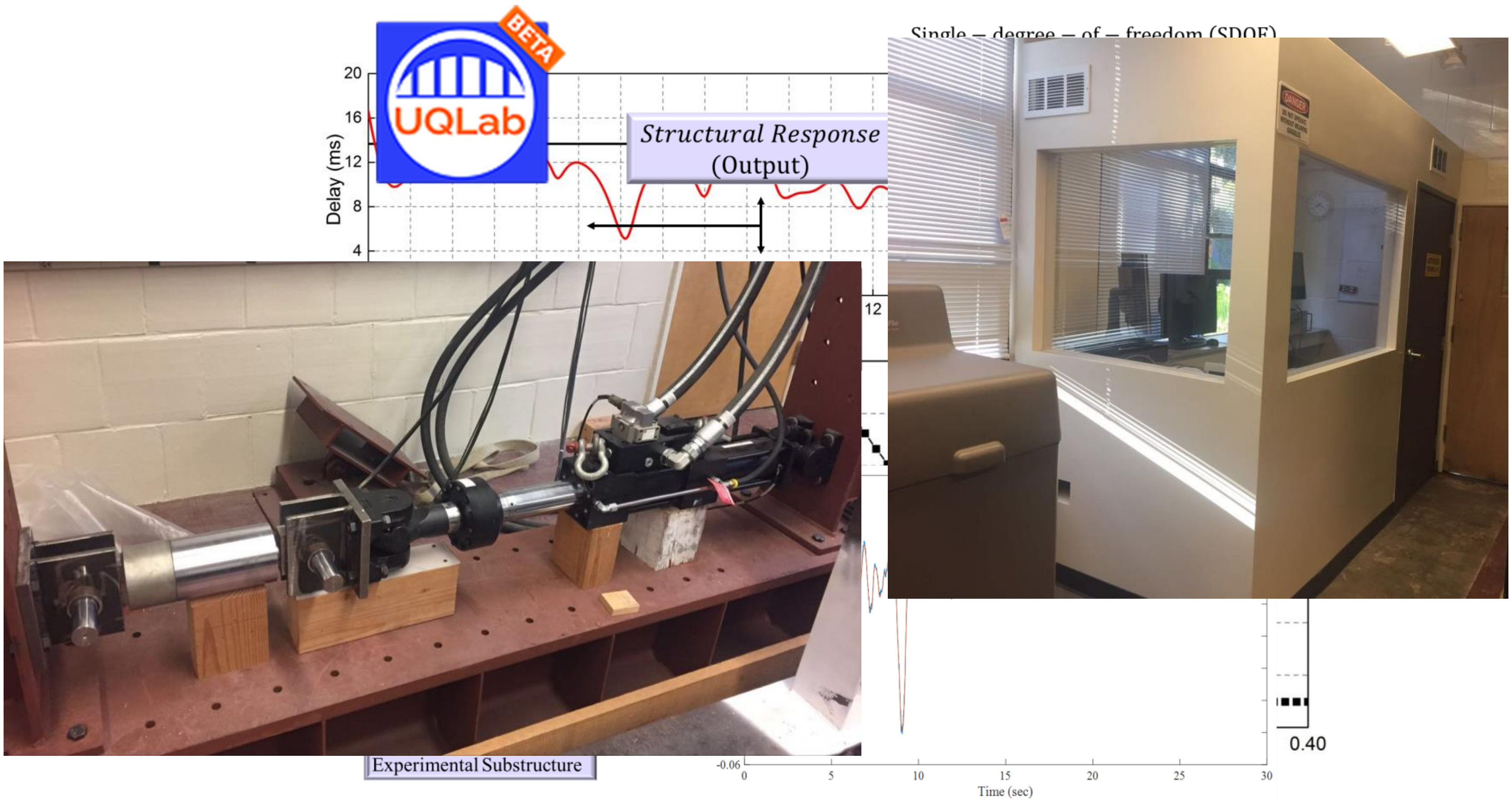
- Hybrid simulation provides the opportunity to investigate effective performance-based mitigation actions to achieve community resilience for different natural hazards:
  - Can account for interrelationships of load-rate dependent components in systems;
  - Enables demand imposed to system to be associated with hazard level;
  - Produce valuable data for the purpose of establishing and validating physics–based models for advanced numerical simulations.
- Some barriers:
  - Complex systems require complex models: many DOF in system, complex state-determination processes in experimental substructure can limit the size of time steps in a simulation and hinder the ability to accurately conduct RTHS;
  - More realistic characterization of loading on buildings and other structures;
  - Realistic boundary conditions between experimental substructure(s) and numerical substructure(s) – rotational, translational DOF; coupling; displacement/force BC.
  - Actuator control in RTHS: strongly coupled, multi-directional DOF in experimental substructure(s); actuator-experimental substructure-analytical substructure interaction effects.

Cheng Chen

San Francisco State University

Cheng Chen, SFSU

- Associate Professor of Civil Engineering



Thoughts on HS Questions

- How can the community (collectively) leverage data/projects from the past?
  1. **Data sharing would be beneficial (replication?)**
  2. **Substructure model information**
- What are technical barriers that prevent us from tackling more complex problems?
  1. **<u>Existing issues</u>: stability under time varying delay for RTHS; realistic modeling of analytical substructure for both HS and RTHS; boundary between substructures; and reliability assessment of experimental results**
  2. **<u>New issues</u>: substructures modeling under other types of loading than seismic; experimental equipment;**

SF STATE

Expect HS/RTHS Applications to

- To geotechnical engineering problems such as soil-structure-interaction

  Siva @ Buffalo

- To structural engineering problems involving fire and blast loading

  NIST

- To wind/coastal engineering problems

  Brian @ U of Maryland; Naru @ Clarkson

- Geographically distributed hybrid simulation or real-time hybrid simulation of civil engineering problems

Chris Gill

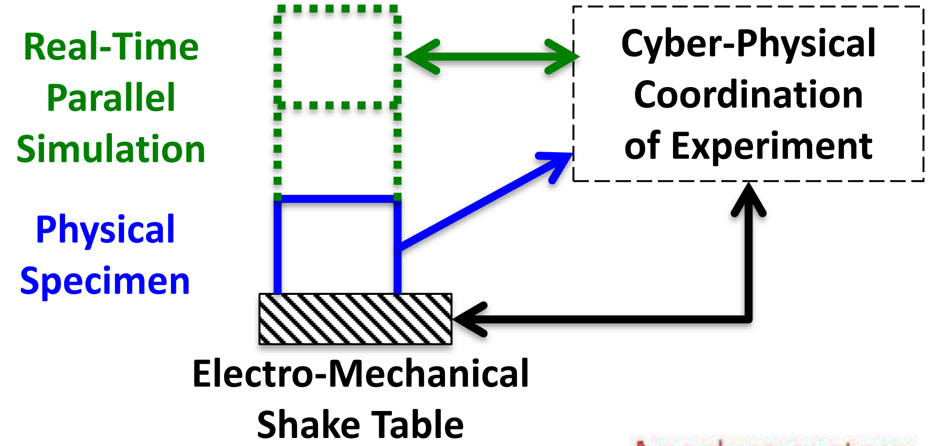
Washington University in St. Louis

Chris Gill, Professor of CSE
Washington University

CyberMech Project

Collaborative with Shirley Dyke and Arun Prakash (Purdue);

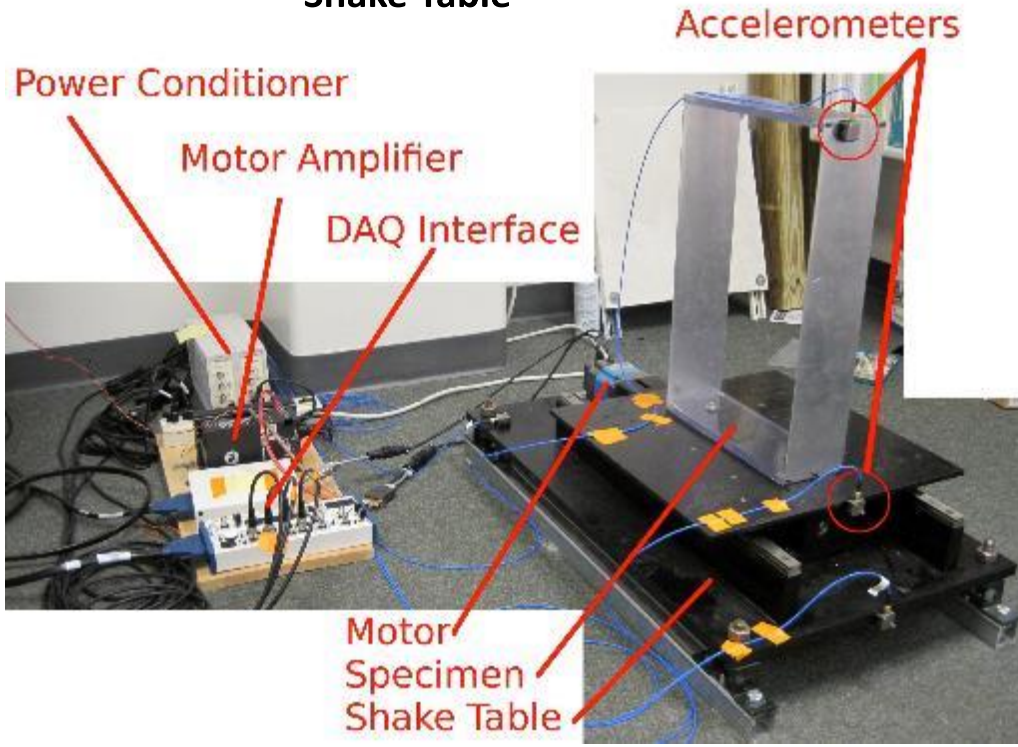
Parallel RTHS at 1024Hz for 1300 DOF simulation



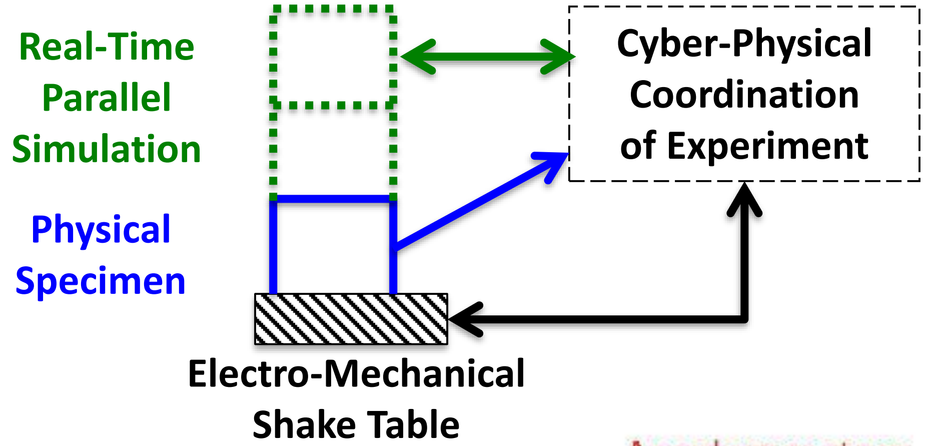
CSE Contributions

Parallel real-time scheduling theory; Multi-core concurrency platform design/eval;

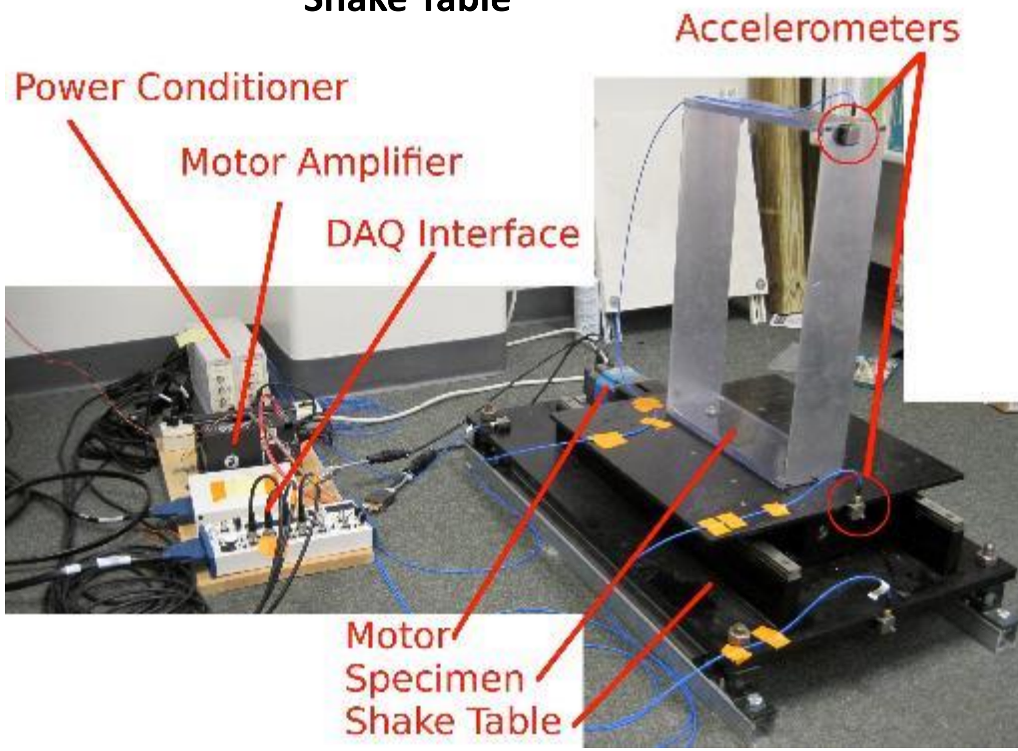
Thread-safe integration with shake table, sensors



What kinds of testbeds / benchmarks would be helpful for building capacity and breaking barriers?



A slightly different way to ask this question:



What is needed beyond current (static, linear) ***parallel real-time*** hybrid simulation platforms?

What I'd Like to Learn at MECHS

What are the current opportunities and technology limitations in **multi-hazard** RTHS?

Tōhoku Earthquake and Tsunami, 2011

What are the most interesting and challenging scenarios for **dynamic**, **real-time** hybrid testing (with multiple hazards, non-linear behavior, other sources of complexity)?

Ho-Kyung Kim

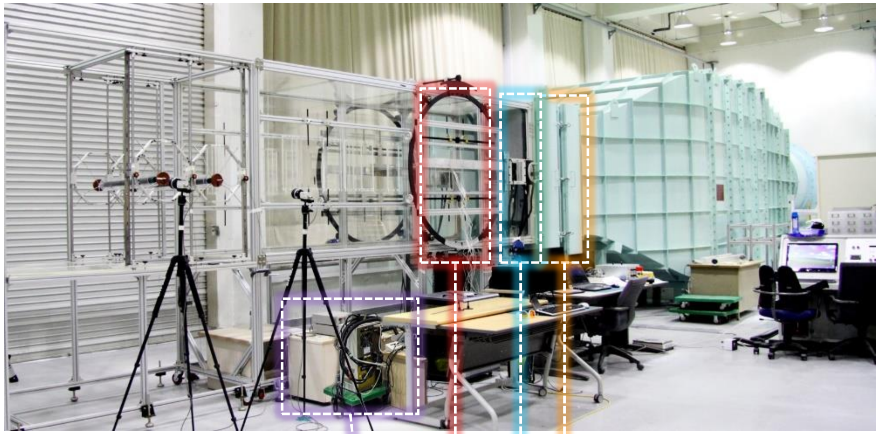
Seoul National University (SNU)

Structural Assessment/Bridge Aerodyn., Seoul National University(SNU)

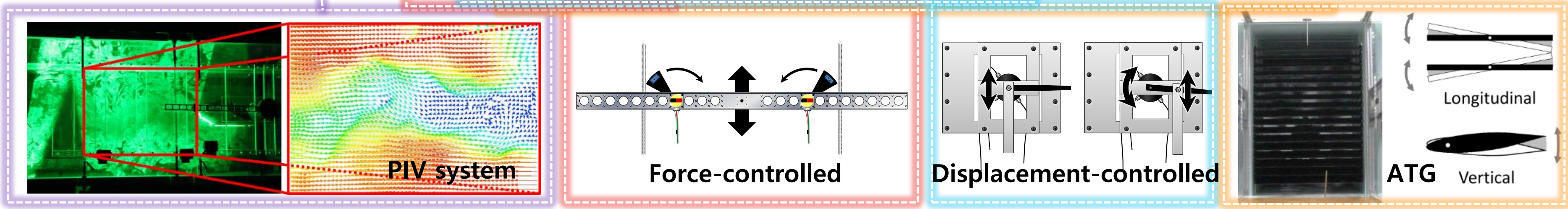
Prof. Kim, Ho-Kyung

- Chair, Department of Civil and Environmental Engineering, SNU
- POSCO Chair Professor
- Director, Korea Bridge Design and Engineering Research Center (KBRC)
- IABSE, Chair of Korean Group, WG10(Super-Long Span Bridge Aerodynamics) member
- Editor-in-Chief, KSCE Journal of Civil Engineering (Springer, Indexed in SCIE)

Le Cachalot Wind Tunnel
Seoul National University



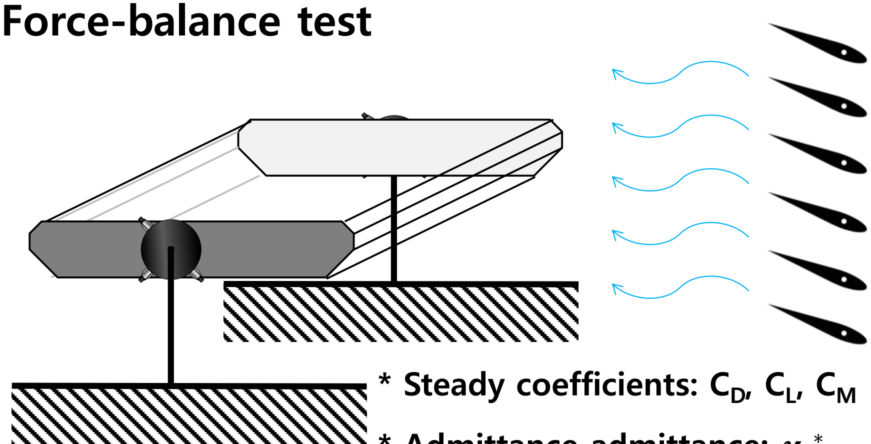
- Wind resistance design for 20+ cable-supported bridges
- Wind tunnel facilities
  - Test section : W(1.0 m) × H(1.5 m) × L(4.0 m)
  - Maximum wind velocity : 23 m/s
  - Force-controlled steady-state exciter
  - Displacement-controlled harmonic exciter
  - Active turbulence generator(ATG)
  - PIV system



Two-Phase Response Evaluation based on Aeroelastic Analysis

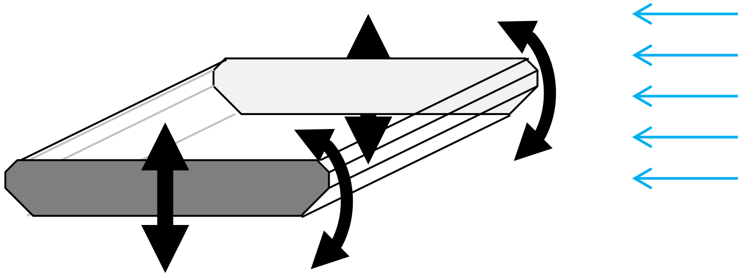
Wind tunnel test for parameter identification

Force-balance test



* Steady coefficients: C_D, C_L, C_M
* Admittance admittance: χ^*

Prescribed motion test



* Unsteady coefficient (Flutter Derivatives): $H_i^*,\ A_i^*\ (i = 1, \cdots 6)$

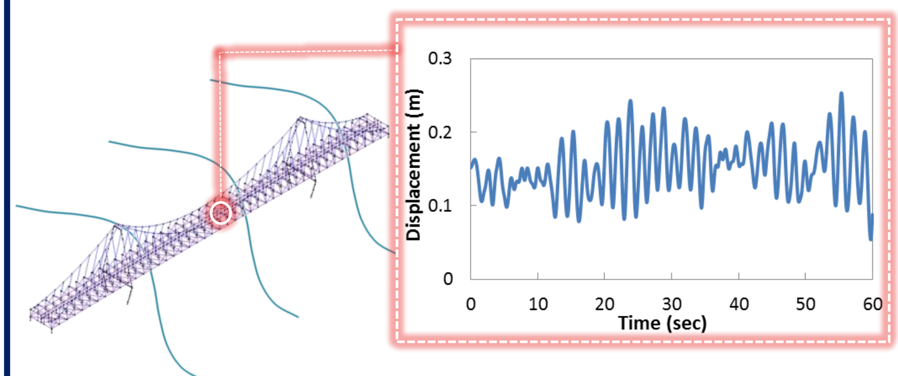
(Scanlan and Tomko, 1971)

Aeroelastic buffeting analysis

$$\begin{bmatrix}F_D\\F_L\\F_M\end{bmatrix} = \boxed{F_{static}} + \boxed{F_{Buffet}} + \boxed{F_{self-excitied}}$$

$$= \boxed{\frac{\rho U^2 B}{2}\begin{bmatrix}C_D\\C_L\\BC_M\end{bmatrix}} + \boxed{\frac{\rho U B}{2}\begin{bmatrix}\chi^*_{D_u} & \chi^*_{D_w}\\ \chi^*_{L_u} & \chi^*_{L_w}\\ \chi^*_{M_u} & \chi^*_{M_w}\end{bmatrix}\begin{bmatrix}u\\w\end{bmatrix}}$$

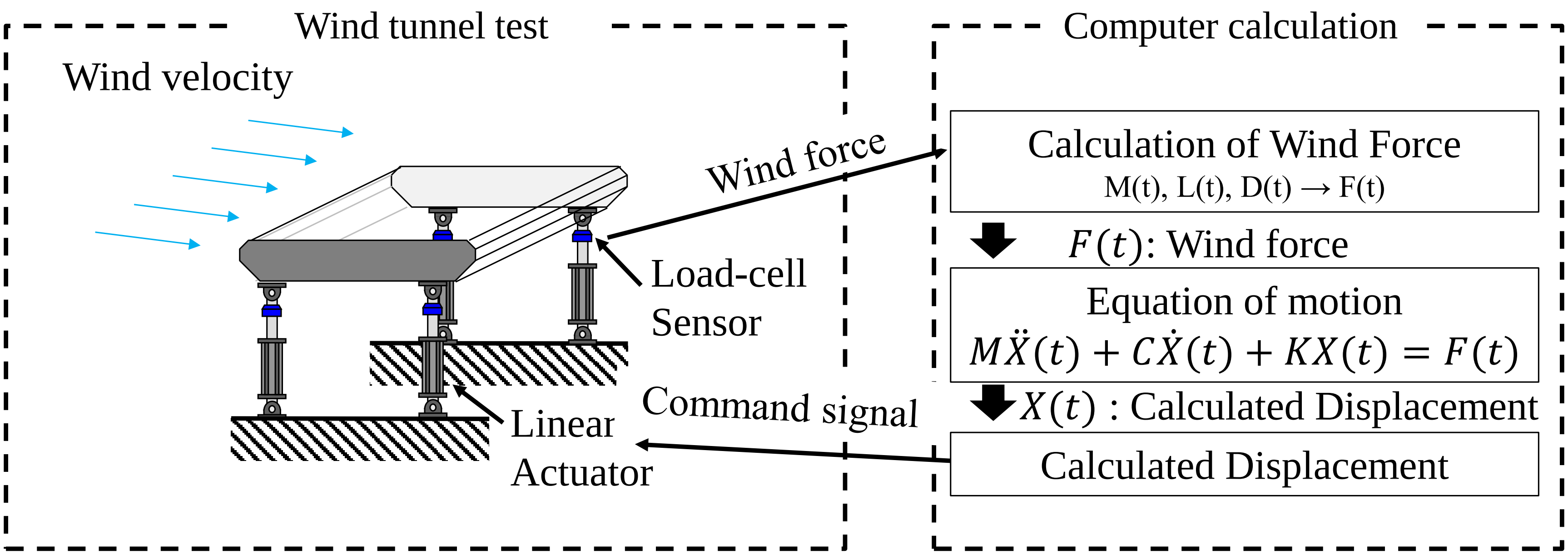
$$+ \boxed{\frac{\rho U B}{2}\begin{bmatrix}P_1^* & P_5^* & P_2^*\\ H_5^* & H_1^* & H_2^*\\ A_5^* & A_1^* & A_2^*\end{bmatrix}\begin{bmatrix}\dot{p}\\ \dot{h}\\ \dot{\alpha}\end{bmatrix} + \frac{\rho U^2 B}{2}\begin{bmatrix}P_4^* & P_6^* & P_3^*\\ H_6^* & H_4^* & H_3^*\\ A_6^* & A_4^* & A_3^*\end{bmatrix}\begin{bmatrix}p\\ h\\ \alpha\end{bmatrix}}$$



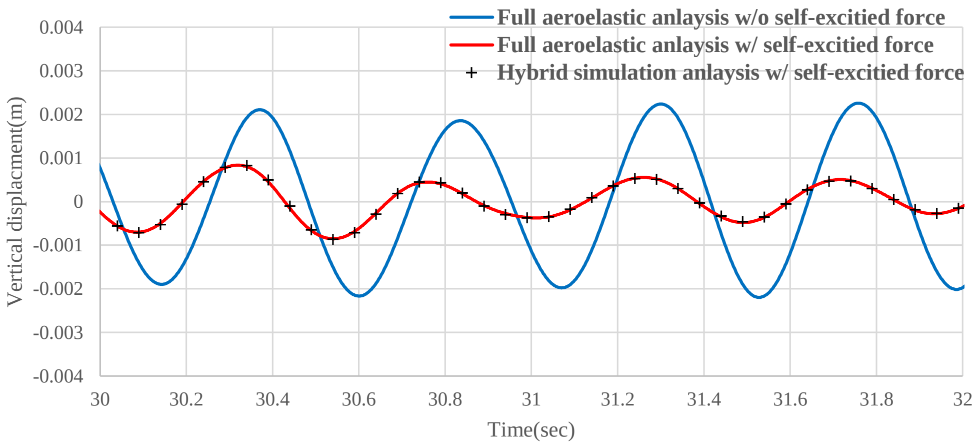
- Basically no advance after Scanlan's approach in 1971.
- Unsteady aeroelastic phenomenon has not been clearly explained by experiments.

Realization of HS technique in wind tunnel test

Proposed HS



Feasibility study by replacing wind tunnel test with time-domain aeroelastic analysis



- Aerodynamic/Aeroelastic forces are evaluated by Fourier series approach (Park et al. 2014).
- Preliminary investigation recommends the maximum time step of **0.004** sec. for converged response compared to a full aeroelastic analysis approach.

Park et al. (2014). Exact Enforcement of the Causality Condition on the Aerodynamic Impulse Response Function using a Truncated Fourier Series, *J EM*, 140-5.

Denis Istrati

University of Nevada, Reno

Application of Hybrid Simulation to Wave Impact and Wave-Structure-Interaction Problems

Denis Istrati and Ian G Buckle

e-mail: distratii@unr.edu and igbuckle@unr.edu

Department of Civil and Environmental Engineering
University of Nevada, Reno, USA

Experimental facilities at UNR: (a) 3D view of EEL and LSSL (b) inside view of EEL, and (c) inside view of LSSL (source: www.unr.edu)

<u>Large-Scale Structures Laboratory (LSSL)</u>

9000 sq.ft test floor and a reaction wall. 10 actuators with 55-934kip capacities for static and/or dynamic loading

<u>Earthquake Engineering Laboratory (EEL)</u>

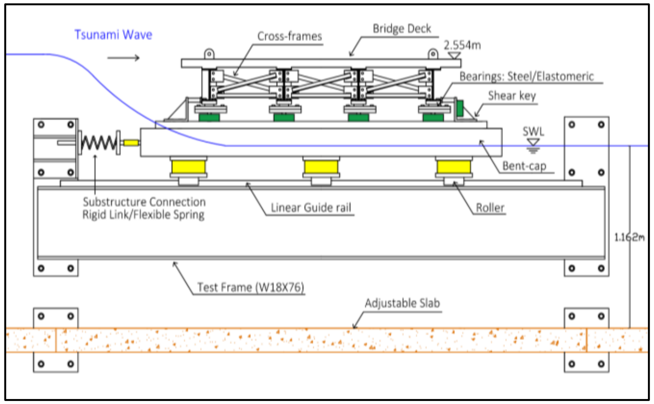
9600 sq.ft of strong floor, three biaxial shake tables and one 6-degree-of-freedom table.

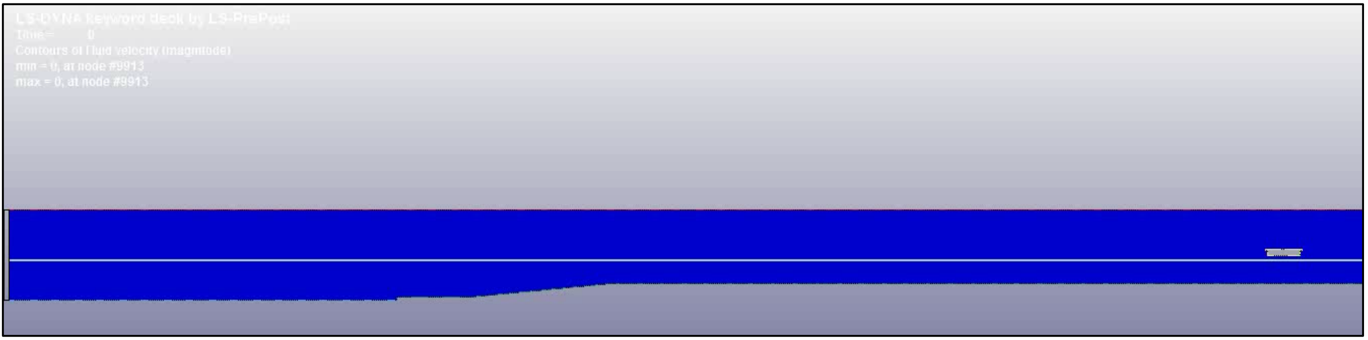
Research on wave impact effects

Recent and on-going work of research team focuses on tsunami and hurricane effects on coastal infrastructure (sponsored by FHWA) via:

A. Advanced computational modeling using High Processing Computing (HPC) and optimized decomposition methods to speed-up calculations

B. Large-scale hydrodynamic experiments in LWF at OSU and development of a unique high-quality database of (a) **wave slamming effects** and (b) **dynamic fluid-structure-interaction.** Available more than 400 tests and 15 structural configurations.





D. Istrati, I.G. Buckle, P. Lomonaco, S. Yim, A. Itani (2016): “Large-scale Experiments of Tsunami Impact Forces on Bridges: The Role of Fluid-Structure Interaction and Air-Venting”, Proc. Twenty-sixth International Ocean and Polar Engineering Conference, Rhodes, Greece, June 26-July 1, 2016

Istrati, D., Buckle, I. G., Lomonaco, P., Yim, S., & Itani, A. (2017). Tsunami induced forces in bridges: large-scale experiments and the role of air-entrapment. Coastal Eng Proc., 1(35), 30

Application of Hybrid Simulation

- Despite the available large-scale facilities for hydrodynamic testing it is not possible to test at full scale, meaning that scale effects might be present. Moreover, space restrictions sometimes require the simplification of experimental models, limiting the physical phenomena that can be studied.

- Hybrid simulation can prove a useful tool for studying multidisciplinary problems such as wave impact and wave-structure interaction by alleviating the aforementioned issues. Several possible approaches, such as:
  A. Coupling of two experimental facilities – Coastal eng. & Structural eng.
  B. Coupling of two numerical codes – a Computational Fluid Dynamics (CFD) & a Computational Structural Mechanics (CSM)
  C. Coupling of a numerical code (CFD or CSM) with an experimental substructure

- Some challenges/needs:
  A. Waterproof actuators and new experimental setup for use in a coastal eng. facility
  B. Validation of Computational Fluid Dynamics and Fluid-Structure-Interaction Methods. Need high-quality reliable experimental data and robust numerical methods.
  C. Wave inundation of coastal infrastructure includes a short-duration force (slamming) where dynamic FSI is significant. Will have to use RTHS to capture this phenomenon.
  D. Currently impossible to conduct CFD analyses in real-time, since it takes days to weeks on HPC for large-scale models with a fairly fine mesh. Need to develop faster numerical methods.
  E. Develop methods that will couple the experimental substructure with computational models running in parallel (HPC).

Possible to use the newly developed high-quality database as a benchmark for HS?

David Ferry

St. Louis University

Rapid Design and Iteration

David Ferry
St. Louis University

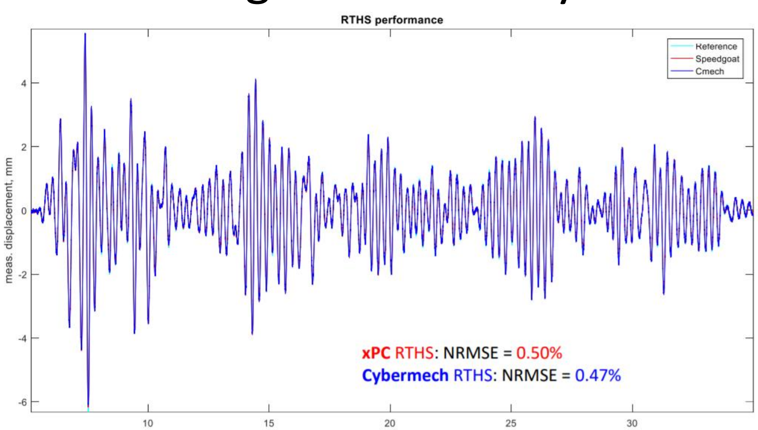
Limitations of Troubleshooting

Experimental performance is verified ad-hoc and post-mortem

- Single domain analysis is quick, cross domain is hard
  - E.g. Timing

```
Deadlines missed for task ./jcuRTHS_FE(6123): 3/35841
Max running time for task ./jcuRTHS_FE(6123): 0 sec  2576316 nsec on iteration 0
Avg running time for task ./jcuRTHS_FE(6123): 264546  nsec
All tasks finished
```

  - E.g. Structural Dynamics



Single-domain post-mortem is insufficient!

- Isolating errors among cyber/physical domains is nontrivial
- System output is a function of combined cyber/physical inputs to the system
- Interdisciplinary debugging is far more time consuming than single-discipline troubleshooting

Identify and Solve Problems Faster

- Static analysis for online constraint generation
  - Can an automatic analysis generate meaningful cyber or physical constraints that can be verified during runtime?
  - Can constraints be specific enough to indicate where problems lie?
- Debugging support
  - Consider a debugger for RTHS
    - Software debuggers allow you to stop and inspect or modify the state of a program- is there an RTHS analog?
    - Different tools in current infrastructure allow modifications and replay
    - No one framework connects cyber and physical sides in one toolkit
- Can the machine help attribute errors to causes?
  - Cyber-physical experiment trace forms a validation log
    - Lots of timing data, simulation data, and physical response data
    - This is something we always do by hand after an experiment, what are the barriers to doing it automatically or online?

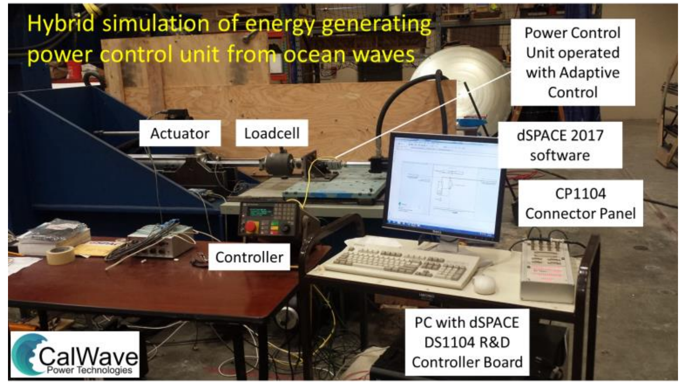
Andreas Schellenberg

University of California, Berkeley

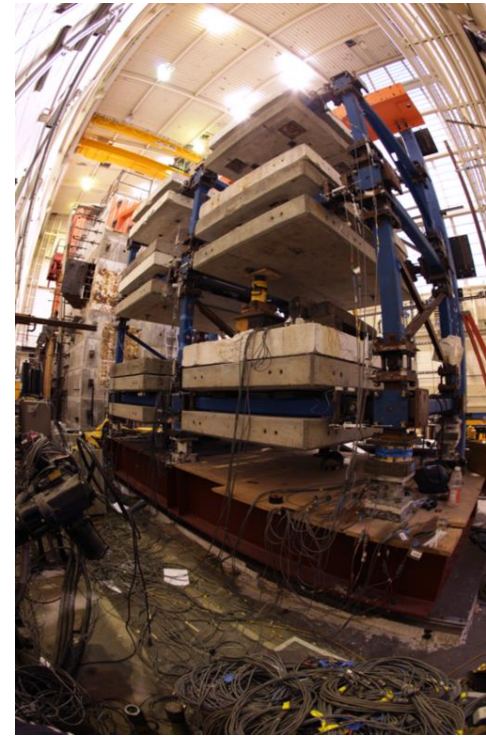
UC Berkeley & NEHRI SimCenter

Seismic or Wind

Wave



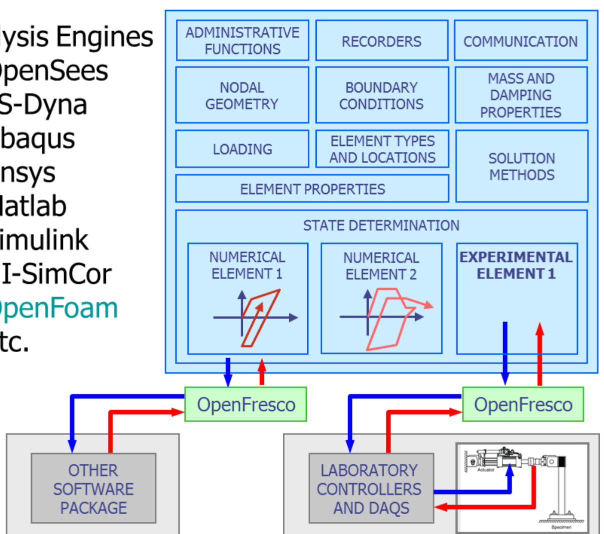
Seismic



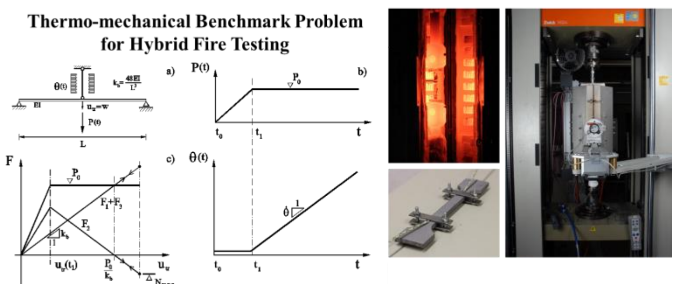
Software Integration & Support

Analysis Engines

- OpenSees
- LS-Dyna
- Abaqus
- Ansys
- Matlab
- Simulink
- UI-SimCor
- OpenFoam
- Etc.



Fire



Courtesy of M. Neuenschwander, ETH

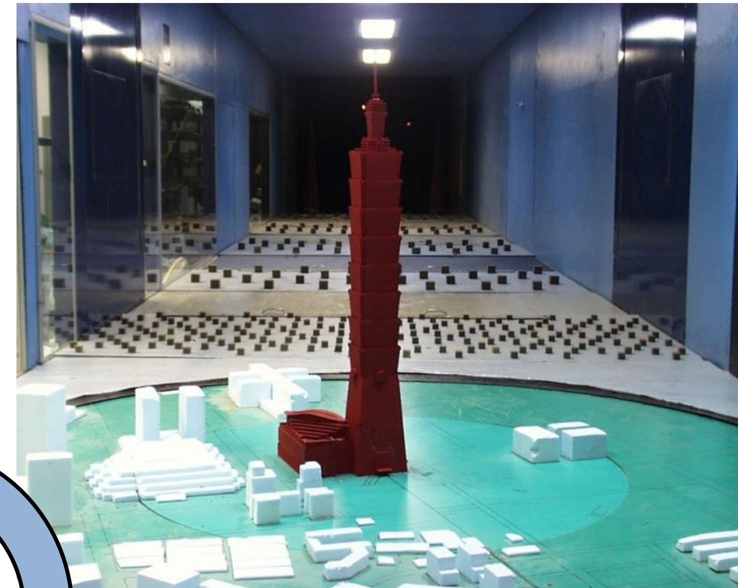
Wave

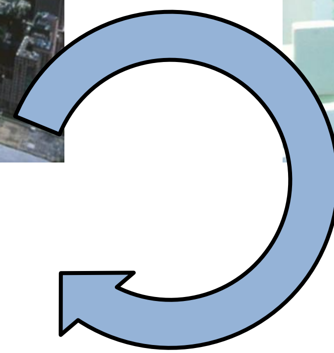
Seismic or Traffic

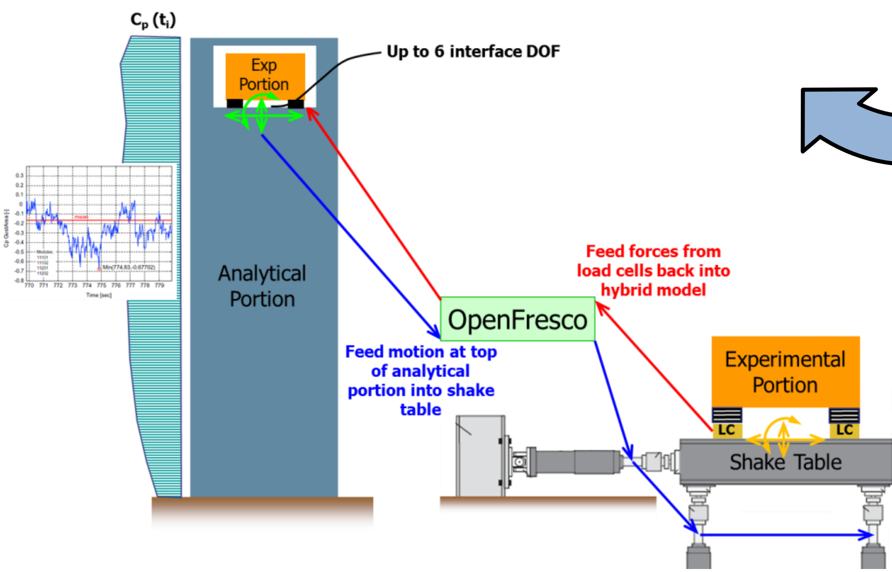
Thoughts on Template Questions

- *What barriers exist for users new to HS?*
  - We are missing a collaborative expert knowledge base (for example a HS Wiki) where beginners and advanced users can easily find information
  - HS user and developer forums where one can ask questions and discuss things with the community would be helpful
  - Develop a collection of educational videos HS101
- *What are technical barriers that prevent us from tackling more complex problems?*
  - Develop more robust control, delay compensation, and filtering (signal processing) techniques to deal with systematic errors caused by the interactions of the control and daq systems with the numerical portion of the hybrid analysis model
  - This is still the most critical issue affecting the reliability and accuracy of multi-DOF and real-time hybrid simulations, especially in the high frequency range of the response
  - Further streamline error assessment measures

Potential HS Application







Similitude laws for fluid–elastic models with Froude number neglected.

Physical quantity	Dimension	Scaling factor with S_l, S_v, S_ρ	Scaling factor with S_l, S_v, $S_\rho=1$	Scaling factor with $S_l=1/30$, $S_v=0.364$, $S_\rho=1$
Length, l	L	S_l	S_l	0.033
Displacement, d	L	S_l	S_l	0.033
Velocity, v	LT^{-1}	S_v	S_v	0.364
Acceleration, a	LT^{-2}	$S_l^{-1}S_v^2$	$S_l^{-1}S_v^2$	3.978
Force, F	F	$S_l^2S_v^2S_\rho$	$S_l^2S_v^2$	0.000147
Time, t	T	$S_lS_v^{-1}$	$S_lS_v^{-1}$	0.092
Modulus, E	FL^{-2}	$S_v^2S_\rho$	S_v^2	0.133
Pressure, p	FL^{-2}	$S_v^2S_\rho$	S_v^2	0.133
Pressure Coeff, C_p	1	1	1	1
Stress, σ	FL^{-2}	$S_v^2S_\rho$	S_v^2	0.133
Strain, ε	1	1	1	1
Strain-Rate, $\dot{\varepsilon}$	T^{-1}	$S_l^{-1}S_v$	$S_l^{-1}S_v$	10.924
Density, ρ	$FL^{-4}T^2$	S_ρ	1	1
Mass, m	$FL^{-1}T^2$	$S_l^3S_\rho$	S_l^3	0.000037
Damping, c	$FL^{-1}T$	$S_l^2S_vS_\rho$	$S_l^2S_v$	0.000405
Stiffness, k	FL^{-1}	$S_lS_v^2S_\rho$	$S_lS_v^2$	0.004420
Period, T	T	$S_lS_v^{-1}$	$S_lS_v^{-1}$	0.092
Frequency, f	T^{-1}	$S_l^{-1}S_v$	$S_l^{-1}S_v$	10.924

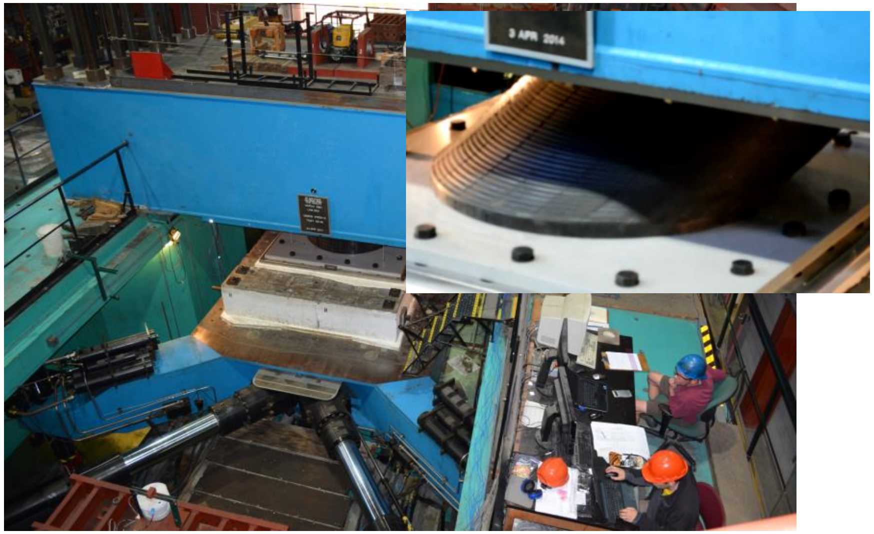
Gilberto Mosqueda

University of California, San Diego

Real-time Hybrid Testing with Large/Full Scale Experiments
Gilberto Mosqueda, Dept. of Structural Engineering

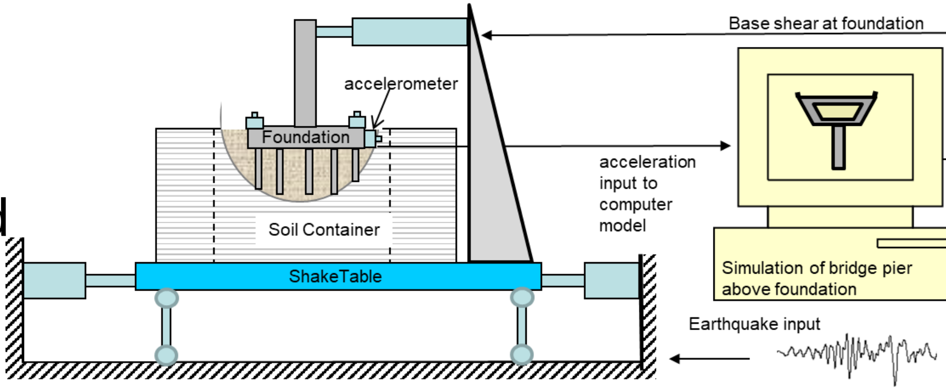
Large scale SRMD facility to test full size bearing using Hybrid Simulation

- Apply 3-D ground motions to subject bearing to combined axial and shear loads
- Capture interaction between structure and bearing under large earthquakes



Large Outdoor Shake table to test structural and geotechnical substructures

- Development of integration and compensation algorithms



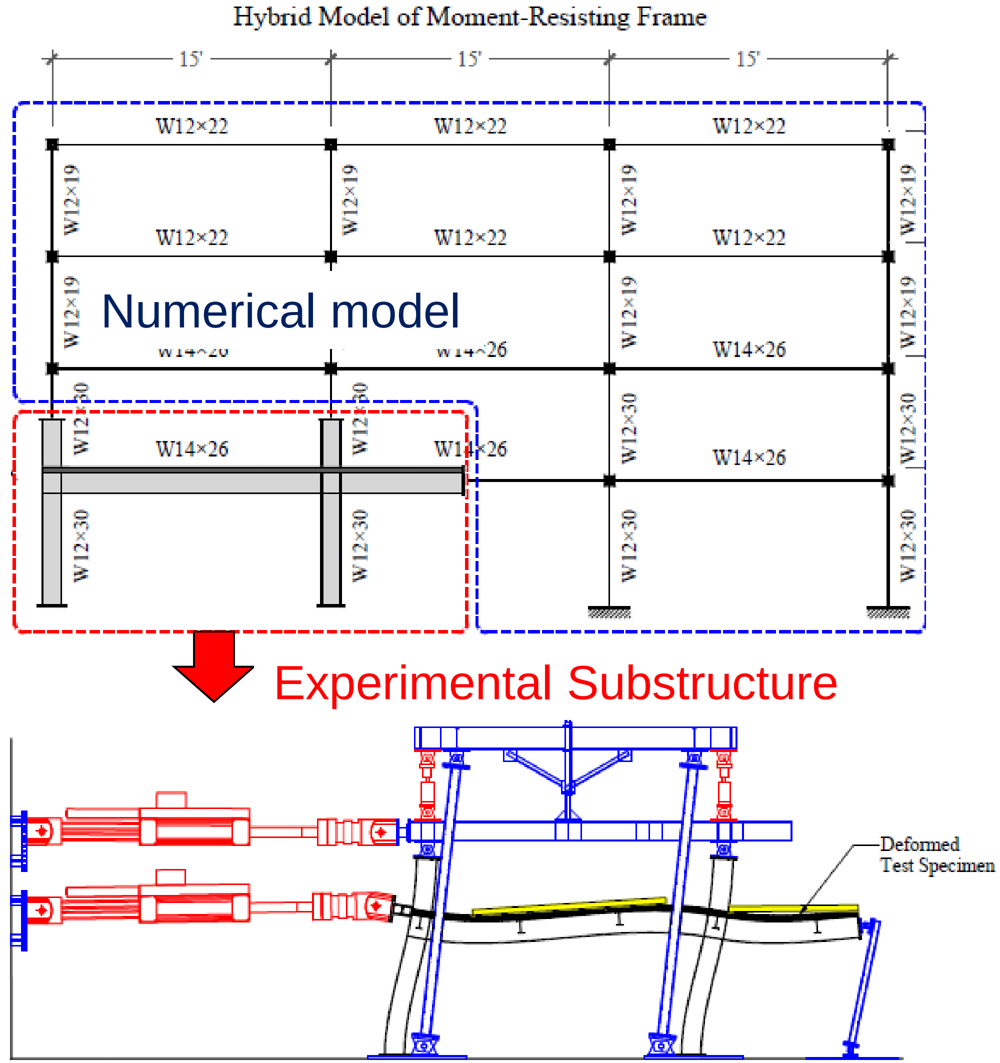
http://nheri.ucsd.edu/
http://go.ucsd.edu/2AwB7Hi

UC San Diego
Structural Engineering
JACOBS SCHOOL OF ENGINEERING

Barriers towards simulations of complex structural systems

Develop and apply hybrid simulation for cost-effective large scale system level testing of complex structural systems to collapse.

- Include complex nonlinear numerical models
- Applications of boundary conditions to large scale experimental substructures
- Extension to shake table substructures



(c) Deformed Configuration

Jian Zhang

University of California, Los Angeles

Introduction: Jian Zhang (UCLA)

- Research Interests
  - Model-based simulation of structural responses (earthquakes, liquefaction)
  - Earthquake hazard mitigation using protective devices (isolation, damper, negative stiffness)
  - Innovative structural systems for economical & efficient performance improvement (Low yield steel plate shear wall, rocking systems)
- Past experience in hybrid simulation
  - Validation of hybrid simulation
  - Optimal design of nonlinear dampers using numerical hybrid simulation platform

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Phone:
(310) 825-7986
Office:
5731G Boelter

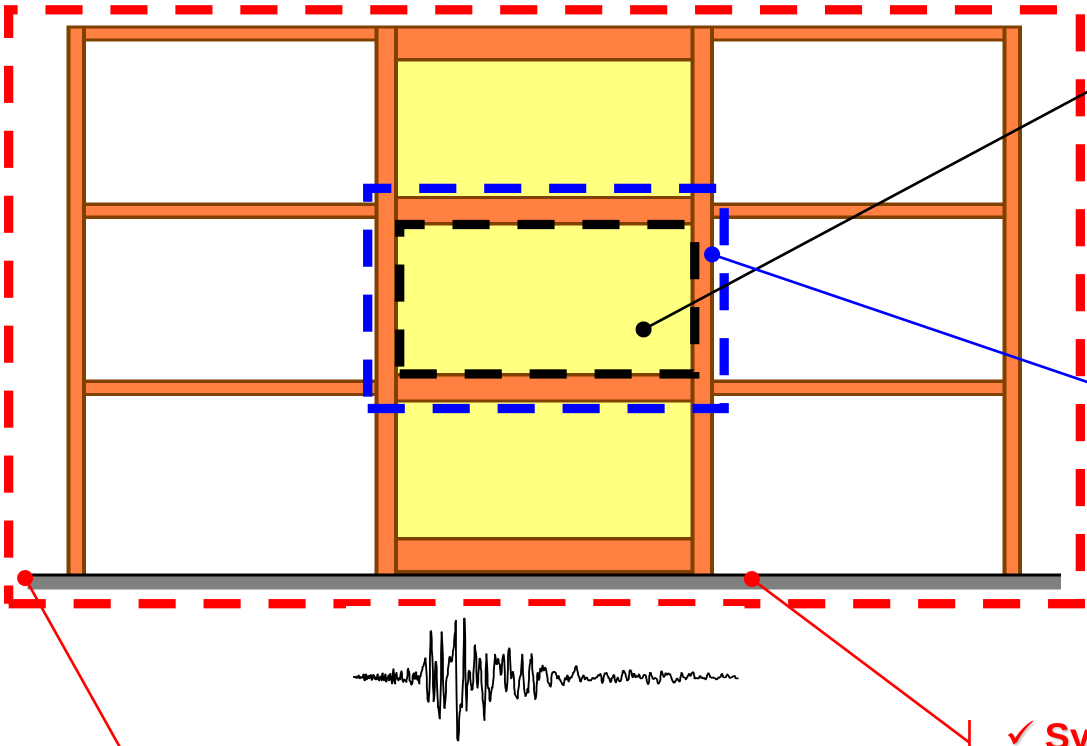
My thoughts on hybrid simulation

- Barriers (Technical and Non-technical)
  - Acceptance of HS as a cost effective and efficient alternative method to traditional structural tests (e.g. shaking table)
  - Minimize sources of inaccuracy (numerical model/simulation, equipment error, time delay, signal loss, coupling experimental and numerical components etc.)
  - Lack of unified standards, platforms, and data formats (US & international)
  - Limited capabilities of RTHS for large scale nonlinear system (real time tracking and compensation, stability of the test,

    → Community based hybrid simulation development, validation and application

Problems for Hybrid Simulation

- Development and assessment of new structural system and devices for multi-hazard mitigation



✓ **Element-level studies:**
Buckling & yielding
Limiting plate thickness

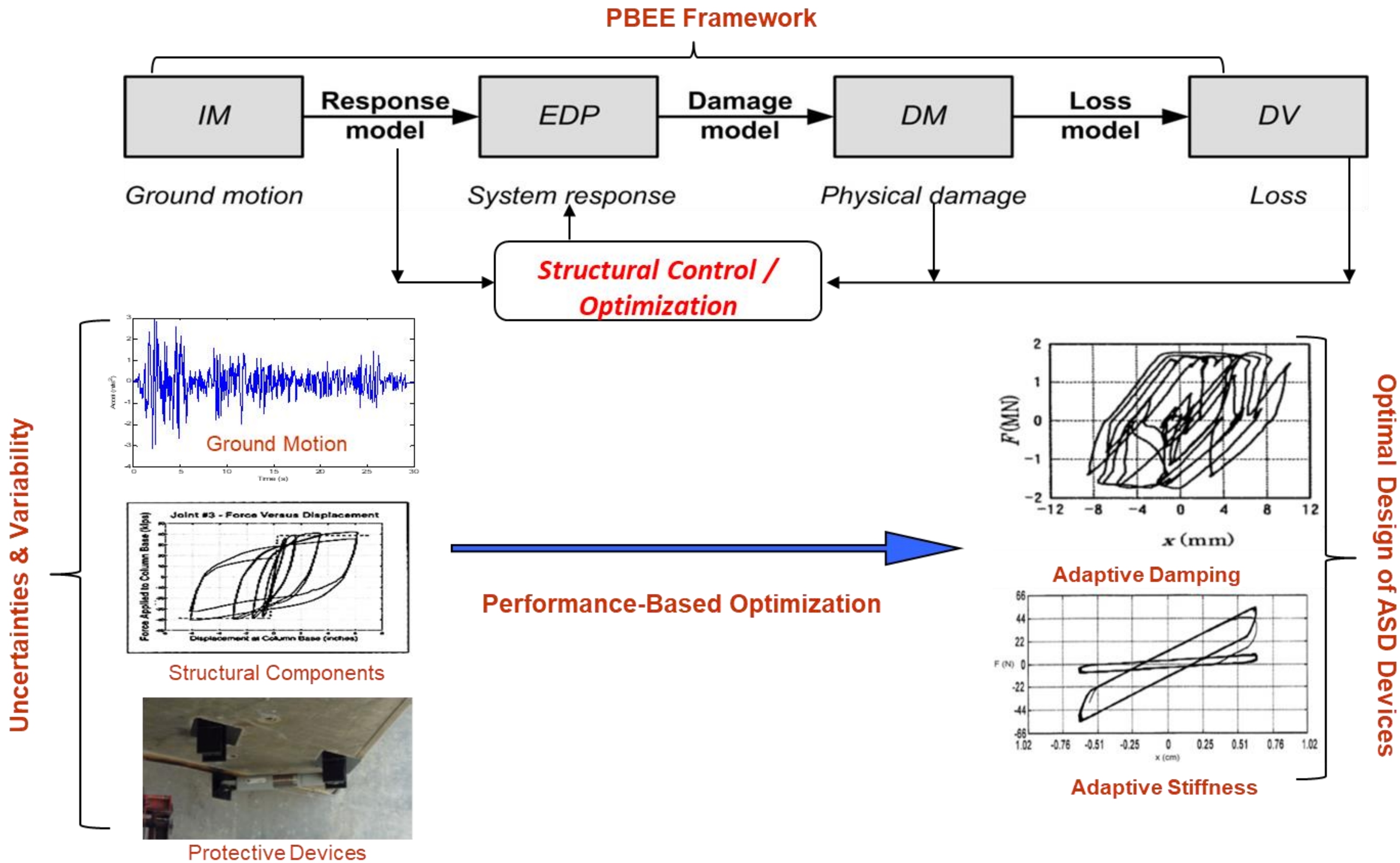
✓ **Component-level studies:**
Slender/Moderate/Stocky
Seismic retrofit & design

✓ **System-level studies:**
Code-designed/Retrofitted SPSWs
Seismic response & performance

✓ **Seismic vulnerability assessment:**
Probabilistic seismic demand analysis
Fragility function methodology

Problems for Hybrid Simulation

- ❑ Performance based implementation of protective devices



Wei Song

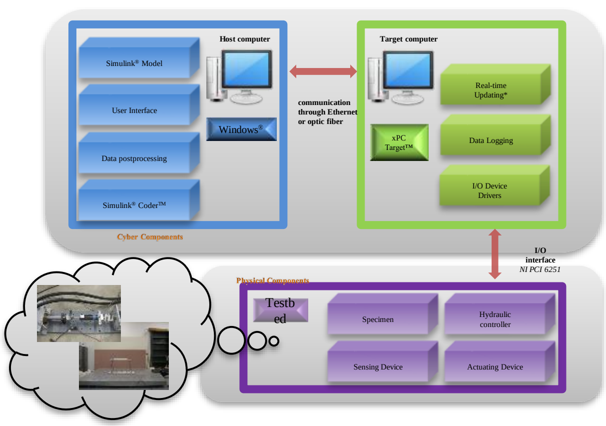
The University of Alabama

THE UNIVERSITY OF ALABAMA

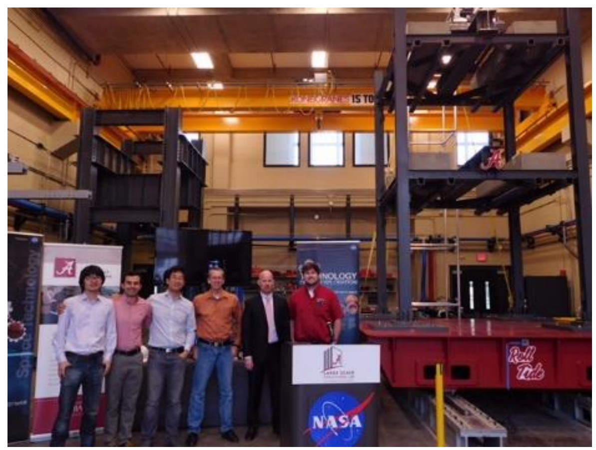
touching lives

Dr. Wei Song, Assistant Professor, Dept. of Civil, Construction and Environmental Engineering

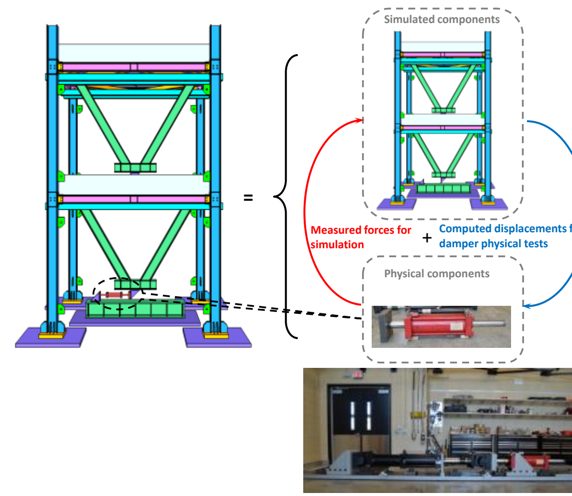
- **Rapid (Real-Time) Structural Condition Assessment Under Disaster Load**
  - Update nonlinear models in real-time during disaster event



- **Structural Response Control Technologies**
  - Develop novel response reduction technology



- **Real-Time Hybrid Simulation Techniques**
  - Investigate dynamic behavior of large scale structural systems via RTHS



Intelligent Systems and Structural Dynamics Laboratory
The University of Alabama, Tuscaloosa, AL 35487
•Phone: (205) 348-0774 •Fax: (205) 348-0783 •Web: wsong.ua.edu

Capacity Building

- *How can the community (collectively) leverage data/projects from the past?*
  - Maintained archives for both numerical and experimental components
    - Numerical models
    - Time integrations algorithms
    - Compensation techniques
    - Documents describing typical development of an RTHS application
  - Educational modules (list of prereqs, course materials, etc.)
- *What kind of testbeds/benchmarks would be helpful for building capacity and breaking barriers?*
  - *Testbeds demonstrating technical challenges*
    - *Separation of numerical and experimental components (adjustable device)*
    - *Compensation (rate dependent device)*
    - *Robustness (nonlinear device)*
  - *Simple but representative (simple device with repeatable behavior)*

My Interest

- *Develop HS for multi-hazard demands*
  - Wind/Costal Engineering
- *Learn and Explore HS of large-scale applications*
  - Civil and mechanical (e.g., automotive) engineering fields
  - Conference sessions
    - 7WCSCM (July 22-25, 2018, Qingdao, China), organized by *Ge (Gaby) Ou* and *Narutoshi Nakata*
    - ASCE-EMI (May 29-June 1, 2018, Boston, US), organized by *Wei Song* and *Richard Christenson* (Abstract submission open until Jan 31, 2018)

Arturo Schultz

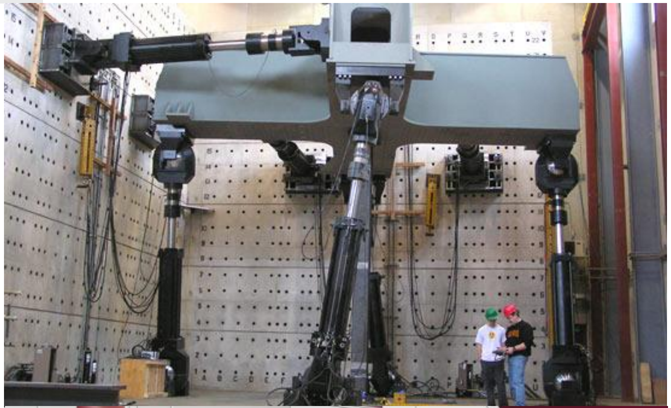
University of Minnesota

Arturo E. Schultz, Ph.D.
Professor of Civil Engineering

MAST LAB
Multi-Axial Sub-Assemblage Testing

MECHS Workshop
UCSD – Purdue University

- Large-scale structural testing laboratory
- One of the original NSF NEES sites
- Not in NHERI network; available non-UMN researchers
- MAST initially had hybrid simulation capabilities:
  - modified (continuous) fast hybrid (U. of Colorado)
  - later implement. used OpenFresco (ramp/hold)
- <u>Evolution in technology</u>, <u>hardware & software changes</u>, and <u>lack of user interest</u> led to loss of HS capability
- Currently upgrading HS capabilities (ramp/hold)
  - host computer running OpenFresco and FE soft.
  - target computer running Matlab Simulink
  - SCRAMnet comm's to/from MAST controller
  - Ethernet communications with host computer
- Local MAST interest group : CEGE, ECE, CSENG, AEM

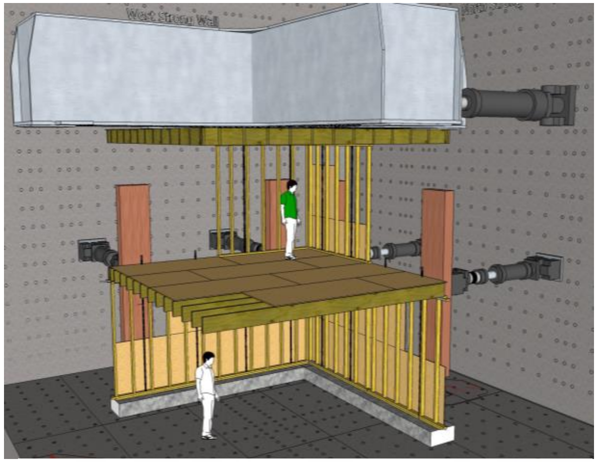


How can this (enhanced HS) be adapted to solve new problems in the WIND/COASTAL engineering?

- Introduce CFD engine either in host computer or an additional ('outside') computer for distributed HS
  - flow field generated by CFD 'engine';
  - wind pressure/load data transmitted to virtual (FE) building model;
  - host computer generates load/displacement increments for MAST controller;
  - MAST controller feedback to virtual model (and CFD engine)
  - if necessary use secondary feedback loop from MAST controller to CFD engine
- Challenges include
  - loading rates vs simulation rates
  - Multi-axial loading directions
  - 'outside' computer

To what problem/issue would you like to see HS applied?

- Performance of main lateral load systems in 'light' framed buildings
- Includes timber buildings and CFS frame structures
- Primary concern with performance under extreme winds (tornadoes, straight-line winds, hurricanes)
- Sustainability is motivating taller timber buildings
- ~ 10 high-rise timber buildings in Europe & North America
- Up to 18 stories, and planned buildings up to 40 stories
- Laboratory requirements for realistic testing are challenging
  - MAST crosshead provides resultant forces on frame
  - translational DOFs in 2 orthogonal horizontal directions
  - vertical DOF to represent uplift
  - ancillary actuators and whiffletree assemblages to represent local pressure along exterior walls (if needed)



Sungmoon Jung

Florida A&M University - Florida State University

Sungmoon Jung

- Buffeting, flutter, vortex-induced vibration
- Wind vulnerability analysis

Photo by floridadisaster.org

Photo by Dr. Ishihara

What are technical barriers that prevent us from tackling more complex problems? (to solve new problems in the wind eng.)

Current Hybrid Simulation Framework

?

Loss due to the earthquake

Photo by Dr. Ger

news.kmib.co.kr

Loss due to the wind

High-rise: about 100% non-structural

Low-rise: about 80% non-structural, 20% structural (sheathing, roof-to-wall, etc.)

What do you hope to get from this workshop?

- Research agenda that can solve wind problems, especially:
  - Abrupt failure in low-rise buildings (ex: roof-to-wall connections)
  - Water ingress

Oh-Sung Kwon

University of Toronto

Introduction

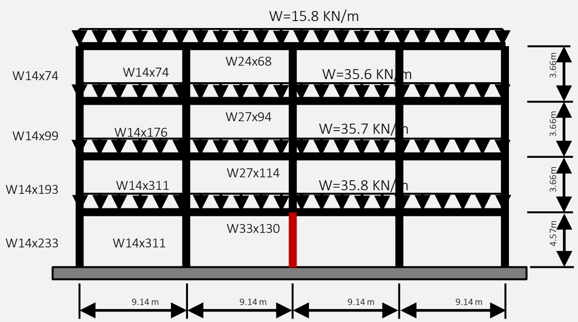
Oh-Sung Kwon
Associate Professor
University of Toronto, Canada

Hybrid Simulation Framework

UI-SimCor (http://mae.cee.illinois.edu/software/software_uisimcor.html)

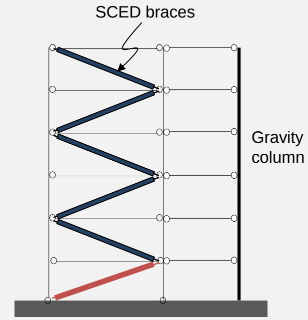
UT-SIM Framework (https://www.ut-sim.ca/)

Hybrid simulation of a structure subjected to fire

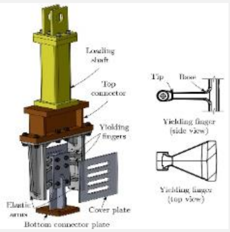


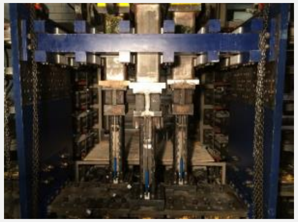
Applications of Hybrid Simulation Methods

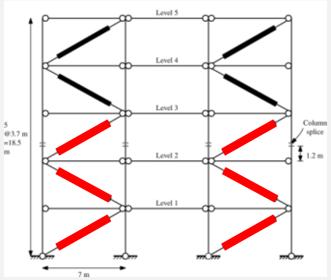
Performance assessment of a frame with SCED braces



Ten-element hybrid simulator







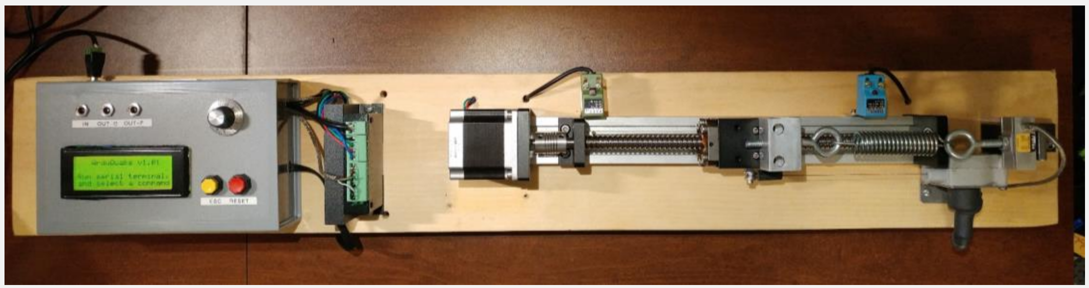
Hybrid simulation of three-storey RC frame
Hybrid simulation of a steel frame with cast steel yielding damper
Hybrid simulation of a bridge deck subjected to wind pressure
Various multi-platform simulations

- *What are technical barriers that prevent us from **tackling more complex problems**?*
  - Difficulty in numerical modelling of loading (e.g. fluid-structure interaction) or element behaviour (e.g. cyclic behaviour of inelastic members)
  - Limited computational resources

- ***Necessary conditions** for application of and benefit from hybrid simulations*
  - Two-way interaction between tested components and the global system
  - Lack of confidence in the numerical modelling of the tested components
  - Accuracy of performance assessment should significantly increase through the hybrid simulations

- *A **fundamental question** that is worth to ask before applying (or even developing) hybrid simulation methods*
  - What can we learn more by running hybrid simulations?

- *What barriers exist for users new to hybrid simulation methods?*
  - Difficult to configure overall model: numerical model, connectivity with hardware, etc.
  - Potential solution: educational hybrid simulation system



- *What problem/issue would you like to see HS applied to??*
  - Problems that are difficult to model numerically:
    - Elements exposed to high temperature
    - Fluid – structure interaction
    - Soil – foundation – structure interaction

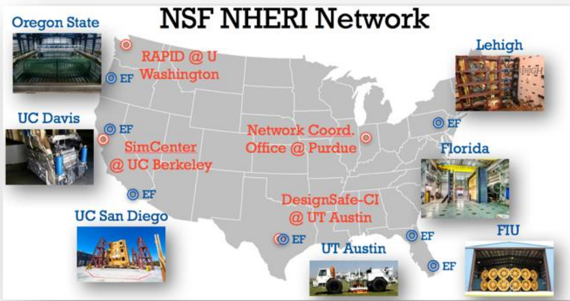
$$\boldsymbol{R}(\boldsymbol{T}(t), \boldsymbol{u}(t)) = \boldsymbol{F}$$

$$\underset{\sim}{m}_s \ddot{\underset{\sim}{u}} + (\underset{\sim}{c}_s - \underset{\sim}{c}_a)\dot{\underset{\sim}{u}} + (\underset{\sim}{k}_s - \underset{\sim}{k}_a)\underset{\sim}{u} = A_m\left(\underset{\sim}{s} - \underset{\sim}{v}_{ym\,0}\right)$$

Forrest Masters

University of Florida

UF NHERI EF



Boundary Layer Wind Tunnel (**BLWT**)

Multi-Axis Wind Load Simulator (**MAWLS**)

High Airflow Pressure Loading Actuator (**HAPLA**)

Dynamic Flow Simulator (**DFS**)

Spatiotemporal Pressure Loading Actuator (**SPLA**)

CMMI-ENH 1520843. Forrest Masters (PI), Kurt Gurley, David Prevatt, Jennifer Bridge

UF EF Science Plan (related to wind)

Obj.	Description
1	Reduce uncertainties in the wind loading chain, especially those related to predicting peak loads and structural response
2	Advance computational wind engineering and reduce our reliance on physical testing
3	Develop methodologies that reliably predict performance as a function of building age and use
4	Advance the state of knowledge regarding collapse limit state fragilities
5	Advance automation and design of hazard resistant infrastructure
6	Introduce high-performance and greener materials
7	Find innovative and cost-effective solutions to retrofit existing infrastructure

EF Efforts to Date

EU-USA-Asia workshop on hybrid testing, Ispra, Italy, 5-6 October 2015

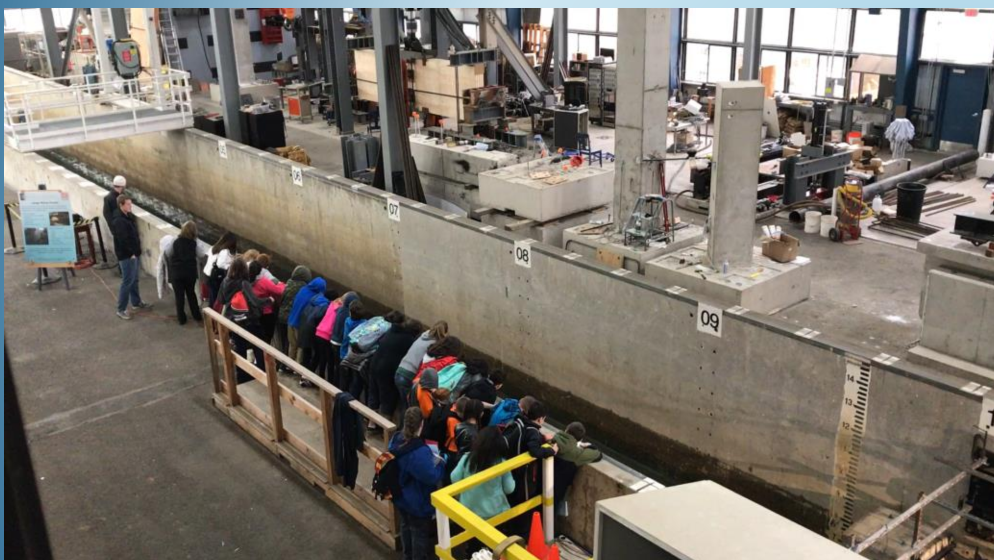
Pedro Lomonaco

Oregon State University

O.H. Hinsdale Wave Research Laboratory, Oregon State University

Pedro Lomonaco, Director HWRL

- Established in 1972 with the construction of the Large Wave Flume.



design of coastal infrastructure.

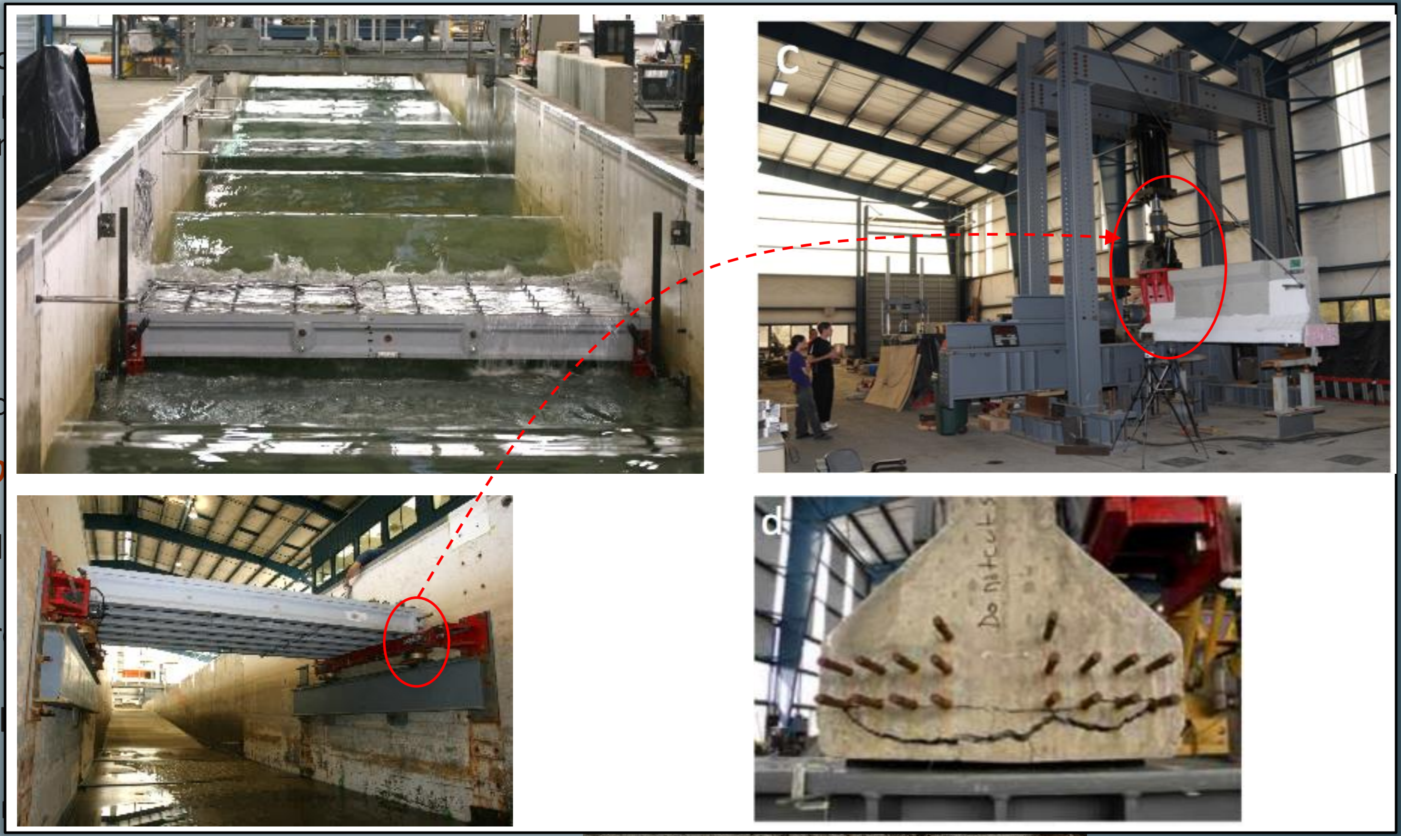
- Testing of Coastal and Nearshore process involving: Nearshore Hydrodynamics, Sediment Suspension and Transport, Tsunami Research, Environmental Fluid Mechanics, Coastal Structures, Floating Structures, …

What are technical barriers that prevent us from tackling more complex problems?

- Incompatibility of model sc
    - Fluid vs Structural res
    - Wind and Hydrodynar
- Real-time simulation
- Boundary problems
- Inexistence of multi-hazard

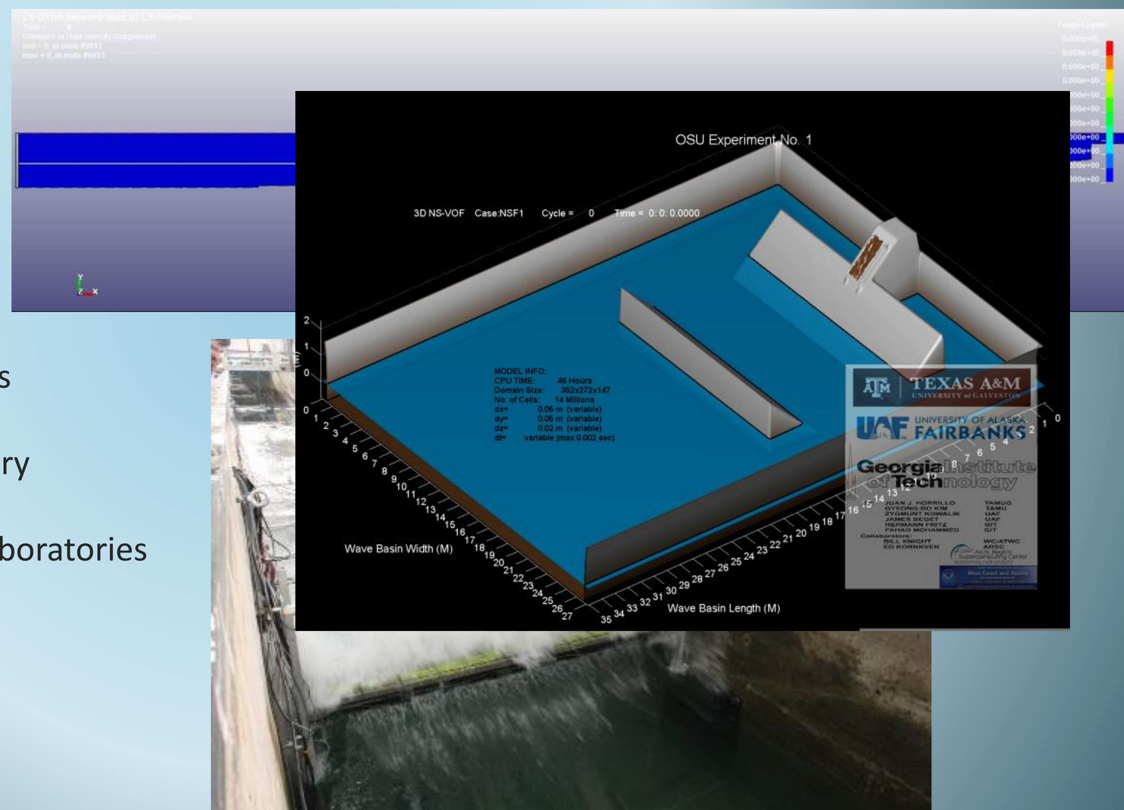
How can this be adap

- Numerical-physical model
- Validation of modelling pr
- Representation of full-scal
- Calibration of field measu



What problem would you like to see HS applied to?

- Wind-Wave Interaction
- Wave-Structure Interaction
- Wave-Current Interaction
- Model-scale effects
- Air-entrapment in Coastal Structures
- Tsunami Generation in the Laboratory
- Earthquake Simulation in Coastal Laboratories

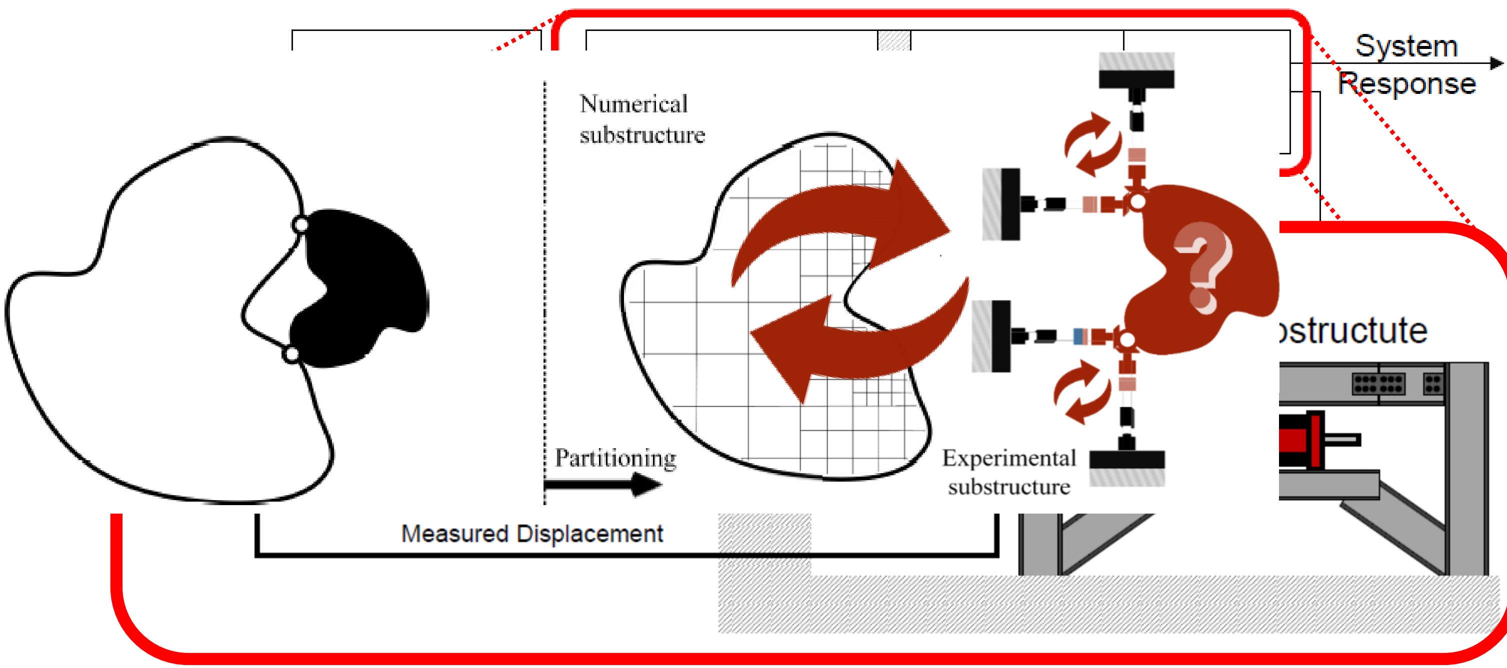


Amin Maghareh

Purdue University

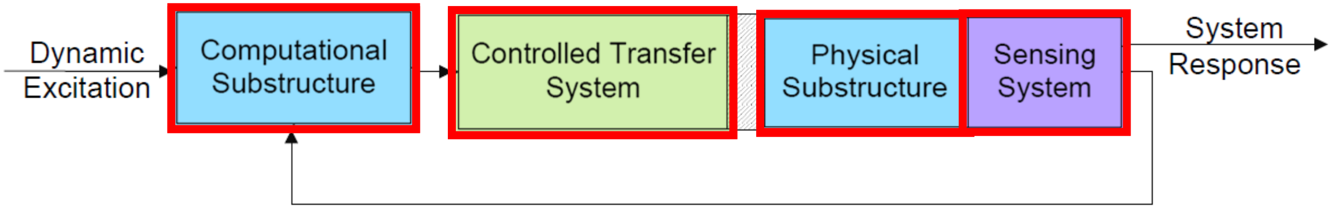
Question ...

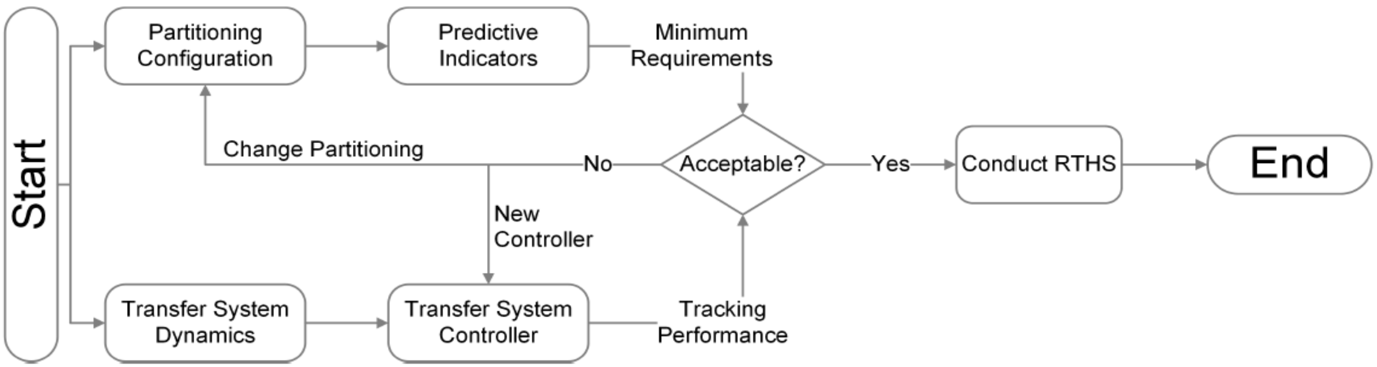
What are technical barriers that prevent us from tackling **more complex problems?**
And how might we overcome those?

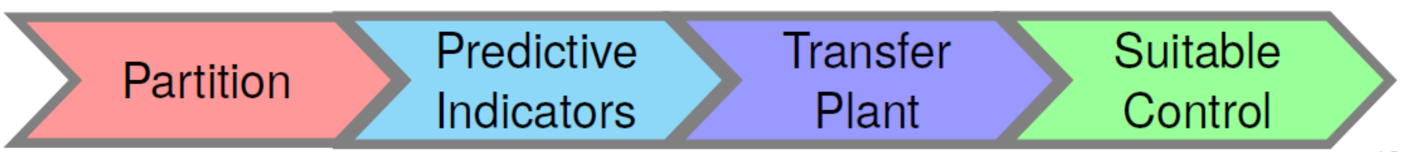


Amin Maghareh

My Approach ….

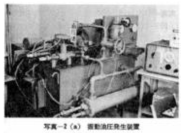


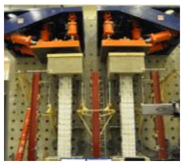




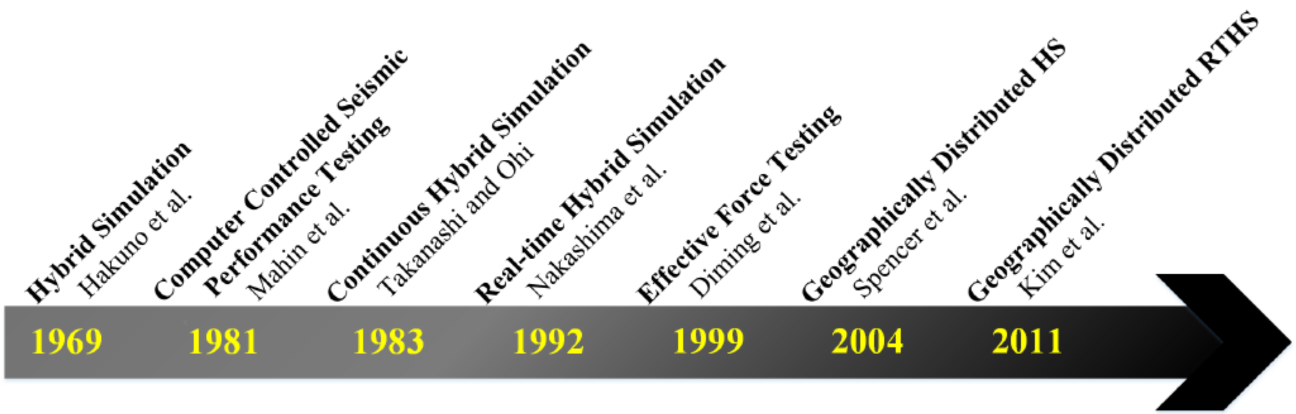
Amin Maghareh

Future Direction …





<u>multi-hazard engineering</u>



Amin Maghareh

Arindam Chowdhury

Florida International University

NHERI Wall of Wind (WOW) EF for Hybrid Wind Testing of Structures

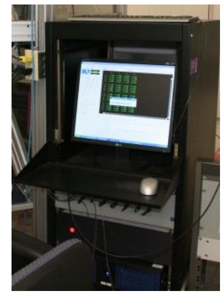
- Up to Category 5 hurricane winds simulations
- Multi-Scale Testing (full-, large-, small-scale)
- Destructive Testing (to predict progressive failures in buildings and infrastructure elements)
- Wind-Driven Rain simulations (to study water intrusion)
- Various Structures (buildings, bridges, renewable energy systems, lifeline infrastructures)

How can RTHS be adapted to solve new problems in the WIND engineering?

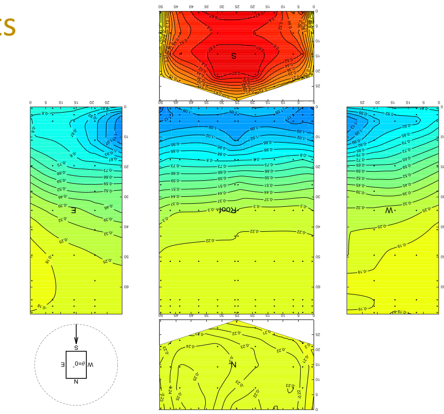
Wall of Wind
NHERI Experimental Facility

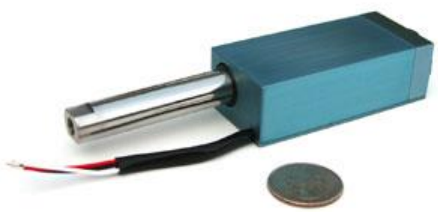
WOW Testing -- Large-Scale Model for Simulating Progressive Damage

DAQ

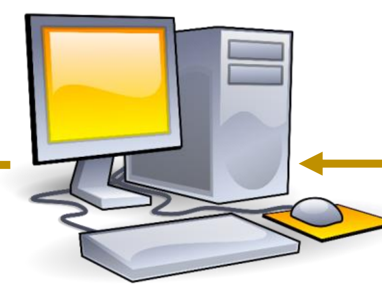


Wind Load Data with Internal Pressure Effects

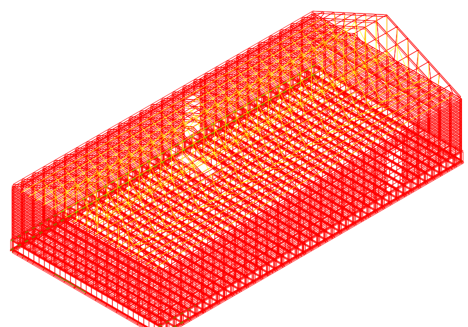




Mini Actuators to Create Progressive Damage



Non-linear FEM



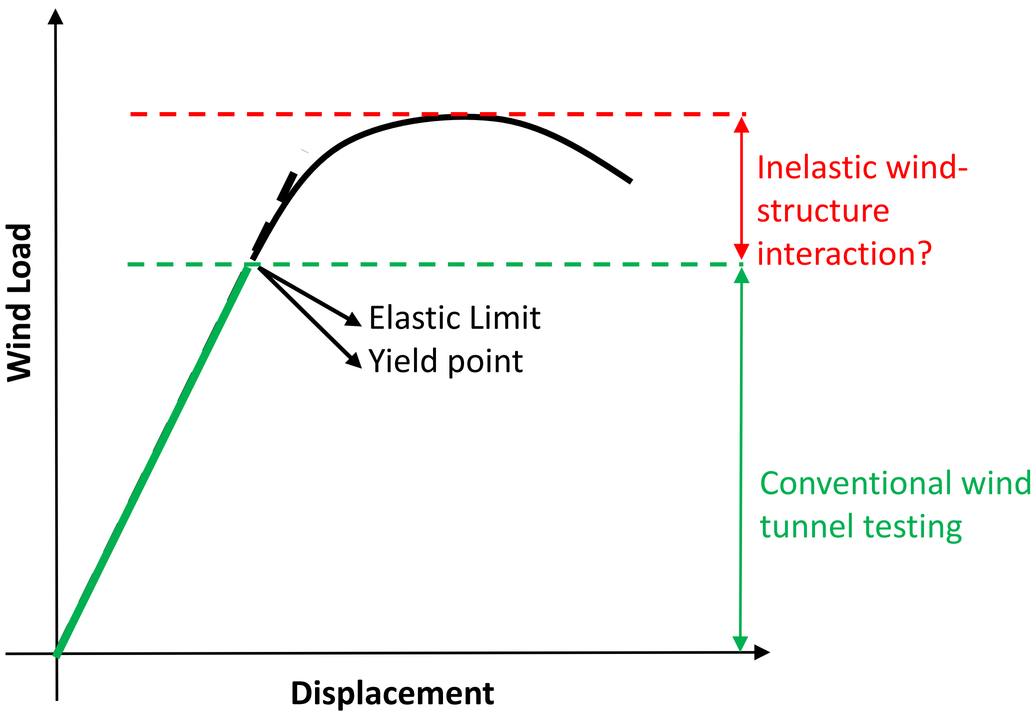
Deformation and Component Failure

Signal generator

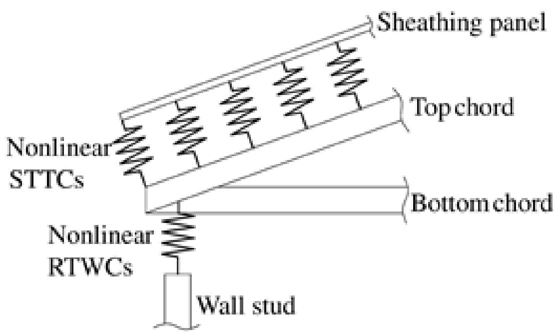
What do I hope to get from this workshop?

FIU Wall of Wind
NHERI Experimental Facility

How to address <u>time-scaling challenges</u> in RTHS to include non-linear structural effects, aeroelastic feedback effects, and explore collapse mechanisms for tall buildings?



How to address <u>scaling issues</u> in RTHS to simulate progressive damage, component performance, and non-linear connections for low-rise buildings?



Bin Xu

Huaqiao University

Related test facilities

Natural Hazards

Test Facilities at HQU

Earthquake

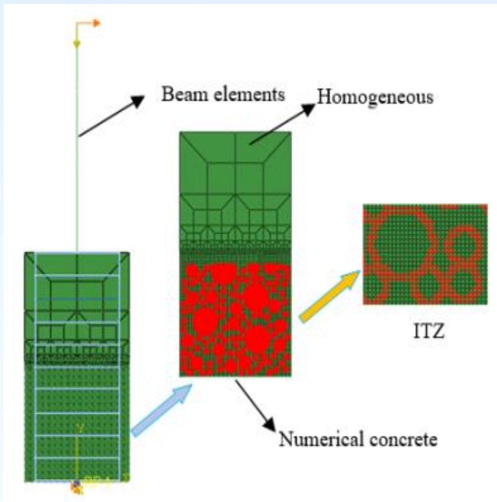
3D 6DOFs 5m*5m MTS shaking table (Payload: 45Ton) with two small shaking tables (Under construction)

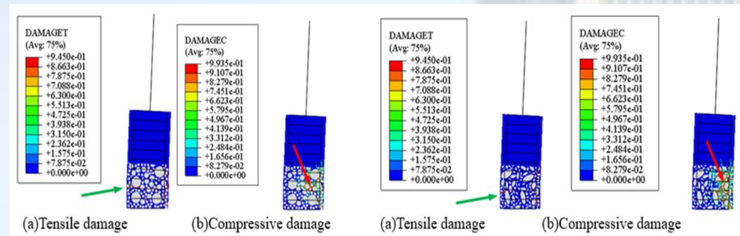
Fire

Large scale fire resistant test chambers

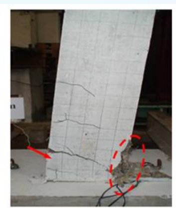
Possible collaborative studies

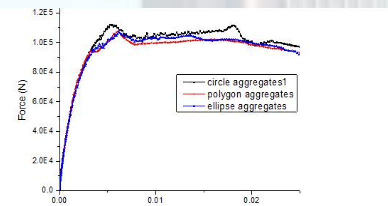
❑ Multi-scale simulation in hybrid simulation for engineering structures





Damage of numerical concrete models with different aggregates shapes





Failure pattern

Load-deformation relationship

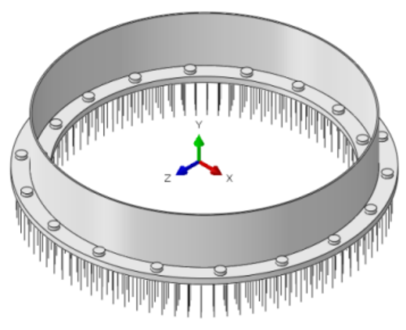
➢ HQU has carried out multi-scale simulation for reinforced concretes including beams, columns and shear walls to understand the local failure pattern and the global behavior of structural members, which will play key roles in hybrid simulations for complicated structural systems.

➢ Dynamic behavior simulation considering strain rate effects has been carried out.

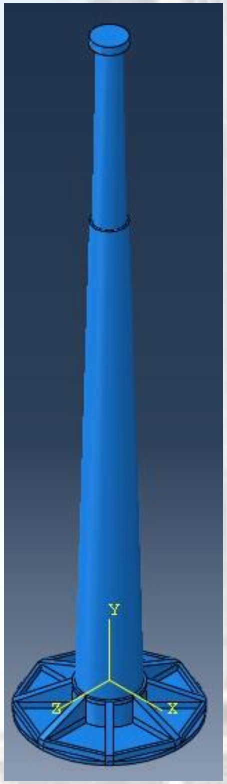
Possible collaborative studies

- ❑ Hybrid simulation on wind turbine structures under multi-hazard

- ➢ Prestressed concrete-steel composite wind turbine structure system has been proposed and experimental and numerical simulation have been carried out.
- ➢ Shaking table test can be carried out under earthquake and wind and the results can be compared with the hybrid simulation.



Connector for prestressed concrete-steel composite wind turbine structure



Prestressed concrete-steel composite wind turbine structure

Thank you

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is supported by a grant from the National Science Foundation, CMMI Division (#1661621).