Hybrid 2020: State-of-the-art and future directions for hybrid modelling and simulation

Scientific Report

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1 Summary

1.1 Research work conducted during the workshop sessions

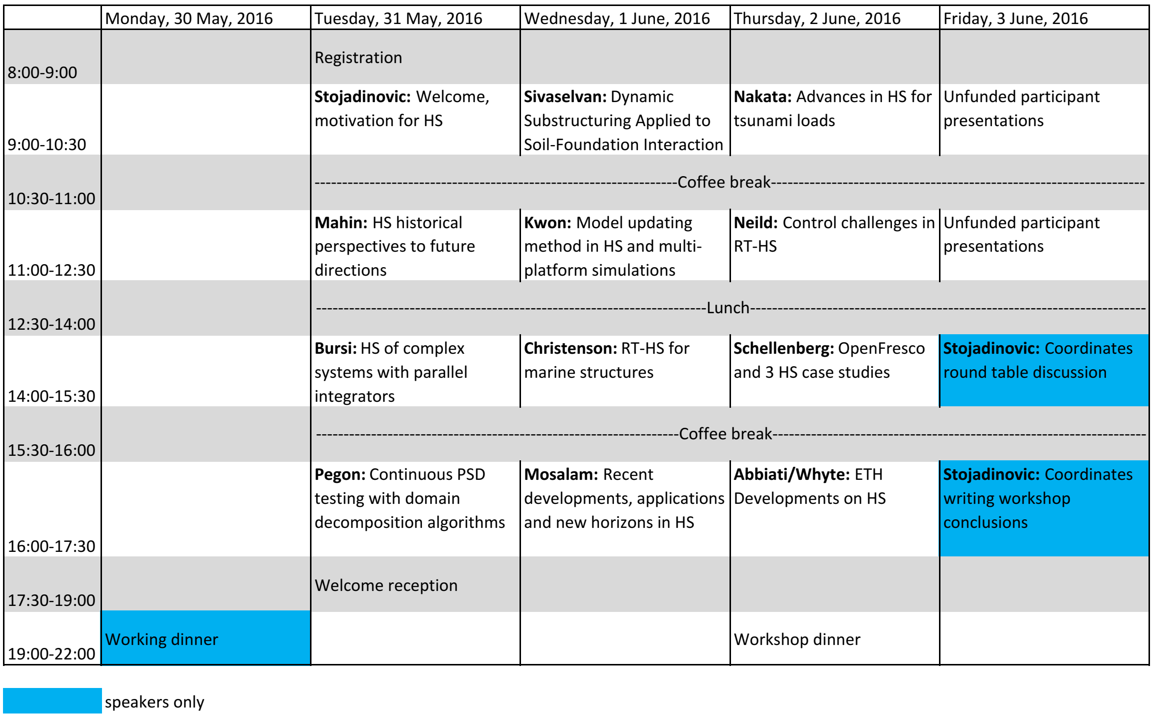
The Hybrid 2020 Workshop was a successful endeavor that brought together researchers, practitioners, and students from all over the world. The final program is shown in Figure 1. In the opening session, which was a working dinner for the speakers on Monday night, there was a group discussion about the state-of-the-art of hybrid simulation (HS) and what developments can be made in terms of standardization and future directions. On Tuesday, Wednesday, and Thursday, the workshop sessions consisted of a series of 90-minute presentations from each of the funded participants. Each speaker presented his or her own research in HS with an overview of past work, current efforts, and future directions. A question and answer session followed each presentation, where other participants had the opportunity to contribute to discussions. On Friday morning, 10 of the unfunded participants volunteered to give 20-minute presentations about the status of research in their home laboratories and their plans or ideas for future research with HS. In these presentations, the unfunded participants were able to use information they learned in the previous 3 days and expand to new directions. The scope of the discussion was significantly broadened, as there were people working on marine structures, wind turbines, blast scenarios, and aerospace applications. HS is a powerful method with many different types of applications, including solving new types of problems through combined physics or researching multi-hazard scenarios. At the end of the workshop on Friday afternoon, there was another discussion among the funded participants about outcomes and future directions.

One theme that emerged from the discussions was the idea that HS is a “method of all methods”, in that it combines physical, laboratory, testing and numerical, finite element modeling. The purpose of HS is to simulate the response of a structure that is divided into numerical and physical subdomains (NS and PS). Well-known substructures are modeled numerically using finite element (FE) software; substructures for which we lack reliable mathematical models or we expect strongly nonlinear response are modeled physically in the laboratory. HS is the most general term for all testing methods. When the NS part is removed, the result is a pure quasi-static test or a shake table test. When the PS part is removed, the result is a FE simulation.

The state-of-the-art of the FE method gives a good indication of a path forward for the HS method. There is now a standard approach to implementing the FE method but many different software packages can accomplish this task. Some come with user-friendly manuals for easy installation and simple tutorial examples. However, others are not necessarily easy for beginners to use but can accomplish very specialized analyses. This situation will continue to exist in the future because researchers will continue to use and further develop the particular FE packages that fit their needs.

In the same way, different laboratories have different equipment and thus different specialties. The future is not to develop a “standard laboratory.” Instead, there is a standard approach to testing and verifying and validating test results.

A HS package (e.g. OpenFresco, SimCor) refers to the middleware between the NS and the PS. It must interface with a FE program (e.g. OpenSees, Abaqus) where the NS is modeled and with a laboratory controller (e.g. ScramNet, NI, Pacific Instruments, D-space) that manages the actuation of the PS and the data acquisition. There is general agreement that we cannot choose one particular HS software and declare this to be the path forward for the future of HS. Instead, it is best to focus on **standardizing the HS methodology, best practices, and evaluation criteria**.



	Monday, 30 May, 2016	Tuesday, 31 May, 2016	Wednesday, 1 June, 2016	Thursday, 2 June, 2016	Friday, 3 June, 2016
8:00-9:00		Registration			
9:00-10:30		**Stojadinovic:** Welcome, motivation for HS	**Sivaselvan:** Dynamic Substructuring Applied to Soil-Foundation Interaction	**Nakata:** Advances in HS for tsunami loads	Unfunded participant presentations
10:30-11:00		----------Coffee break----------			
11:00-12:30		**Mahin:** HS historical perspectives to future directions	**Kwon:** Model updating method in HS and multi-platform simulations	**Neild:** Control challenges in RT-HS	Unfunded participant presentations
12:30-14:00		----------Lunch----------			
14:00-15:30		**Bursi:** HS of complex systems with parallel integrators	**Christenson:** RT-HS for marine structures	**Schellenberg:** OpenFresco and 3 HS case studies	🟦 **Stojadinovic:** Coordinates round table discussion
15:30-16:00		----------Coffee break----------			
16:00-17:30		**Pegon:** Continuous PSD testing with domain decomposition algorithms	**Mosalam:** Recent developments, applications and new horizons in HS	**Abbiati/Whyte:** ETH Developments on HS	🟦 **Stojadinovic:** Coordinates writing workshop conclusions
17:30-19:00		Welcome reception			
19:00-22:00	🟦 Working dinner			Workshop dinner	

🟦 speakers only

Figure 1: Final Program

Methodology: HS can enable tests that can be performed no other way, but they have to be carried out with informed and deliberate designs. Careful engineering thinking is necessary before starting a test. The problem must be approached step by step. The simplest version of the problem must be solved before attempting something more complex. The question is not just whether it is possible to do a HS, but also when HS is appropriate and what we can get out of it. In many cases, especially involving multiple physics (e.g. mechanical and thermal loads), it might not be clear how to properly couple the NS and PS. Maybe it is obvious how one part affects another but not vice versa. In this case, while a HS could be performed, it would not be solving the right problem. This is the question of **validation**: is the HS solving the right problem? Sometimes it is appropriate to neglect part of the coupling, but only if it is done deliberately as a first step towards the ultimate goal of a fully coupled simulation. The second step is **verification**: are the results correctly solving the problem as defined? This involves quantifying the uncertainty and the errors of the test. In the case that the interaction between the substructures is not clear enough or the necessary application of the boundary conditions is beyond the testing capabilities in the laboratory, then focusing on field testing could be a better approach until more information is gathered.

Best Practices for HS: It is critical to think through the whole problem and the desired outcomes before beginning a HS. This includes identifying the problems, needs, desired outcomes, and the methods of evaluating the errors. It is better to choose a simple HS over a complex one to make the test repeatable many times in the same laboratory, as well as implementable and repeatable in other laboratories. This will, eventually, help with HS standardization. A list of best practices is compiled below, regarding important HS topics:

Boundary and Initial Conditions: The challenges lie along the interface between the subdomains. The question is whether the boundary and initial conditions are represented properly. For example, the specimen may be "fixed" in the FE model or in the laboratory, but is this boundary represented properly? This can be the source of significant bias in results. If we are not satisfied with the available physical test setups in the laboratory, do we need to develop something new?

Testing Speed: It is better to make a good test that is slower rather than a bad test that is faster. If the PS is not rate dependent, then a slower than real time, pseudodynamic HS can be performed. However, if the PS is rate dependent (e.g. exposed to elevated temperatures that induce creep), then performing a slower than real-time HS must be carefully considered in the light of possible physics errors and similitude violations. Sometimes the laboratory equipment is not capable of performing a real-time test, and may introduce test conduct errors. Errors introduced in this way must be evaluated carefully and judged for their acceptability. It is better to use the best of the hardware rather than use a prediction of its behavior (i.e. avoid delay compensation when possible).

Control: It is important to understand the needs for stability, accuracy, and controls (e.g. open or closed loop). The method of performing the HS may bias the results (e.g. how much dynamics is added to the simulation by the controller itself?)

Geographically Distributed Tests: HS can be performed as a geographically distributed test between laboratories worldwide. This is an asset when it brings together specialized equipment that cannot be found all at the same location. It might be too expensive to build all the necessary facilities at the same laboratory. For multi-physics, then we have different facilities that are experts in different physics, distributed HS is very relevant. This can enable tests that would not be possible to perform otherwise. However, it is again important to think about the distortions of the data. Are any of the PSs rate dependent? Is the delay in communication over the internet a problem? If the physics of the problem is not completely clear, then performing geographically distributed tests will only add further complications.

Evaluation Criteria: For both simple and innovative HS, we need a standard for verifying and validating the test and quantifying uncertainty. With new directions in performance-based engineering, it is important to understand the outcome and its meaning. For example, if the outcome is fragility curves, what is the meaning of that for multi-hazard situations?

For uncertainty quantification, two people will never get exactly the same analysis results with a HS using the same computers and facilities, just as no two shake table tests will apply the intended ground motion excitation the same way. However, with the shake table test, the shake table input is also recorded, and it is possible to discern the output relative to the input and compare to other tests. This approach should be adopted for HS as well.

Accessibility: In addition to the methodology and best practices, there were discussions about making HS approachable to new users and how accessible does it need to be in general? Do we need an operator dedicated to hybrid simulation? How many PhD students are required to run a HS?

New Users: There are good reasons to have some simplified HS packages available for beginners without much technical background to start in this area. These should come complete with HS primer documents that give a clear description of the standards we can establish and provide procedures for starting with some simple benchmark HS tests. HS packages should use transparent and open data transfer between different FE programs and laboratory controllers.

When a researcher wants to do a HS in a new area (e.g. using a hybrid shaking table), then this is a research project. It might be necessary to start writing code from line 1. As this is research, it is not necessary to coordinate everything with other laboratories from the start. Instead, the standardization might exist only for internal use within a university of a laboratory at the outset. Different researchers will explore different areas. However, it is very useful for these researchers to ultimately implement their new developments in a HS platform that can be accessible to others.

Required Technical Skills for HS: There is the question of the expertise needed to perform a HS. Do we need an operator for HS? People who drive trains are called engineers because this used to be a very complicated and technical job. Over time, operation of trains became more and more automated, and now it is much simpler job to drive the train. In the early stages of HS, which is the current state-of-the-art, perhaps it is necessary to have an operator. There is an operator for a shake table, so maybe an operator will be necessary for HS too. As there are so many components to a HS, it takes a user a long time to be well-versed enough in all aspects to perform a test alone. Expertise is needed for FE modeling (including integration methods), interfacing hardware and software, control methods, experimental testing, instrumentation, photography, etc. It is possible for an individual to focus on some of these aspects, but perhaps not to become an expert in all areas. The future of HS could always be a team effort, or the operator will have enough expertise in all of these topics to stand alone.

Future of HS: The future of HS is multi-hazard and multi-physics: structural interactions with fluids (e.g. water, wind), structural interactions with hot fluids (e.g. fire), aerospace applications (e.g. airplanes, satellites). HS can be used to solve complex problems that can be solved no other way. Instead of using deterministic input values, probabilistic approaches will be followed. The transfer of knowledge from one generation of HS students to the next is something that is important to retain. Too often, students graduate and the knowledge gained in HS is lost.

1.2 Research results

The presentations by the funded participants have been recorded (slides synched with voice) and published online publically (http://www.video.ethz.ch/events/2016/hybrid2020.html), along with pdfs of the slides. Abstracts of these presentations along with short biographies of the speakers are included in the appendix and posted online (http://hybrid2020.ethz.ch/index.php/lectures/). The lecture series provides valuable reference material about the state-of-the-art of HS. People who were not able to attend the workshop can benefit from this resource. A subset of the unfunded attendee presentation pdfs (20-minute presentations) has also been posted.

The list of funded and unfunded participants is provided in the tables below. Dr. Pierre Pegon could not attend at the last minute, but Dr. Giuseppe Abbiati presented on his behalf. In total, there were 9 funded participants and 17 unfunded participants.

Participants to be funded by the SNSF (max. 10):

Last Name	*First Name*	*Where will the participant travel from?*	*Home institution*	*Position currently held at home institution*
Bursi	Oreste	Trento, Italy	University of Trento	Professor
Christenson	Richard	Stoors, Connecticut	University of Connecticut	Associate Professor
Kwon	Oh-Sung	Toronto, Canada	University of Toronto	Assistant Professor
Mahin	Steve	Berkeley, California	University of California, Berkeley	Professor
Mosalam	Khalid	Berkeley, California	University of California, Berkeley	Professor
Nakata	Naru	Potsdam, New York	Clarkson University	Associate Professor
Neild	Simon	Bristol, United Kingdom	University of Bristol	Professor
Pegon	Pierre	Ispra, Italy	European Commission - Joint Research Centre (JRC)	Research Engineer
Schellenberg	Andreas	Berkeley, California	University of California, Berkeley	Research Engineer
Sivaselvan	Siva	Buffalo, New York	University at Buffalo	Associate Professor

Other participants (unfunded):

Last Name	*First Name*	*Where will the participant travel from?*	*Home institution*	*Position currently held at home institution*
Aguado	Jose	Nantes, France	Ecole Centrale Nantes	Postdoctoral Researcher
Correia	Antonio	Lisbon, Portugal	LNEC	Professor
Ferraiuolo	Michele	Capua, Italy	CIRA Scpa	Postdoctoral Researcher
Grolimund	Reto	Zürich, Switzerland	ETH Zürich	Doctoral Student
Jockwer	Robert	Zürich, Switzerland	ETH Zürich	Postdoctoral Researcher
Karagiannis	Demis	Zürich, Switzerland	ETH Zürich	Doctoral Student
La Salandra	Vincenzo	Trento, Italy	University of Trento	Doctoral Student

Lignos	Dimitrios	Lausanne, Switzerland	EPFL	Assistant Professor
Miraglia	Gaetano	Turin, Italy	Politecnico di Torino	Doctoral Student
Neuenschwander	Martin	Zürich, Switzerland	ETH Zürich	Postdoctoral Researcher
Roller	Christoph	Efringen-Kirchen, Germany	Fraunhofer Institut	Research Engineer
Sadeghi Marzaleh	Abdola	Zürich, Switzerland	EMPA	Research Engineer
Salmanpour	Amir	Zürich, Switzerland	ETH Zürich	Doctoral Student
Sauder	Thomas	Trondheim, Norway	NTNU AMOS and MARINTEK	Research Engineer
Schulthess	Patrick	Zürich, Switzerland	ETH Zürich	Doctoral Student
Shahverdi	Moslem	Zürich, Switzerland	EMPA	Research Engineer
Tekeste	Gidewon	Lisbon, Portugal	LNEC	Doctoral Student
Wittel	Falk	Zürich, Switzerland	ETH Zürich	Senior Scientist

2 Research output and further collaboration

The duration of this project is too short for generating immediate research output. In the round table discussion among the speakers at the end of the workshop, there were discussions of future collaborations. All funded participants expressed a great interest in making this Hybrid 2020 Workshop into a recurring event. The initial idea is to organize a summer school in 2 years.

The speakers also agreed to work on publishing elements of their presentations and recent work in a special publication. The tentative table of contents of the publication is provided below. The agreed time frame is to collect the draft contributions by the end of 2016 and publish the special publication in 2017. The speakers will meet briefly during the 16th World Conference in Earthquake Engineering (January, 2017) to review the progress on this special publication.

Title: State-of-the-art and future directions for hybrid modelling and simulation

Editors: Abbiati, Whyte, Stojadinovic

1. Introduction: What is hybrid simulation? (Stojadinovic, Mahin, Mosalam, Bursi, Pegon).
    a. Provide an overall description of the simulation paradigm
    b. Convectional PSD method and geographically distributed testing.
    c. Continuous PSD method and exact synchronization of subdomains.
    d. Real-time testing for rate-dependent physical subdomains.
    e. ...
2. Experimental design: Why performing hybrid simulation? (Abbiati, Stojadinovic)
    a. Substructuring scheme and dependency to epistemic uncertainty.
    b. Uncertainty propagation, global sensitivity and reliability analysis.
    c. ...

3. Numerical modeling and integration (Mahin, Bursi, Pegon)
    a. Monolithic integrators (stability, accuracy and noise propagation)
    b. Partitioned integrators (velocity coupling).
    c. Modeling strategies (FEM, analytical equations, transfer functions).
    d. ...
4. Automatic control (Nakata, Sivaselvan, Neild, Christenson)
    a. Simplified and refined modeling of the actuator.
    b. PID, tuning, delay compensation.
    c. Mixed-mode control and loop shaping.
    d. Adaptive control.
    e. MIMO systems.
    f. Substructuring with shake tables.
    g. ...
5. Middleware (Schellenberg, Kwon)
    a. Architecture of a generic middleware (control, time integration and modeling).
    b. Existing middleware (OpenFresco and UI-SimCor).
    c. ...
6. Example applications (Everyone)

The authors should present their work in two or three parts, the theory in Chapters 2, 3, 4 or 5, and the applications/examples in the last chapter. Each chapter should highlight strategies for novice and expert users. Each example should address the issues of similitude, scaling and errors, and give a flow chart for implementation, verification and validation of HS.