Report on Discussions

Joint Workshop ETH &
Multi-hazard Engineering Collaboratory for Hybrid Simulation:

New Frontiers and Innovative Methods

Workshop held March 13-15, 2019
at the ETH Zurich, Switzerland

Summary

Our increasingly interconnected communities rely on resilient strategies to maintain steady operation. However, resilient infrastructure requires that we strive to obtain a deeper understanding of the salient behaviors and uncertainties present when structures are exposed to hazardous loading conditions. The growing prevalence of virtual testing as a replacement for physical experimentation also drives the need for mathematical models of such systems. When structural systems are too large or complex to test in the laboratory, the cyber-physical testing method known as hybrid simulation (HS), a.k.a. dynamic virtualization, provides an important tool for their examination. HS has great potential to increase our expectations regarding standard engineering practices, but engineers and researchers should be able to run HS without needing the advanced skills of developers. Furthermore, synergetic efforts are needed to develop a new generation of HS platforms with which multi-hazard scenarios can be investigated as we aim to provide rigorous solutions to future infrastructure challenges.

The objectives of this joint ETH-MECHS workshop were to establish a vision for future research and to identify best practices for the field of HS. The workshop was organized as a series of presentations mixed with discussions about the scientific challenges and opportunities that will motivate transformative advances in this versatile class of methods. Attendees learned about both the basics and leading-edge developments of the method, aiming at building capacity at more laboratories around the world. Another significant goal was to bring together a diverse group of international researchers to spark new collaborative opportunities.

The 2nd MECHS Workshop "New Frontiers and Innovative Methods" was held on March 13-15, 2019 in Zurich, Switzerland in partnership with ETH. A group of 35 researchers participated, including multi-hazard engineering researchers, graduate students, international partners and interdisciplinary collaborators. This report provides a summary of those joint discussions.

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

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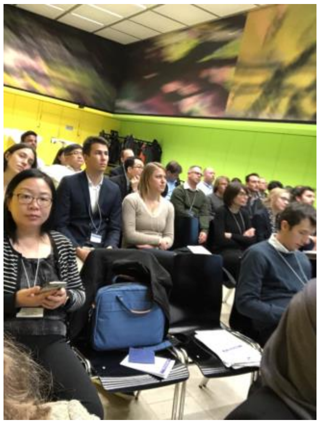
Introduction

The 1st MECHS Workshop titled “Breaking Barriers and Building Capacity” was held on December 12-13, 2017 at the University of California, San Diego. At that workshop, some early discussions were held on the challenges and opportunities for using the emerging class of testing methods known as hybrid simulation to go beyond earthquake engineering, and tackle wind, tsunami and storm surge problems. Similarly, from May 31-June 3 2016, a Workshop titled “Hybrid 2020: State-of-the-Art and Future Directions for Hybrid Modeling and Simulation,” was held at ETH to bring together a broad set of researchers to discuss a vision for best practices and standardization of hybrid testing methods. Since that time, there has been an explosion of new applications for this powerful class of testing methods. In March 2019, the 2nd MECHS Workshop was held jointly with ETH, Switzerland. Thirty-five researchers mainly from the U.S. and Europe attended, including several from Asia, Mexico, Canada and South America to participate in discussions and networking activities revolving around the common goals we share to reduce the consequences of the multiple hazards that affect our infrastructure systems.

Based on the participation and the discussions, it is clear that an explosion in the use of hybrid simulation methods is now taking place. The performance of infrastructure systems toward resisting the demands imposed by wind, tsunami, or storm surge is advancing rapidly. And well beyond that, researchers are also exploring thermo-mechanical, earthquake-induced fire, fluid-structure interaction, aerospace, and even biomedical engineering implementations of hybrid simulation are all being explored, significantly expanding the scope of this technology. Cutting-edge research is being performed in industrial settings as well, in particular to demonstrate and validate novel designs that are subjected to wave loading.

During this workshop, it was clear that a great deal of progress had been made since the past workshops in 2016 and 2017. One plenary talk focused on experiments already taking place between Florida International University and Lehigh University to develop methods and identify special challenges for wind loads on buildings. Hybrid tests are spreading to several new locations, capacity is building, especially in wind, coastal and fire engineering fields. The ETH laboratory facility tour included a demonstration of thermo-mechanical hybrid simulations focused on aerospace structures. Nonlinear and adaptive control theory are being applied to tackle especially challenging cases involving damage or changing dynamics. Machine learning methods are also being adopted and applied to design and conduct hybrid simulations, supporting greater efficiency. Webinars inspired by and conducted since the 1st MECHS workshop have been useful for engaging new research groups in hybrid simulation testing, and those will continue. A recently developed benchmark tracking control problem has also captured the attention of a large group of researchers interested in showcasing their achievements and novel methods for RTHS. The aim is to document these accomplishments through special issues of several journals that are being organized around these themes.

This report is intended to document those discussions, and is being incorporated into the next generation of Research Agenda on Hybrid Simulation. This report and that research agenda are being posted on the MECHS site for the community: http://mechs.designsafe-ci.org. With this newly found momentum, the various classes of hybrid simulation methods are breaking through barriers that have traditionally limited these methods to linear physical specimens and reduced order models. However, many challenges remain, and over the next several years we will continue to overcome those challenges and advance the science and theory or hybrid simulation for future generations to use and explore as they tackle challenges in multi-hazard engineering.



Discussion Group A — New Frontiers & Applications I

Co-Chairs: Pedro Lomonaco (*Oregon State University*)
Thomas Sauder (*SINTEF Ocean*)
Recorder: Wei Song (*University of Alabama*)

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The objectives of this working group were to identify solutions to the challenges that are revealed through new application areas for hybrid simulation that go beyond earthquake engineering. For example, new applications with challenges include wind and coastal engineering, fluid-structure interaction in general, etc. This group focused on the questions: *What are the new hybrid simulation frameworks in engineering fields beyond earthquake engineering? What are the advantages brought by hybrid simulation comparing with conventional testing methods? What are the technical challenges in establishing these new hybrid simulation frameworks, and what are the possible solutions to them?*

Main Points of Discussion

Hybrid simulation (HS) and real-time hybrid simulation (RTHS) have brought unparalleled opportunities in answering research questions in engineering fields beyond earthquake engineering. The complex nature of these engineering fields has also posed technical challenges in establishing the corresponding HS and RTHS frameworks. The advantages and challenges of HS and RTHS in wind and coastal engineering were discussed, and possible solutions to some of the challenges have been proposed. These discussions are summarized in the following subtopics.

HS and RTHS in Wind and Coastal Engineering

Among the seven presentations within this discussion group, four presentations were in the field of hydrodynamics (coastal engineering and marine technology), two presentations were in wind engineering, and one presentation raised research questions on fluid-related hazard engineering in general.

In **hydrodynamics** (**coastal engineering and marine technology**), RTHS is currently performed for applications in *i*) active wave absorption, *ii*) advanced control for marine renewable energy (energy harvesting), and *iii*) in testing of marine structures, such as floating wind turbines. Only in the latter, there is a numerical substructure representing a physical system.

In **wind engineering**, a RTHS framework for bridge decks has been presented, and a model-in-the-loop framework has been developed for tall building design optimization considering wind hazards. Both frameworks have utilized wind tunnel testing environment. The latter is really more an adaptive testing method than a “true” RTHS.

In a **wind-wave multi-hazard** setting, RTHS framework for marine structures has also been presented.

Benefits for RTHS in Wind and Coastal Engineering

In both hydrodynamics and aerodynamics, the rate dependent nature of the problem demands a real-time test environment. In **hydrodynamics**, the focus is placed on the study of fixed or floating structures subjected to wave load (including tsunamis). Due to fluid-structure interaction (FSI), structural response has an influence on the wave load. The benefit for considering RTHS is clear once we mention the two following facts:

- It was emphasized that computational fluid dynamics (CFD) for FSI problems is computationally intensive and mesh sensitive, requires experimental validation, and might not provide a reliable indication of the uncertainties of wave impact.
- On the other hand, purely empirical methods are difficult to apply for reasons ranging from infrastructure-related challenges (e.g., accommodating the whole pier model in a wave flume, or a full mooring system in an ocean basin) to scaling issues (e.g., for offshore wind turbines).

Therefore, RTHS has the potential to study the abovementioned phenomena: the physical substructure would be subjected to the complex wave loads, while the numerical substructure would consist in the part of the structure not directly subjected to wave loads, but which participate to the structural response. These include, for example, the lower section of piers, the rotor/nacelle assembly of offshore wind turbines.

In **wind engineering**, the benefits of using RTHS are also similar to those in the field of hydrodynamics. In one of the presentations, an RTHS framework for a bridge deck has been developed to capture aeroelastic behavior of bridge sections, and can possibly realize multiple modes. The physical-numerical interaction idea has also been applied in a model-in-the-loop design optimization framework for tall buildings under wind load. In both cases, the physical structures are tested in wind tunnel environment.

In addition to the above benefits, RTHS can provide an efficient experimental platform, reducing specimen construction effort, and generally saving time and costs.

Challenges for RTHS in Wind Engineering / Coastal Engineering / Marine Technology

Several challenges in implementing RTHS in wind and coastal engineering have been identified:

- Scaled models have been applied in the RTHS platforms presented in the group discussion. To consider scale effects, similitude theory has been applied to establish these RTHS platforms which subsequently determines the associated scaling laws, including time scale. For example, in hydrodynamics, RTHS platform, Froude scaling is applied to preserve the dynamic effect generated by water wave.
- In hydrodynamics, RTHS platform, actuators that can work under water are needed, and thus far seem to be costly to acquire.
- Errors that are present when using RTHS should be quantified and understood, but it is generally difficult to do so without a reference for comparison. Two approaches can be considered: i) compare RTHS result to that obtained in conventional scaled tests (e.g., wind tunnel test), and ii) compare RTHS result to measurements obtained from full-scale real-world structures. The latter represents the actual error in comparison to reality, but it is difficult to achieve. The former represents the difference between RTHS and accepted scaled tests, and can be pursued as the first step in quantifying the accuracy of RTHS.

Action Items and Future Research Needs

Based on the challenges identified, the following are proposed as the action items:

- Development of new actuators that can be used underwater
- Development of benchmark problems that can provide sufficient data for error/accuracy analysis of RTHS.

Discussion Group B — Innovations in Modeling and Simulation I

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Oh-Sung Kwon *(University of Toronto)*
Chris Gill *(Washington University in St. Louis)*

The objectives of this working group were to share new approaches to successfully model and test highly nonlinear or coupled systems, including online updating. This group focused on the following questions: *What is the state-of-art on analog controllers? Can analog controllers be useful to solve stability and convergence issues during numerical integration in RTHS? What is the role of HS? How does it fit with uncertainty and model validation? How to select the best few numbers of HS tests to provide necessary information to inform models and analysis? What are the challenges in highly nonlinear numerical substructures and how proper boundary conditions in physical substructures are satisfied to represent crucial issues for the accuracy of HS data? What are the challenges while using HS for wind applications? How can we connect HS with educational/learning activities?*

Main Points of Discussion

There are several vital points in this discussion group. New approaches for modeling in RTHS with an analog controller was discussed, which can be useful to solve stability and convergence issues during numerical integration. The role of HS in the overall analysis of a system was discussed, where HS can be used as a tool to calibrate and validate numerical models either at the structural, or at the sub-structural level. Technical issues were discussed regarding simulating high nonlinearity in numerical substructures and it was noted that the reproduction of proper boundary conditions in physical substructures represent crucial issues for the accuracy of HS data. The system challenges for HS for wind applications were summarized, and a fundamental study on this regard was presented. Lastly, the use of HS for educational purposes and learning activities, and how to develop these for users new to HS, was summarized.

Analog RTHS – Exploring Old Techniques to Enable New Innovations

An approach to modeling in RTHS with analog controllers was discussed where it was suggested as a useful way to solve stability and convergence issues during numerical integration. Digital computers allow researchers to conduct RTHS testing in larger and more complicated systems. However, errors due to the presence of discrete errors caused by quantization, and the corresponding half step time delay numerical integration time step limitation, persists in RTHS. Quantization in magnitude, and sampling in time can impose limits on the measurements, such as restoring force, used in RTHS. The numerical integration time step can limit the bandwidth and nonlinearities of the system being studied in a RTHS.

To investigate the challenges with analog controllers, an analog computer using electronic circuits was designed and constructed to perform the modeling required to conduct RTHS of a base isolated structure with an added, physically tested, viscous damping device. The analog computer provided the ability to model a portion of the dynamic system and solve the ordinary differential equations of motion required in RTHS testing without the need for a digital computer. The results of the RTHS tests using the analog computer were compared to RTHS tests implemented with a digital computer to model the system and conduct numerical integration. Benefits and potential of the analog approach were discussed.

Seismic Fragility Analysis of a Tank-Piping System Based on HS and Kriging Surrogate Modelling

A seismic reliability analysis was conducted for a coupled tank-piping system. A seismically-isolated tank-piping system model was considered with low- and high-fidelity computational structure and ANSYS elbow290 elements the high-fidelity computational simulator. The idea was to carry out seismic fragility assessment of the coupled system introducing the uncertainties which are in the ground motion.

To obtain the necessary input for a stochastic ground motion model able to generate synthetic ground motions coherent with the site-specific analysis, a deaggregation analysis of the seismic hazard was performed. The space of parameters of the stochastic ground motion model was based on the reduced space of parameters, a large set of artificial waveforms were generated and selected as an input for experimental HSs. Seven ground motions were selected where 4 of them were chosen to keep the system in the linear regime, and 3 to activate a non-linear regime. The hybrid simulator was composed by a numerical substructure, able to predict the seismic sliding response of a steel tank, and a physical substructure made of a realistic piping network. Both low- and high-fidelity model of the tank-piping system was calibrated against hybrid simulation. A multi-fidelity Kriging surrogate of the tank-piping system response was calibrated based on low- and high-fidelity model computational structure. Finally, the methodology to carry out a seismic fragility analysis based on this surrogate model was presented.

Hybrid Simulation Capabilities and Recent Developments at UNR

A new HS setup that has been developed at the University of Nevada, Reno (UNR) for braced frames demonstrations and education purposes was introduced. The experimental setup allows for using a small-scale brace as the experimental substructure along with a steel frame at the prototype full scale for the analytical substructure. The analytical system can be modelled using either Simulink or the OpenSees platform. Moreover, the system is capable of running both real-time and pseudo-dynamic (slow) experiments.

The UNR system was used to demonstrate a new way to test or model CBFs with HS. Most of the existing simulation tools used for CBFs and braces fatigue life estimation were developed and calibrated mainly using cyclic-loading experimentation. Thus, there is a need for new datasets for CBFs tested under realistic earthquake excitations, and, in turn, the presented HS system is rendered a potential feasible system for testing braces and better understand the overall seismic response of the CBFs. Preliminary results showing the difference in damage accumulation in braces between cyclic loading and RTHS tests with earthquake loading was presented. Moreover, the duration effect on braces was also investigated by using this small-scale test setup. Lastly, the system was used to explore the transfer system challenges for HS wind applications. Wind Real-Time Hybrid Simulation (wRTHS) is an evolving approach that can be utilized to improve aeroelastic modeling and current wind tunnel testing approaches. The performance validation of hardware, computational components, and the transfer system as envisioned for future use in wind tunnels was summarized and challenges were discussed.

Prototype Demo-Scale Equipment in Support of Distributed Hybrid Simulation

The project EXCHANGE-RISK (Experimental & Computational Hybrid Assessment of Natural Gas pipelines Exposed to Seismic Risk) was introduced, which envisaged to implement the combined experimental-analytical method of distributed HS for the identification of the principal failure modes of a soil-pipeline system. The universities involved in this project include the University of Toronto, the University of Bristol, the University of Naples Federico II, and the University of Patras. The overall concept of this project is to have a relatively simple and low-cost device that could perform small-scale experimentation on a simplified physical system which would enable the testing and calibration of hybrid simulation protocol before going-lab scale. So far, incarnations of this demo-scale scale setup have been assembled at the University of Toronto, the University of Naples Federico II, and the University of Bristol.

Development of the prototype is divided into two parts: i) the actual implementation of the demonstration actuator and the electronic components of the control system; and ii) coding the controller's processor for imposing displacement-controlled operation and communication with the HS software. The actuator consisted of a ball-screw driven by a stepper motor in a linear guide, equipped with proximity sensors and force/position measurement devices. Control over the actuator and communication with the hybrid simulation software was performed via the micro-controller of an Arduino open-source-electronics board. Additional electronic components involved in measurement analog signal acquisition and issuing control-command digital signals were deployed and integrated into the controller board. Communication with the computer and numerical analysis software and issuing of movement commands for the actuator is achieved via the LabView-based NICON hybrid simulation software platform developed at the University of Toronto.

A Model Order Reduction Framework for Hybrid Simulation of Stiff Prototype Structures

A model order reduction framework for HS of stiff prototype structures was discussed. Testing of stiff physical substructures still poses major technical issues that prevents HS from becoming a standard structural testing method. A stiff specimen produces large restoring force oscillations with small actuator displacement perturbations. In seismic engineering, the vertical degree of freedom is usually handled by force-controlled actuators, which are typically associated to stiff axially loaded members and excluded from the time integration loop. Vertical forces are either kept constant or adjusted during the experiment based on simplified redistribution rules. In addition, to increase restoring force sensitivity to displacement perturbation, stiff physical substructures naturally increase the frequency bandwidth of the prototype structure, whose higher eigenfrequencies divided by the testing time scale may fall outside the frequency bandwidth of the actuation system and destabilize the experiment.

A component-mode synthesis approach was proposed, with the primal aim at reducing computational cost of dynamic simulations of large finite- element models, as a rigorous approach for deriving reduced-order physical and numerical substructure mass and stiffness matrices that minimize the frequency bandwidth of the prototype structure. The proposed methodology allowed for performing hybrid simulations of a load bearing masonry structure including both horizontal and vertical degrees-of-freedom with a standard three-actuator setup used for cyclic testing.

The main conclusion on this study is, to ensure stability of HS, the frequency bandwidth of the frequency bandwidth of the transfer system should include the frequency bandwidth of the prototype structure. Moreover, the researchers believe that the component-mode synthesis should be a part of the standardized HS platform, since it would eliminate the dynamics that would be excited by control error.

Using HS to Improve the Seismic Performance of a Soft Story Building Retrofitted with Buckling-Restricted Braces

HS was used to improve the seismic performance of soft-story buildings. A five-story frame characteristic structure model with a soft story problem in the ground floor was selected and numerically modeled. Once the frame was modeled numerically, it was retrofitted with either BRB or a conventional brace (CB) to examine the behavior of the devices on the response of the structure. Hybrid simulation tests have been conducted where the brace was the experimental substructure, and the original structure was modeled numerically.

Comparisons of the structure's performance, in terms of ductility demand, hysteretic behavior, inter-story drifts, and floor accelerations showed that the soft story problems must not be eliminated but controlled to acceptable limits because the excess of added capacity could put other stories at risk of severe damage.

Action Items and Future Research Needs

- A parametric study to highlight the problems of digital controllers and see if these problems can be solved with analog computers, as well as the state of the art of analog computing.
- Exploring the role and potential areas of benefit of HS/RTHS in testing of structural systems.
- Extending the use of HS as a tool to calibrate/validate numerical models, capture critical operating conditions/points, and include uncertainty
    - Investigate how to select the best few numbers of HS tests to provide necessary information to inform models and analysis
- Extend the use of HS in educational/learning purposes
    - Development and implementation of a cost effective small-scale distributed HS setup
    - Development and implementation of tools to be useful for unskilled users in HS

Discussion Group C — New Frontiers & Applications II

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Reto Grolimund (*ETH Zurich, Switzerland*)
Giuseppe Abbiati *(University of Aarus)*

The objective of this working group was to identify challenges and solutions that arise in new applications of hybrid simulation in fire testing; e.g., hybrid fire testing (for example, when fire is induced by an earthquake) and thermo-mechanical simulation, blast response, etc.

Main Points of Discussion

This group discussed the following topics:

- Hybrid simulation frameworks (e.g., UT-SIM, OpenFresco, etc) and their application to structures subjected to earthquake or fire loading
- Adaptive control for hybrid fire testing
- Use of PI-control for hybrid fire testing
- Preliminary studies, hybrid fire testing of a virtual steel frame
- Ongoing studies, coupled experimental and numerical Framework for the analysis of steel structures subjected to fire
- Real-time hybrid fire simulation algorithm based on dynamic relaxation.

Existing Hybrid Simulation Frameworks

- In the UT-SIM framework, the implementation of hybrid simulation is generalized such that multi-platform sub-structure simulation can be readily carried out with commercial or open-source software.
- The network interface program, NICON, has been developed to facilitate the implementation of PsD hybrid simulation using a conventional actuator controller and low-cost AD/DA converters.
- The sub-structure simulation method can be applied to fire load without significant algorithmic or hardware development.

Hybrid Fire Testing

Fire following earthquakes has historically produced large post-earthquake damage and losses. Standard fire tests use simplified mechanical boundary conditions for the tested structural element. For some elements, these conditions can lead to results that are overly conservative. To circumvent full-scale fire testing, hybrid fire testing (HFT) can be used to cost effectively assess the global behavior of structures exposed to fire on a realistic scale. Hybrid Fire Simulation (HFS) utilizes sub-structuring: the part of the structure that is difficult to simulate is modeled physically in a furnace; all other parts are simulated numerically. For example, a column can be built and tested inside a furnace with actuators at the end of the column to reproduce the necessary boundary conditions; the rest of the building can be numerically simulated to represent the remaining structure.

Hybrid Fire Testing of a Virtual Steel Frame

Because the behavior of structures and elements subjected to fire loads is strongly non-linear, a nonlinear finite element analysis is needed. There are two types of nonlinearities: geometric and mechanical. A nonlinear thermo-mechanical beam element was proposed for the simulation of the thermomechanical behaviour of steel elements. For the geometric nonlinearity, the corotational formulation was used to consider second-order deformations on members induced by large displacements. For the mechanical nonlinearity, the stress-strain relationship for carbon steel at elevated temperatures was used, including the degradation of mechanical properties at elevated temperatures.

Virtual Simulation: The effectiveness of the proposed method was demonstrated via a virtual simulation of a three-story, three-bay moment-resisting frame. All beams and columns were characterized by standard commercial metric cross-section without any fire protection. Only the ground floor columns and first-story beams were subjected to fire loading whilst the upper part of the frame remained at ambient temperature. Only the translational DOFs at the boundary conditions between the two subdomains was taken into account, according to the most typical setup in a laboratory. Since the HFT campaign is virtual, a nonlinear finite element model was used to obtain the response of the hot physical sub-structure. The response-history response of the frame was obtained via real-time simulations and showed good agreement between the monolithic and the partitioned solutions.

Ongoing SERA Project (geographically distributed fire testing): The validation shows promising outcomes for future experimental implementations and will be soon applied to an experimental program: 2020 SERA EQUFIRE. The objective of EQUIFIRE is the multi-hazard performance assessment of structural and non-structural components subjected to fire following earthquake via geographically distributed testing. The prototype structure will be a four-storey steel concentrically braced frame. The ground floor of the concentrically braced frame will be sub-structured at the ELSA Laboratory at the Joint Research Centre (JRC, Ispra, Italy) and at the BAM (Bundesanstalt für Materialforschung und –prüfung, Berlin, Germany) facilities (one column will be simulated inside the furnace of BAM and all the other elements of the ground floor will be simulated at JRC). The remainder of the structure will be simulated numerically according to the finite element method UNITN (University of Trento, Trento, Italy) and/or ETH Zurich (Swiss Federal Institute of Technology, Zurich, Switzerland). This numerical sub-structure will be kept at ambient temperature throughout the test. At the JRC, the designated element will be tested under lateral cyclic loading at ambient temperature. At BAM, the element will be subjected to the fire to simulate the fire after earthquake loading. One test will not include fire protection while the other tests will include different types of fire protection. The last test will include a fire wall in two of the bays (seismic test only).

Adaptive Control for Hybrid Fire Testing

Given the necessity of real-time simulation due to the fire loading and the very large stiffness ratio that can take place between the two sub-structures in real cases of HFT, the development of a stable and accurate control algorithm is a challenging task. Existing methodologies for hybrid fire testing (HFT) use precise estimation of the stiffness of the physical sub-structure to ensure the stability of the iterative procedure. Usually this estimation is made for the initial tangent stiffness. However, this tangent stiffness is subject to large changes during the fire test and can lead to the loss of the stability and the accuracy of the HFT. Large variations of the tangent stiffness are likely to occur during the HFT because of the thermal degradation of materials, non-linear materials laws or geometric nonlinearities that can lead to loss of accuracy or divergence.

The implementation of a quasi-sliding mode based control methodology can be used to overcome these limitations. This concept creates a sliding hypersurface that cancels out the error and its first time derivative and then to force the system to stay in the vicinity of this hypersurface with a high gain adaptive controller. The main advantage of this approach is that the control algorithm does not need the estimation of the stiffness matrix of the physical sub-structure. A case study of a nonlinear structure was presented to compare the performance of existing proportional and proportional integral controllers with the presented adaptive controller. The command of the velocity of the actuators can be achieved without modification of this controller and could tackle the problem of the large forces spike due to the thermal expansion of the specimen. Some limitations of the presented controller are: the lack of precision at the beginning of the test in the presence of strong measurement errors and non-obvious extension to floating sub-structures.

Coupled Experimental / Numerical Framework for the Analysis of Steel Structures Subjected to Fire

The global response of structures exposed to fire might exhibit unstable behavior due to local/global buckling or bolt rupture. The load re-distribution that follows such an event is dynamic, and the failing member temporarily exhibits a negative tangent stiffness. For the numerical-experimental assessment of the full global structural response to fire, a dynamic solution procedure is needed if the structure undergoes local or global failures on member level. The thermomechanical structural response must be obtained in real-time. If this is not possible due to restrictions in the coupled framework, a mixed static and pseudo-dynamic analysis is suggested.

A four-story steel building with a fire at the ground floor compartment was presented as a case study. The physical sub-structure included the column at ground floor. The numerical sub-structure included the first-story beam as a linear elastic spring. The frame was subjected to a compartment fire scenario that affected exclusively the column and eventually lead to failure of the column due to thermal expansion, axial restraint and the consequential axial load increase. First, the load was increased on the column until it exhibited column buckling. During buckling, the framework used an implicit dynamic solver to perform a pseudo-dynamic analysis of the load redistribution. When it was not possible to find static equilibrium, the algorithm automatically switched to a dynamic implicit procedure with a different time scale.

Real-time Hybrid Fire Simulation based on Dynamic Relaxation

Fires are typically modelled via time-temperature curves. Due to the fire loading, the ground floors start expanding. This expansion is constrained by the upper part of the prototype structure, which is cold. This causes a force re-distribution in the sub-structures in terms of moments and axial forces. This axial force is variable during the fire development due to the restrained thermal expansion. In contrast to earthquake loading, this response is static. To include the axial force history, it is necessary to add other actuators in different positions. This causes the frequency bandwidth of the prototype structure to increase because of the inclusion of higher modes of the systems, which are characterized by high stiffness and a low mass.

For the numerical-experimental assessment of the full global structural response to fire, a dynamic solution procedure is needed if the structure undergoes local or global failures on member level. The thermomechanical structural response must be obtained in real-time. If this is not possible due to restrictions in the coupled framework, a mixed static and pseudo-dynamic analysis is suggested. To solve this problem, this study employed dynamic relaxation and fictitious mass and damping matrices that are functions of stiffness matrix and force the frequency bandwidth of the system. This was done to stay in a frequency range compatible with the normal actuators. Equivalent dynamic equations of motion are then solved where mass and damping are fictitious. This methodology will be used in the SERA EQUFIRE project.

Action Items and Future Research Needs

- Fire loading entails axial deformation of structural members and a static structural response; therefore hybrid testing algorithms developed for seismic loading need to be adapted.
- Need for a dynamic solution procedure to obtain thermo-mechanical structural response in real-time
- Need for a better differentiator for the error, use of the velocity output to drive the servo-valve directly, extensions to floating sub-domains
- Implementation for a multi-degree-if-freedoms for full-scale fire testing
- Methods for controlling the actuators in axial loading (characterized by high axial stiffness)

Discussion Group D — Innovations in Modeling and Simulation II

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Amal Elawady (*Florida International University, USA*)
Wei Song (*University of Alabama, USA*)

This group focused on developing innovative strategies and solutions for tackling resource-demanding hybrid simulation with timing, physical, control, communication and computational resource constraints in near-real-time and real-time simulations involving nonlinear, coupled and/or uncertain hybrid models in single- or multi-physics situations.

Main Points of Discussion

Six presentations given in this break out session represent innovative strategies for two themes and innovative solutions in new areas, as detailed below.

Soft vs. Hard Causality Analysis and Implementation

The first innovative strategic theme addresses causal consistency between strict versus relaxed models of time in hybrid simulation (HS). One way to approach this theme is from the computer science perspective. The CyberMech platform, collaboratively developed at Washington University and Purdue University, utilizes elastic and mixed-criticality real-time scheduling theory but maintains strict local timing behavior and performs simulation and control (including sensor and actuator input/output) at the rate of 1024 Hz. It was pointed out that globally asynchronous locally synchronous (GALS) approaches, discrete event simulation, rollback techniques, etc. can be exploited to combine such strict local approaches with distributed approaches or others for which strict timing is not possible. However, how the HS results can tolerate the asynchronous process together with other uncertainties in the test setup and specimen requires further investigation.

A more traditional way to address this theme is to establish a distributed real-time hybrid simulation (dRTHS) testing platform utilizing existing off-the shelf technology and products, such as one developed at Western Michigan University. The testing platform utilized the National Instruments software and hardware and can be used to test various controller algorithms (i.e., delay compensation) and test soft causality when multiple sites are involved in one dRTHS.

Complex Hardware & Specimen Interactions

The second innovative strategic theme tackles complex hardware and specimen interactions. An adaptive inverse control technique for RTHS developed at ETH Zurich is capable of adapting the HS hardware to unknown and/or unpredictably changing specimens to minimize the varying effects in the HS setup on the test results. Specifically, the adaptive feature of this controller can be switched on without significantly increasing computational demand through a mainly matrix multiplication process.

The challenges associated with multi-axial loading in RTHS are well recognized and a robust dynamic compensation method was implemented on the loading and boundary condition box at the University of Illinois at Urbana-Champaign. A transformation between Cartesian coordinates and actuator coordinates was established in a linearized form and a small-scale verification RTHS on an axially stiff specimen was conducted to demonstrate the controller's capability.

Innovative Solutions

Two directions towards innovative solutions in HS were discussed. One is innovatively developing and implementing HS methods. For example, a stochastic HS concept is proposed in which the behavior of a prototype is stochastic that needs to be predicted to facilitate parameter design for HS. Thus, instead of conducting HS on every possible prototype behavior, a few carefully designed HS tests can be performed that lead to meaningful HS results matching the predicted prototype behavior. Another innovative HS development may address requirements necessary for multi-everything HS (i.e., multi- DOFs, multi-physics, multi-sites and multi-scales). The complications resulting from this multi-dimensional expansion of HS methods, noted as {Hybrid Simulation}^2, requires a holistic while multi-disciplinary solution. A more general HS approach shall be the end product of this innovative HS development (instead of a unique single-discipline HS application).

The second direction towards innovative HS solutions discussed in this session is its application/ implementation in bio-engineering and medicine. An effort is being made at the Technical University Munich to apply RTHS to prosthetic feet experiments. A prosthetic foot is the experimental component in the RTHS and its interaction with a patient's body is simulated. The unique feature of this RTHS with contact is that the experimental component changes its state (repeatedly) from non-contact to contact (to the numerical component). It was found out that the bottleneck for stable RTHS with contact is the bandwidth and delay of the actuator, which may be addressed by advanced delay compensation, such as iterative learning control. The group expects that this type of innovative RTHS may have profound applications in the development of customized medicine and devices in this aging society. For example, an active prosthetic device, which adjusts its support (through adjustable stiffness) to the body based on the person's recovery condition, can be tested using RTHS. Human response data can be collected during the experiment and sent to HS model to optimize the design of the device. This innovative solution reflects the concept of HS in the design cycle and also represents a good example of HS being applied completely outside of civil engineering.

Action Items and Future Research Needs

- HS methods in civil engineering may have a different name in other disciplines such as hybrid dynamic substructure testing. It was suggested that the HS community reach out to other disciplines, for example, through organizing a tutorial session in the next IMAC conference.
- RTHS with contact represents an innovative solution that requires (and motivates) further development. It has broader application in bio-engineering and other similar scenarios, such as rendezvous and docking of satellites.
- Continue developing innovative strategies in RTHS, including
    - Realistic loading and boundary conditions using multi-actuators through accurate position control and elimination of the adverse effects including friction at the bearing and flexibility of the reaction frame.
    - Robust RTHS controllers whose design are specimen-free. During the RTHS, these controllers will self-adapt to its best performance based on the numerical simulation and the physical response. On the other hand, the controller will not adapt too much that alter the purpose of HS.

Discussion Group E — Building Capacity and Standardization

Co-Chairs: Erik Johnson (*University of Southern California*)
David Wagg (*The University of Sheffield*)
Recorder: Amal Elawady (*Florida International University*)

Participants/Affiliations:
Pedro Lomonaco (*Oregon State University*)
Christina Insam (*Technical University of Munich*)
Jean-Marc Franssen (*Liege University*)
Ana Sauce (*NIST*)
Silvio Renard (*CERIB & Bordeaux University*)
Richard Christenson (*University of Connecticut*)
Georgios Tsialiamanis (*The University of Sheffield*)
Ho-Kyung Kim (*Seoul National University*)
Georgios Baltzopoulos (*University of Naples Fedrico II*)
Oh-Sung Kwon (*University of Toronto*)
Shirley Dyke (*Purdue University*)
Barbara Simpson (*Oregon State University)*
Arturo Schultz (*University of Minnesota*)
Gaston Fermandois (*University of Santa Maria, Chile*)
Steve Wojtkiewicz (*Clarkson University*)
Pedro Fernandez (*University of Maryland*)
David Wagg (*The University of Sheffield*)
Erik Johnson (*University of Southern California*)
Amal Elawady (*Florida International University*)

The objectives of this working group were to discuss how to expand HS/RTHS capabilities to enable more labs, develop standards to provide some guarantees on the quality of the conducted tests and to broaden the range of testing.

Main Points of Discussion

The session included six presentations covering the following topics: efficient solvers for mostly linear models in the numerical portion of RTHS, possible criteria and required procedures to assess and assure the accuracy of hybrid testing methods, enabling RTHS and HS in wind tunnels while considering expected wind-induced vibrations and responses. The final presentation and discussion was dedicated to the history and future of building capacity and standards for hybrid simulation.

Efficient Numerical Solvers

The first part of the session included a presentation, and subsequent discussion, on the development of a numerical solver to reduce high-order (*i.e.*, many degrees-of-freedom) mostly linear numerical models to a set of low-order Volterra integral equations that can be solved up to several orders of magnitude faster than conventional nonlinear solvers. The approach, as applied to RTHS, moves most of the computation to offline pre-processing and post-processing steps to minimize the computation that must be performed in (hard) real time. The concept was first demonstrated using a 2-DOF system model, and was subsequently applied to a 263,178-DOF numerical bridge model coupled with two physically-tested magnetorheological fluid dampers. Issues of stability with reduced-order models were discussed.

Accuracy of HS/RTHS

The accuracy of HS and RTHS methods is essential but approaches to verify the accuracy are not yet clearly understood much less standardized. The session included presentations and discussions of two different aspects of this challenge.

Verification and Validation: Mathematical approaches were posed to validate and verify RTHS techniques and simulations, identifying the level of confidence in the numerical methods and the selection and verification of the discretization. Further, the definition of accuracy itself, and metrics to evaluate it, were discussed. Specifically, it was emphasized that accuracy be quantified from the interface signals and that adaptive compensation techniques can improve RTHS accuracy. The RTHS community needs to jointly develop and pose benchmark problems and accuracy analyses to help RTHS users to validate new techniques. Ideally, comparisons to field measurements can be used to confirm the RTHS accuracy. Validation can focus on the level of accuracy obtained based on minimization of the interface errors.

Role of Friction: Friction in an experiment setup, specifically in the joints between the specimen and the testing frame, must be “subtracted” from the numerical model (as it provides forces on the physical specimen that do not exist in the full structure) or steps must be taken to minimize friction. The University of Minnesota MAST (Multi-axial Sub-assemblage Testing) facility, which can apply 6DOF loading on full-scale structure components until collapse and was recently upgraded for multi-axial hybrid simulation, was designed using hydrostatic bearings that were intended to provide ultra-low friction so that no friction compensation would be necessary in the numerical model. A case study of a 5.5m steel column showed strong experimental repeatability and robustness, and the actual friction forces were found to be negligible, verifying the intended design.

HS/RTHS of Aeroelastic Structures in Wind Tunnels

Most of the HS/RTHS testing in the civil engineering arena to date has been for seismic tests. However, emerging approaches for HS/RTHS of aeroelastic structures subjected to wind loads, with the structure physically tested in a wind tunnel to enable accurate wind loading, are being developed. Some of the challenges for RTHS in wind engineering were discussed, followed by presentation of an approach that has shown success in ongoing research.

Challenges in RTHS for Wind Engineering: These challenges include, but are not limited to, quantifying the fluid-structure interaction and incorporating their effects in the numerical model in real time. In addition, wind tunnel testing with scaled models requires structures with frequencies scaled relative to the full-scale, which may then require advanced capabilities of HS controllers and algorithms to properly compensate for any possible delays in the HS closed loop. The nature of wind tunnel testing and simulated wind loading raise questions regarding the repeatability of wind testing and wind forces correlation. Moreover, it is very difficult to predict the aeroelastic effects and wind-induced instabilities before testing, possibly leading to discrepancies between the wind loading acting on the numerical substructure relative to that of the physical substructure.

First Aeroelastic RTHS (AeroRTHS) Demonstration: A presentation detailed a series of RTHS carried out in the University of Florida NHERI Boundary Layer Wind Tunnel experimental facility by researchers from University of Connecticut and Clarkson University. This study used 128 pressure sensors on a rigid laboratory-scaled tall building in the wind tunnel to determine the aerodynamic forces, including the wind-speed dependent behavior of vortex induced vibration, on the structure; the numerical model determined the resulting building deformation and used a transfer system to induce real-time motion in the building. The challenges of simulating the cross-wind aerodynamic effects were discussed. The study indicated that testing of an aeroelastic building is feasible via a rigid building with pressure taps and a transfer system to control the building motion in the wind tunnel, as well as the use of vibration mitigation devices in the numerical model.

Building Capacity and Standards for HS/RTHS

The discussion considered the history and future of RTHS, pioneering facilities and the software developed thus far. In particular, it was noted that the workshops sponsored by NEES (the NSF-funded George E. Brown Network for Earthquake Engineering Simulation) significantly advanced RTHS technologies and collaborations, but these workshops have been infrequent since NEES ended.

Regarding standardization, the analogy was made to the FEMA 461 "Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Nonstructural Components" that made some progress on standardizing conventional component testing techniques, and the question posed whether a "FEMA 461-HS" could be developed to recognize HS/RTHS as a standard test method.

Action Items and Future Research Needs

- Development of testing procedures and standards
- More workshops and conferences focused on RTHS
- More discussions/studies related to fluid-structure interaction studies using RTHS.
- Further development of efficient solvers that provide high accuracy and good stability but minimal online computation
- Identifying benchmark problems and full-scale measurements to enable new testing procedures for validation and verification

Discussion Group F — Innovations in Modeling and Simulation III

Co-Chairs: Cheng Chen (*San Francisco State University*)
Giuseppe Abbiati (*University of Aarhus*)
Recorder: Nick Wierscheim (*University of Tennessee*)

Participants/Affiliations:
Elif Ecem Bas (*University of Nevada, Reno*)
Oreste Bursi (*University of Trento*)
Patrick Covi (*University of Trento*)
Yushan Fu (*University at Buffalo*)
Chris Gill (*Washington University in St. Louis*)
Hector Guerrero (*National Autonomous University of Mexico*)
Denis Istrati (*University of Nevada, Reno*)
Vivek Bhaskar Kote (*University at Buffalo*)
Elke Mergny (*Liege University*)
Jim Ricles (*Lehigh University*)
Valentina Ruffini (*University of Bristol*)
Thomas Sauder (*SINTEF Ocean*)
Xiaoyun Shao (*Western Michigan University*)
Wei Song (*University of Alabama*)

The objective of this working group was to discuss challenges and solutions related to modeling and simulation in hybrid and real-time hybrid simulation. Of specific interest to this working group were demanding issues related to the numerical and physical substructures and uncertainty quantification.

Main Points of Discussion

The presentations and the discussions in this group were wide ranging. While many topics were discussed, these topics can be broadly sorted into three categories: uncertainties, practical considerations, and nonlinearities. Below is a summary of the discussions related to these three categories.

Uncertainties

To date, most hybrid simulation studies have been done in a deterministic manner. However, uncertainties exist in hybrid simulation. To address these uncertainties, stochastic hybrid simulation is currently being considered and developed.

On one side, uncertainties characterize the transfer system, which adjusts the boundary conditions of the physical substructure to mimic the interaction with the numerical substructure. In this case, uncertainties produce artifacts in the physical substructure response, which propagate through the hybrid system. On the other side, the numerical substructure and/or the loading excitation cannot be defined deterministically. Uncertainties in the loading / ground motion are very important and may be more important than the uncertainties in the physical substructures being tested. Work advancing the consideration of loading uncertainties and moving beyond the use of a single loading record needs to be considered. This work should consider uncertainties beyond the frequency distribution of the load.

Tools from the field of uncertainty quantification can be used to study how all sources of uncertainty propagate through the hybrid system response. Some key questions that need to be addressed in the field of stochastic hybrid simulation, and should be at least considered in deterministic hybrid simulation, are 1) which are the sources of uncertainty sensitive to the hybrid system response, 2) how many experiments are required to characterize the probabilistic response of the hybrid system, and 3) can the bounds of uncertain variables that define artifacts and still yield high fidelity results be defined.

Practical Considerations

Through the practical experience gained in executing projects utilizing hybrid simulation and real time hybrid simulation, NHERI facilities and other investigators have gained valuable insights in to the many practical considerations involved in running HS. To allow for new users to adopt HS and excel at its implementation, mechanisms to transfer the knowledge gained from these experienced facilities and experienced investigators should be developed. Below are some examples of these important practical considerations.

The speed of the simulation is very important for efficiently running HS and feasibly running RTHS. Explicit integration methods are one way to allow for much faster run times. One of the results of using explicit numerical analysis methods can be the growing presence of unrealistic high frequency behavior in the test. The addition of numerical damping can eliminate this unrealistic behavior but needs to be applied carefully. The element type used for the member in the numerical substructure is also very important for run times. Some less computationally demanding element types exhibit unrealistic behavior, so they also need to be used cautiously. By incorporating efficiencies into the numerical analyses, the resulting fast run times can help to enable RTHS and can also allow for probabilistic studies that require many HS tests. Physical modeling of dynamic systems based on analog circuits seems to offer a viable solution for raising the sampling rate of the time integration process up into the MHz range, which could be necessary to handle some fast dynamics e.g., excited by blast or impacts.

The experimental configuration is very important for achieving good results with a hybrid simulation. Fixturing issues, slop, backlash, misalignment, etc. can critically pollute the results of a test. Instabilities/negative damping can result. Unmodeled compliance in the fixtures can be an issue as well. Coupling in complex systems make these issues even more important.

Successfully addressing these practical issues will allow HS and RTHS to be applied more broadly and efficiently for answering research questions in wind engineering, earthquake engineering, and beyond.

Nonlinearities

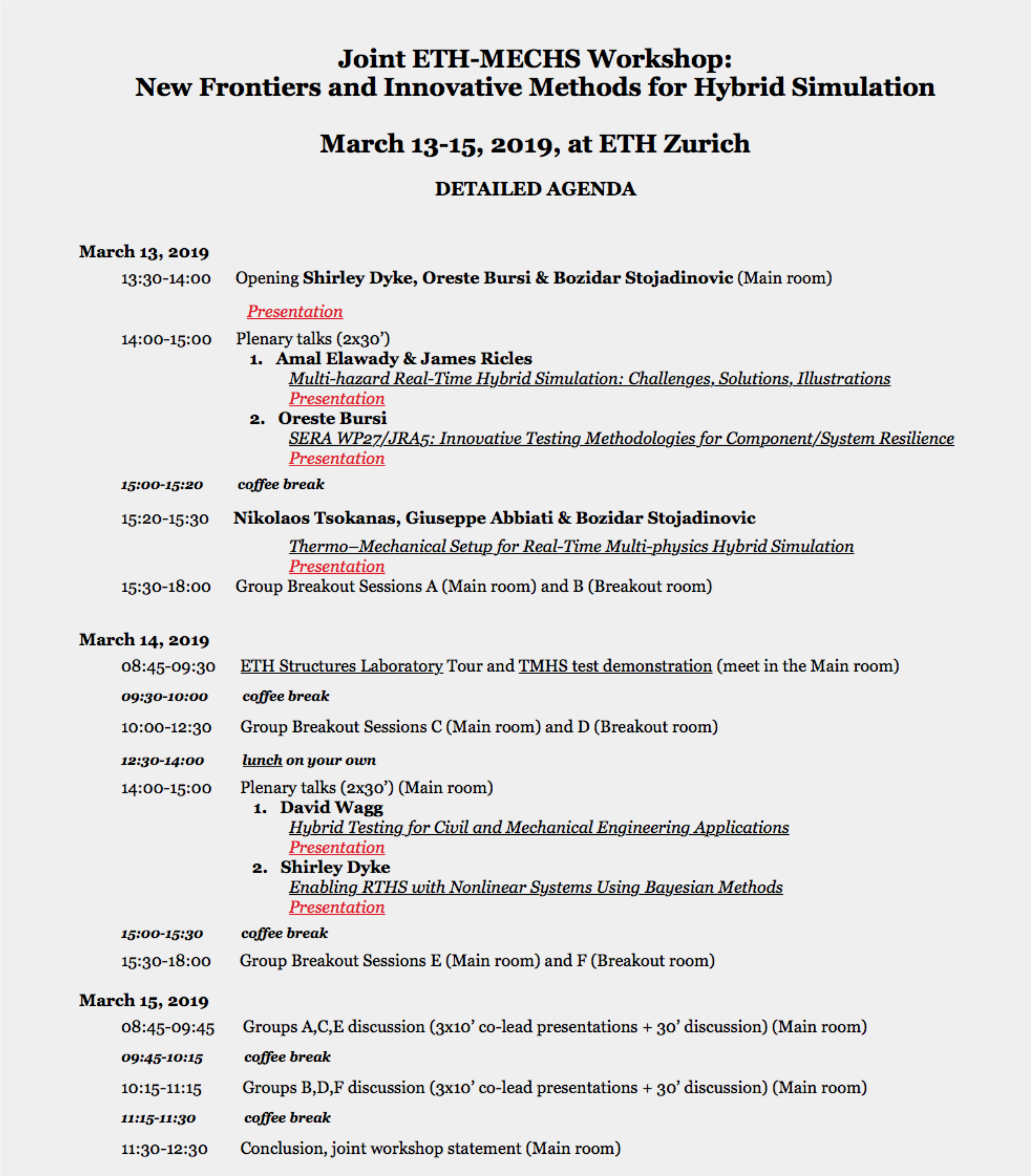
Nonlinearities in the physical substructure make it difficult to interface with a numerical model and run a convergent hybrid simulation, particularly in real-time hybrid simulation. Weak nonlinearities, which often appear as perturbations to overall linear behavior, have been considered in hybrid simulation for many different problems. Methods have been developed, and are currently under development, to allow for efficient and stable hybrid simulation with these weakly nonlinear physical substructures.

There are communities of researchers, for example the structural control and vibration mitigation community that would like to implement HS and RTHS methods into their studies, but have physical substructures that include strongly nonlinear effects. Unlike weak nonlinearities, these strong nonlinearities often produce system behavior that is incompatible with linearized estimates. Work is currently ongoing to extend hybrid simulation from weakly nonlinear systems to strongly nonlinear systems. The strong nonlinearities that need further consideration include hardening systems, systems with impacts, and state switching systems. In particular, emulating impacts emerged as a new challenge for hybrid simulation. Applications range from vibration mitigation, prosthetic legs, and satellite docking. Many of these challenges have not been addressed by prior HS and RTHS work. To allow for HS and RTHS to be used to study strongly nonlinear systems, work is needed to develop more advanced methods that are specifically designed to accommodate these challenging phenomena.

Action Items and Future Research Needs

- To move hybrid simulation beyond solely deterministic HS and into stochastic HS, more work regarding the consideration of uncertainties is required.
- The sampling of uncertainties is important and should be further considered.
- Consideration of uncertainties in the loading / ground motion is needed and may be very important.
- Further work related to the quantification of which uncertainties are important for the simulation fidelity is necessary.
- The determination of if high-fidelity results can be obtained given uncertainties in the transfer system is important.
- Further improvements in computational efficiency are needed to allow for the consideration of RTHS in larger systems.
- The transfer of knowledge regarding practical considerations is needed to allow new groups to be successful in HS and RTHS.
- It is necessary to develop RTHS methods that can handle nonlinearities, including strong nonlinearities

APPENDIX: Agenda for the 2nd Workshop



Joint ETH-MECHS Workshop: New Frontiers and Innovative Methods for Hybrid Simulation

March 13-15, 2019, at ETH Zurich

DETAILED AGENDA

March 13, 2019

13:30-14:00	Opening **Shirley Dyke, Oreste Bursi & Bozidar Stojadinovic** (Main room) *Presentation*
14:00-15:00	Plenary talks (2x30’) 1. **Amal Elawady & James Ricles** *Multi-hazard Real-Time Hybrid Simulation: Challenges, Solutions, Illustrations* *Presentation* 2. **Oreste Bursi** *SERA WP27/JRA5: Innovative Testing Methodologies for Component/System Resilience* *Presentation*
15:00-15:20	***coffee break***
15:20-15:30	**Nikolaos Tsokanas, Giuseppe Abbiati & Bozidar Stojadinovic** *Thermo–Mechanical Setup for Real-Time Multi-physics Hybrid Simulation* *Presentation*
15:30-18:00	Group Breakout Sessions A (Main room) and B (Breakout room)

March 14, 2019

08:45-09:30	ETH Structures Laboratory Tour and TMHS test demonstration (meet in the Main room)
09:30-10:00	***coffee break***
10:00-12:30	Group Breakout Sessions C (Main room) and D (Breakout room)
12:30-14:00	***lunch on your own***
14:00-15:00	Plenary talks (2x30’) (Main room) 1. **David Wagg** *Hybrid Testing for Civil and Mechanical Engineering Applications* *Presentation* 2. **Shirley Dyke** *Enabling RTHS with Nonlinear Systems Using Bayesian Methods* *Presentation*
15:00-15:30	***coffee break***
15:30-18:00	Group Breakout Sessions E (Main room) and F (Breakout room)

March 15, 2019

08:45-09:45	Groups A,C,E discussion (3x10’ co-lead presentations + 30’ discussion) (Main room)
09:45-10:15	***coffee break***
10:15-11:15	Groups B,D,F discussion (3x10’ co-lead presentations + 30’ discussion) (Main room)
11:15-11:30	***coffee break***
11:30-12:30	Conclusion, joint workshop statement (Main room)