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Earthquake Engineering Simulation

NEES

Report on the Discussions During the Hybrid Simulation Workshop

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Reno, Nevada

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Introduction

The NEES cyberinfrastructure enables researchers to pursue novel investigations using the latest technologies, educators to bring the latest methods and models into the classroom, and practitioners to contribute to and utilize results from the research community. NEES has facilitated the development of unique capabilities to accomplish these goals. An example, is the ability "to conduct computational and hybrid simulations that may combine the results of multiple distributed experiments, and link physical experiments with computer simulations to enable the investigation of overall system performance." [1]

Hybrid Simulation is increasingly being recognized as a powerful technique that offers the opportunity for global system evaluation of civil infrastructure systems to extreme dynamic loading while testing at the component or subsystem level. Using hybrid simulation methods enables more cost-effective and efficient evaluations of infrastructure systems under realistic conditions. Recent community-wide reports on the future needs in earthquake engineering in the US have documented the need for hybrid simulation methods to advance the resilience of our infrastructure.[2] [3]

During the Quake Summit in Reno, a workshop was held on hybrid simulation to lay the foundation for the development of a roadmap for advancing these enabling technologies moving forward. The steering committee[4] organized the workshop and thirty-four participants joined the discussions during the workshop. Based on the recent survey to collect user requirements[5], the following key topics were identified for discussions at Quake Summit: establishment of standards, communication protocols for interoperability; training and user support for the various tools developed to date; needs regarding education and awareness of what this technology is and how it can enable more efficient and varied activities; and, NEEShub infrastructure requirements that will support the HS/RTHS community. In this report we document and summarize the discussions during that workshop, and develop a roadmap to accomplish the goals.

ORGANIZATION OF THE WORKSHOP

The discussions were grouped into six broad areas including acceptance criteria, communicating the message, user guides/dictionary, framework development, NEEShub and visualization needs, and data exchanges and cyber security. The group topics were chosen based on the results of the recent hybrid simulation survey by NEEScomm from the users and prospective users of hybrid simulation (HS), real-time hybrid simulation (RTHS) and distributed hybrid simulation techniques.

To facilitate participation from the broad community in earthquake engineering and to collect input from users that were not able to attend the workshop, a group discussion page was created in the NEEShub. It is open for all to join, and the page will be used as a forum for discussing new developments and future needs in this emerging field. The "Hybrid Simulation Workshop" group discussion page is available here: http://nees.org/groups/hybrid_simulation_workshop.

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[1] Wikipedia page: http://en.wikipedia.org/wiki/Network_for_Earthquake_Engineering_Simulation

[2] "Grand Challenges in Earthquake Engineering Research: A Community Workshop Report (2011)" http://www.nap.edu/catalog.php?record_id=13167.

[3] "2020 Vision for Earthquake Engineering Research: Report on an OpenSpace Technology Workshop on the Future of Earthquake Engineering," https://nees.org/resources/1636.

[4] *Steering Committee:* Narutoshi Nakata, Shirley Dyke, Khalid Mosalam, Carol Shield, James Ricles, Bill Spencer

[5] The report on the hybrid simulation survey is available at: http://nees.org/announcements/results-for-hybrid-simulation-survey.

In session 1, the group topics and group members were as follows.

Session 1			
	Acceptance Criteria	**Communicating the Message**	**User Guides/Dictionary**
	Rich Christenson	Shirley Dyke	Naru Nakata
	Mettupalayam Sivaselvan	Khalid Mosalam	Adel Abdelnaby
	Gilberto Mosqueda	Xiaoyun Shao	Gemez Marshall
	James Ricles	Steve Mahin	Sameer Tilak
	Wei Song	Brian Phillips	Nacho Lamata Martinez
	David Ferry	Benson Shing	Jian Zhang
	Shawn You	Hussam Mahmoud	Selim Gunay
	Oreste Bursi	Monique Head	Cheng Chen
	Amin Maghareh	Bin Wu	Thomas Hacker
	Tony Fountain	Xilin Lu	Michael Bletzinger
		Gaby Ou	Ali Irmak Ozdagli
		M. Javed Hashemi	Ray Sydeski

In session 2, the group topics and group members were as follows.

Session 2			
	Framework Development	**NEEShub & Visualization Needs**	**Data Exchanges and Cyber Security**
	Benson Shing	Gemez Marshall	Thomas Hacker
	Selim Gunay	Khalid Mosalem	Xiaoyun Shao
	Mettupalayam Sivaselvan	Cheng Chen	Brian Phillips
	Gilberto Mosqueda	Monique Head	Rich Christenson
	Shirley Dyke	Adel Abdelnaby	Hussam Mahmoud
	Jian Zhang	Naru Nakata	James Ricles
	Michael Bletzinger	Xilin Lu	Shawn You
	David Ferry	Nacho Lamata Martinez	Tony Fountain
	Sameer Tilak	Gaby Ou	Bin Wu
	Oreste Bursi	Steve Mahin	Ali Irmak Ozdagli
	Amin Maghareh	Ray Sydeski	Wei Song
			M. Javed Hashemi

AGENDA

Wednesday, August 07, 2013	
8:00 am to 8:15 am	Introduction to the Working Meeting
8:15 am to 9:20 am	Session1: Topics 1, 2, 3 1. Communicating the Message – Led by Shirley Dyke 2. User Guides/Dictionary – Led by Narutoshi Nakata 3. Acceptance Criteria – Led by Richard Christenson
9:20 am to 9:35 am	Break
9:35 am to 10:40 am	Session 2: Topics 4, 5, 6 1. Framework Development – Led by Benson Shing 2. Data Exchanges and CyberSecurity – Led by Thomas Hacker 3. NEEShub and Visualization Needs – Led by Gemez Marshall
10:40 am to 11:00 am	Break
11:00 am to 11:45 am	Group Summaries – 5 minutes each group
11:45 am to 12:15 pm	Concluding Remarks

Overview of Discussion Outcomes

Although we held six different discussion groups during the workshop, several suggestions were brought up in multiple discussions. Thus, we attempt to first synthesize the common recommendations into some overarching recommendations to lay the groundwork for the future of hybrid simulation.

A significant number of the new users are new faculty and graduate students interested in learning how to implement hybrid simulation methods. At this time, these researchers feel that there is a high barrier to overcome regarding getting started with the hardware and software used for these methods. Note that there is already a page available on the NEEShub to direct users to resources and projects related to hybrid simulation. This page (https://nees.org/topics/RTHSwiki) is a good starting point for such information, but more resources are needed.

To facilitate access and to lower the barriers for new users, the participants requested that the NEEShub development team look for ways to: provide user manuals, terminology and examples; make it easier to find information on hybrid simulation documentation and resources; ensure that the project data is complete; improve mechanisms to integrate and use the data from hybrid simulations; provide mechanisms for new users to gain experience by participating in a hybrid simulation; and, disseminate the role of hybrid simulation in earthquake (and multi-hazard) engineering.

Existing user manuals are written for specific tools and hardware, and thus are limited in terms of usefulness for new users who need a more general understanding of how the components all fit together. Furthermore, various researchers in this emerging field are using different terminology when referring to the same components or algorithms. A high-level user guide based on a typical setup for a hybrid simulation and an associated glossary are needed to enable users to wade through the literature and guides associated with this technology. The user guide may be supplemented with online tutorials or video presentations to engage broad users and allow them to delve into the details.

New users also need guidance on what is needed to set up a hybrid simulation, what sort of components are required, and what role the hardware at the equipment sites play in hybrid simulation . Information about the hybrid simulation setup at the various NEES equipment sites could be made accessible. The Sites section of the NEEShub should be enhanced to indicate which of the facilities have experience in performing hybrid simulation. Note that in theory any of the sites could play a role in performing hybrid simulations.

New users also need to gain some experience with this method by having access to clear examples that demonstrate how a hybrid simulation is performed. Examples should take the form of problems with gradually increasing complexity that can be executed on a desktop computer. Users can vary the experimental setup, computational needs, etc. of the various examples to better understand hybrid methods. Simple case studies with experimental components that are reproducible in other labs are desirable, as well.

Additionally, in several discussions it was proposed that we find a mechanism to support travel expenses for graduate students and young faculty to visit NEES sites where a hybrid simulation is being planned or performed, to allow researchers to gain experience. Perhaps individuals who travel would be required to prepare a presentation or webinar about his/her experiences and contribute to the user manuals that are needed.

Also, NEEScomm, NEES researchers, and equipment site personnel need to ensure that hybrid simulation data are documented in their entirety. The hybrid data model has been integrated into the NEES data repository, but some feedback is needed to improve usability. Researchers should be sure to document their projects with a complete description of the test parameters, equipment, and algorithms, and feedback should be provided to NEEScomm to ease the process of upload for such data reuse. Perhaps a checklist or visual representation of the setup is needed to ensure that hybrid simulation data are described in their entirety. For instance, PID gains on the actuators, compensation or correction algorithms used, computational models and codes used, and physical descriptions of the actuators/servo-valves/manifolds etc, are all important if one is to reuse the data from a hybrid simulation test. Currently, this information is not always provided or documented in the NEES data repository.

It is important to be able to quickly visualize the responses and performance of the system and components in a hybrid simulation to better communicate the results of a test. Hybrid simulations are not as visually obvious as shake table tests, and thus integration of the data from the physical and computational portions is needed in a visual tool to clearly disseminate the behaviors observed in a test. A simple plug-in for RDV is available now, but improvements are needed.

Furthermore, it is crucial to raise awareness of hybrid simulation techniques at this time. Success stories about hybrid simulation activities at the NEES sites and info about the capabilities within the NEES network must all be disseminated to convey the research potential of this method. Articles in trade magazines, learning tools, and multi-media presentations are all great dissemination tools for conveying the successes of the research community and the capabilities of this technique.

Overall, the participants felt that this workshop was a very appropriate starting point for the development of a roadmap. We identified several short-term and long-term steps to take. Some of these goals still need to be fleshed out. As mentioned previously, a hybrid simulation user group has been established on the NEEShub, and all are welcome to join the group to participate in the discussions and development of these materials. Identifying best practices will require contributions from the entire community. Focused workshops on key topics (e.g., user guides/terminology, acceptance criteria, standards) and training materials should be developed to enable new users to access this technology. Funding mechanisms may need to be identified for some of these activities.

WORKING GROUP 1: COMMUNICATING THE MESSAGE

The group started the discussion by addressing the following questions:

- What examples of past successes (new designs, code changes, component validation) have been enabled by hybrid simulations?
- What are the advantages of this approach? Beyond cost-savings and efficiency? What will this approach allow us to do that no other method would facilitate?
- Is there a demonstration (NEESR project) that we can point to that would demonstrate the power of this technique? Enabling new developments?
- What scientific breakthroughs may be achieved by further developing these methods?
- How do we communicate the need for, and power of, hybrid simulation better?
- Funding needs for such activities?

Summary of Discussions

Advances in the development of the range of hybrid simulation methods (including traditional, real-time and distributed methods) are enabling more cost-effective and efficient evaluations of new structural systems under realistic conditions. The power of these methods lies in their promise to advance earthquake engineering. However, challenges do remain for those who employ hybrid simulation methods for experimentation.

This discussion focused on how we can, as a community, better explain hybrid simulation methods and demonstrate the value of this method as a viable technique. Special focus was given to the scientific breakthroughs that would be enabled with broader access to these testing methods. For instance, soil-and-structure interaction is an example of a test that is difficult to run using a shake table. However, through hybrid simulation, the interaction between the structure and the soil can be considered in the test, and the shake table can be used to apply more realistic test conditions for the specimen.

Hybrid simulation is often described as using a numerical simulation to consider the components of a test that are well understood, and focusing the physical component on the parts of a system that are not understood as well. Thus, as the test results yield a better understanding of the physical behaviors and how to model those, we can make the physical portion of the test more focused. Scaling and instrumentation needs should be clearly identified for the intended purpose of the test.

Some of the advantages of hybrid simulation and real-time hybrid simulation methods are:

- more readily available in typical laboratories
- global response evaluation
- local failure mode analysis under realistic loading, such as joint connection
- more realistic boundary conditions
- more efficient testing
- more cost-effective testing
- more flexible testing (many conditions, structures, loadings, are possible)
- fewer limitations, especially regarding scale, than shake table testing
- may be safer than shake table testing, especially in the case collapse tests

The audiences that the hybrid simulation community is trying to reach are not the engineers and researchers that develop and use hybrid simulation regularly. Rather, the target audiences include researchers in earthquake engineering that are not using these methods, practitioners and engineers, and government agencies or funding organizations. For reaching all of these audiences here are some clear suggestions:

1. Shake table testing is very visual and it is very obvious to the observer how the test specimen is responding. It is important to be able to more quickly visualize the responses and performance of the system and components in a hybrid simulation to better communicate the results of a test.
2. A cost/benefit analysis would be useful in comparing shake table testing and hybrid simulation. Such a comparison might also include the flexible nature of the hybrid method in conducting many tests on different specimens, as well as the limitations regarding scaling in both methodologies.
3. Hybrid simulation and real-time hybrid simulation are very different techniques, requiring very different equipment, knowledge and skills for implementation.
4. To perform a hybrid simulation, it is important to properly prepare for the test and gain experience with the components used in a test. Before researchers adopt hybrid simulation techniques, it is strongly recommended that they learn the fundamental skills associated with the hybrid simulation, as well as the capabilities and limitations of the equipment and the test as designed.

A significant number of young researchers are interested in learning more about hybrid simulation methods and using them in their laboratories. These researchers feel that there is a high barrier to overcome regarding getting started with the hardware and software used for these methods. Also, the number of options to choose from and the costs associated with the components are barriers. The discussion revolved around various methods that might be useful to help these researchers gain experience and become more comfortable with these methods. Several ideas were suggested including:

- webinars directed toward the implementation of the methods;
- simple demonstrations that might be reproduced by new users;
- centralized workshops focused on the design of hybrid simulations and not the specifics of the equipment at one site or another;
- benchmark problems for new users to gradually add complexity to their models; and
- travel support for young researchers to participate in the planning phase of a test at an experienced site.

These approaches will lower the barriers for new users to access this technology. Benchmark problems and simple experiments that can be set up by a new user were identified as being particularly important for facilitating access. Explicit documentation on how to combine the components into a single test is also critical for moving past that initial step. Educational materials are also viewed as being extremely important by the group discussing user guides and terminology.

If we direct our attention to the practitioners and engineers, it is important to not only increase awareness among this constituent group, but to demonstrate (i) the validity of the method and (ii) its importance for realistic testing. For instance, there are some projects that employed testing methods using both predetermined cyclic load histories and hybrid simulations. Case studies that compare the two methods should be highlighted to provide guidance on when hybrid simulation testing makes sense . For instance, in a hybrid simulation the goal is to apply more realistic boundary conditions to the physical component than would be possible in cyclic tests. This capability is important for validation of models and global response evaluation.

A NEEShub project (Project 981) on semi-rigid frames has clearly demonstrated that cyclic testing yielded very different outcomes and behaviors than hybrid simulation due to the reliance of the outcomes on the loading history. Similar results have been observed for concrete shear wall and wood structure tests. Also, in China pseudo-dynamic methods were used for pre-cast shear walls.

To reach the public, government officials, and funding agencies, the difficulty lies in conveying how the technique itself works and what the benefits are. Often, the development of the technique is confused with the purpose of the test that is being conducted. However, there is still a need to dedicate some resources to advancing the technique itself. Several ideas were proposed. It would be helpful to have an article in some trade magazines or on public television about the use of these techniques. YouTube videos or newspaper articles may also be helpful. In addition, a simple explanation of hybrid simulation is needed that can be conveyed to the layman.

Clearly there is great promise for this methodology to advance earthquake engineering. There are over twenty hybrid simulation projects in the NEEShub that are publicly available.[6] It would be worthwhile to consider those projects and what we might learn from the data and results as a community. Resources on hybrid simulation sites, projects, resources are available in the NEEShub at: https://nees.org/topics/RTHSwiki.

Next steps:

Near-term recommendations to convey the message:

- NEES should provide a simple explanation of hybrid simulation to convey the approach to government agencies, policy makers and even practicing engineers.
- Seek out opportunities to publish an article in a trade magazine or on public television about the use of these techniques. Case studies and research projects that demonstrate the benefits and capabilities of hybrid simulation should be highlighted.
- Examine the hybrid simulation projects on the NEEShub and consider what the community might learn from the data and results.
- Resources on hybrid simulation sites, projects, resources should continually be updated in the NEEShub at: https://nees.org/topics/RTHSwiki.

Long-term recommendations to convey the message:

- Perform a cost/benefit analysis to compare shake table testing and hybrid simulation. Such a comparison might also include the flexible nature of the hybrid method in conducting many tests on different specimens, as well as the limitations regarding scaling in both methodologies.
- To support young researchers that are interested in learning more about hybrid simulation methods and using them in their laboratories (to gain experience and become more comfortable with these methods), several ideas were suggested including: webinars directed toward the implementation of the methods; simple demonstrations that might be reproduced by new users; centralized workshops focused on the design of hybrid simulations and not the specifics of the equipment at one site or another; benchmark problems for new users to gradually add complexity to their models; and travel support for young researchers to participate in the planning phase of a test at an experienced site.

[6] See resource available: "Hybrid Testing in NEESR Projects," http://nees.org/resources/5414.

- Researchers employing and developing hybrid simulation methods should be consistently documenting their methods, data, and results to objectively assess and provide additional evidence of the benefits of hybrid simulation at the experimental level.
- Cooperation between the experienced users/developers and the new users must be encouraged to establish new opportunities for hybrid simulation applications that will address a broader range of realistic engineering problems. Funding opportunities should be explored.
- To facilitate access and to lower the barriers for new users, the group suggests benchmark problems, simple experiments that can be set up by new users, explicit documentation on how to combine the components into a single test, and educational materials.

WORKING GROUP 2: USER GUIDES/DICTIONARY

The group started the discussion by addressing the following questions:

- What is the most effective way to develop a user guide and dictionary?
- How would we ensure that a user guide and dictionary meet the needs of users?
- How would the guide be updated with new technologies?
- What are good ways to get community involvement for the development, dissemination, and maintenance of a user guide and dictionary?

Summary of Discussions

One of the bottlenecks that were pointed out in the user-requirement survey for hybrid simulation (HS) and real-time hybrid simulation (RTHS) is a lack of resources for novice uses to start with. Although there are several user guides available, they are either difficult to find or they are specific to particular tools, equipment sites, and applications. Even if novice users find resources, they are not sure whether the tools and equipment sites described are the right ones for their study.

The participants in this group strongly agreed that the need of a high-level user guide for HS and RTHS. The main user guide that needs to be developed is a “getting started with ...” type document that is targeted to people who do not have any knowledge of HS and RTHS. This user guide should provide a brief introduction, list advantages and great examples of HS and RTHS, and generally serve as the first reference for new users. It is also recommended that the guide should have navigations/links to different methods (RTHS, geographically distributed HS, etc.), tools, and equipment sites so that users can reach to the resources they need. A recommended format for the user guide is a printable PDF, though a wiki is easier for developing such a document. The other recommendations include a video clip with narration; a desktop hybrid simulation application that users can run on their computer; and results and data from successful applications that demonstrate capabilities of the range of hybrid simulation methods. The discussion focused on the relative usefulness of the various options.

The group also agreed that a dictionary or a collection of terminologies in HS and RTHS is needed. Because of confusing terms (e.g., several different terms with the same meaning), even experienced users sometimes have difficulty understanding technical details. Removing such barriers is essential to promote HS and RTHS. Among the challenges: How should we develop a dictionary? Who should do it? Where will it be located? How will it be maintained?

The other suggestion for attracting new users is to have a person to contact or a place where users can ask questions. Very often, people, particularly new users, do not know where to ask, what to ask, and who to ask questions regarding HS and RTHS. Because learning curves for HS and RTHS are so high at the beginning, it would be helpful if NEEScomm could provide a full-time employee who could take general as well as technical questions from users and direct the questions to those who can likely answer. With such a support, we can increase the number of users and researchers in HS and RTHS.

Next steps:

Near-term recommendations to provide a user guide and dictionary:

- Create a web page for HS and RTHS on the NEEShub to disseminate resources. (Note, this is complete.)
- Form a committee of volunteers (~5 members) to develop a user guide and dictionary for HS and RTHS. Establish a NEEShub group to collect input for this guide. The group page also will provide a forum for relevant discussions. (Note, this is complete.)
- Design a series of example problems of increasing complexity to assist researchers new to hybrid simulation to get started using this promising technology. Begin with an initial example at a basic level, and get feedback to improve.

Long-term recommendations to provide a user guide and dictionary:

- A committee on hybrid simulation would exist to maintain the dictionary and support the community.
- That committee will need to meet one/twice a year to discuss the user guide and dictionary to keep them updated (with input from users).
- Continue with the development of examples that consider more complex situations, with improvements based on feedback from the user community.

WORKING GROUP 3: ACCEPTANCE CRITERIA

The group started the discussion by addressing the following questions:

- What is the purpose of acceptance criteria?
- Who is the intended audience for acceptance criteria?
- Is the acceptance criteria most needed before, during or after a HS/RTHS test?
- What are people currently using for acceptance criteria to evaluate the quality of a HS/RTHS test (or other test methods)? What are the strengths and weaknesses of each?
- What are some proposed acceptance criteria?

Summary of Discussions

The participants in this working group agreed that the accuracy of the hybrid simulation method depends on several factors, including the integration scheme, hysteretic behavior of the specimen, various parameters in the actuation and associated control scheme, boundary condition, etc. For hybrid simulation to be considered a "standard" procedure in earthquake engineering, such as shake table testing or numerical simulations, acceptance criteria are needed. At this point, the quality of the result is the most important concern, independent of the devices and components used in the hybrid simulation.

The acceptance criteria are likely to take the form of properly defined error measures and associated error bounds specific to hybrid simulation. These errors should capture the uncertainty and variability in the modeling assumptions (boundary conditions), numerical errors (integrators, numerical substructures) and experimental errors (actuator control). A common set of these error measures and bounds is not currently recognized in hybrid simulation. It was proposed that various error measures are likely already present in various theses on hybrid simulation. A precursor to defining the acceptance criteria is to clearly identify the objectives of any acceptance criteria and to better understand how acceptance criteria should play a role in hybrid testing.

A number of potential users of acceptance criteria were identified. These users include: the clients who are paying for hybrid simulations for qualification of equipment or testing of components; the facility owner who is looking to accept or recertify a hybrid simulation setup; and researchers and customers of the facility who need the confidence that the test procedure will yield proper results. The acceptance criteria should be intended for both technical and non-technical people. It was also expressed that the intended audience should be the research and practicing community so that they can gain confidence in the results of a hybrid simulation.

It was agreed that acceptance criteria should be available before, during and after the hybrid simulations. Various end-users, as defined above, will be interested in understanding and quantifying the errors at each stage of a hybrid simulation. The working group focused on the benefit of acceptance criteria and understanding the quality of the test before the simulation. It was noted that lab managers as well as researchers specifying the test would benefit from acceptance criteria before the simulation. This might be used in the context of pretesting and could help to identify necessary actuator control schemes, integration algorithms, boundary conditions, etc. Furthermore, because some things may not be able to be accurately estimated prior to testing, having acceptance criteria during and after a test also is necessary.

A working workshop that brought hybrid simulation specialists together was identified as necessary to identify meaningful acceptance criteria. The workshop should request input from the various users. The attendees should be people that work closely with and understand the current methods and limitations of hybrid simulation systems in order to identify and prioritize these errors.

Additional items were discussed during this session. The importance of a benchmark in hybrid simulation was identified by the group, and various potential tests were discussed. The need to record all information and parameters (PID gains, controllers, integration schemes, etc.) for a hybrid simulation was identified as critical for understanding and possible repeatability of the tests. Lastly, the group advised that the hybrid simulation community should be aware and cautious of the language they use internally and externally to convey the challenges and results of tests; the group agreed that the HS community should seek to use more positive and less intimidating language in their descriptions.

Next steps:

Near-term recommendations to provide evaluation of these tests:

- The NEES community should ensure that all data preserved from HS testing documents all information and parameters from a test. This step will enable data reuse.
- Best practices in the design, setup, operation and assessment of a hybrid simulation should be identified. Perhaps this process can begin through the NEEShub group set up for this workshop.

Long-term recommendations to provide evaluation of these tests:

- To establish meaningful acceptance criteria for the community, NEES should hold a working workshop to bring hybrid simulation specialists together.
- The NEES community should seek methods to develop experimental benchmark problems that can be used as a learning tool for new users and an evaluation tool for experienced users.

WORKING GROUP 4: FRAMEWORK DEVELOPMENT

The group started the discussion by addressing the following questions:

- What kind of structural/finite element analysis software have you used or do you anticipate using for HS? What are the current challenges?
- What kind of software platform do you use to develop HS algorithms and control strategies? What are the current challenges?
- What type of local system network do you use for HS?
- Is there a middleware (e.g., OpenFresco, Simcor, or others) you have used for system integration?
- What limitations do we currently have regarding interoperability?
- What tools and standards should be developed to overcome the limitations of existing middleware for quasi-static, real-time, and distributed HS tests? Will recent advances in computer science help overcome these limitations for better integration of the tools?

Summary of Discussions

Based on the recent hybrid simulation survey conducted by NEEScomm, the main bottlenecks in using hybrid simulation methods, as identified by a number of the respondents, were the lack of interoperability of hardware and software, the high degree of expertise required, and the lack of standards and benchmark problems. On the same note, one of the major needs identified was the availability of standards to offer more flexibility in the software and hardware used. These point to the need of a versatile and user friendly framework with which researchers can incorporate appropriate simulation tools and hardware to develop hybrid simulation capabilities that will best suit their applications. Additionally, the adoption of documented standards for enhancing such interoperability would be appropriate to ensure that those following such standards would be able to "plug in" to the framework.

Hybrid simulations may be purely numerical, or may involve physical testing in a single laboratory or in a network of geographically distributed laboratories. Hybrid simulation may also be executed at a range of speeds, from tests taking several days to those that take place in real-time. Laboratory simulations are carried out with a variety of testing apparatus and equipment, including hydraulic actuators with different force/velocity capacities and performance levels, actuator controllers with different control capabilities, and data acquisition systems. Simulation can be carried out with different integration algorithms and solution strategies using custom developed software based on Matlab/Simulink, or open-source codes like OpenSees and UI-Simcor. Analytical substructures considered in hybrid simulation may be modeled using various commercial and open-source codes depending on the specific capabilities and level of details required for the problems at hand. Hence, such a framework has to be versatile and flexible and provide a mechanism for users to plug their codes, modules and equipment into that framework.

This working group was charged with discussing how to achieve such a framework and identify an action plan to have such a framework available to the community. A summary of this discussion is presented below.

It is important to point out that there have been steps toward the development of such "framework" software packages. The most notable are OpenFresco, developed at PEER, and UI-SIMCOR, developed at UIUC.

OpenFresco is a middleware that integrates interfaces from different analysis software packages, such as ABAQUS, LS-DYNA, and OpenSees, with custom-developed software based on MATLAB and Simulink to build simulation models and conduct hybrid simulations. OpenFresco also interfaces with laboratory hardware like actuator controllers and data acquisition systems. Data transfer is through TCP/IP protocols or SCRAMNet (common shared memory) protocols. OpenFresco itself does not provide simulation/analysis capabilities, but can incorporate some other computational tools for hybrid simulations.

SIMCOR has a built-in computation module for hybrid simulation. Furthermore, similar to OpenFresco, UI-SIMCOR provides interoperability to utilize a number of commercial and open-source analysis packages.

One interesting fact is that both OpenFresco and UI-SIMCOR have interfaces to link with each other, and a certain level of interoperability between them has been achieved. However, these softwares do not (as far as was determined) conform to a documented standard that would allow an outside researcher to easily integrate his work.

Currently, framework software is being developed independently across NEES sites. Typically such software is not conducive to simple changes in operating environments, such as different hardware controllers or software interfaces. There are many components of a HS or RTHS setup that, in principle, should be interchangeable (hardware controllers, integration methods, FEM solvers, controllers/compensators, numerical models). Currently this is not the case.

In 2007, a survey was conducted and a workshop was organized by NEESinc to identify the needs of the hybrid simulation community, and to discuss how the two main tools, OpenFresco and UI-SIMCOR, could be further advanced as a community-based effort. The following wish-list was compiled:

- Flexibility to use different simulation programs individually or together.
- Portability – can be used with different data-acquisition and actuator-control systems.
- Support fast or real-time test systems as well as slow or geographically distributed testing (which may require two different communication middlewares and protocols).
- Support hybrid simulation systems that utilize shake tables as well as individual dynamic actuators.
- Support effective force method.
- Support force, displacement, and mixed control of actuators.
- Support on-the-fly control switch between force and displacement.

Even though no concerted community-based efforts have materialized since that survey, some of the aforementioned capabilities have been developed and implemented in SIMCOR and OpenFresco, and possibly other tools as well.

The current working group identified three major purposes for having a standard:
1) To ensure that code from one NEES site can be used at another NEES site;
2) To ensure network interoperability between NEES sites during a multi-site hybrid test; and
3) To allow software to be modified and updated easily (such as when new computational codes emerge).

With respect to constructing a standard, two needs were identified. At a low level, things such as interfaces and protocols must be agreed upon so that two distinct softwares can interoperate. At a higher level, a good standard can ensure encapsulation to achieve the aims of interoperability above. This would allow experimenters to only worry about the components of the system that are critical for their test (for hybrid simulation, the network and experiment; for real-time hybrid simulation, the experiment and hardware interfaces, etc.).

The benefit of such a standard would be to imply a correct architecture and improve ease-of-use and interoperability by segmenting experiment code into distinct sections. With a standard, the experimenter would only have to worry about the semantics of the experiment they construct; the network expert would only have to worry about the semantics of the network being used; and the technician would only have to worry about the specific hardware involved and how to control it. The experimenter doesn't need to understand how the network operates or how the actuators are controlled; the network expert and technician don't need to understand what the experiment is; and so on. (Note: This is a classic standards example taught to computer science students is the OSI Model for networking.)

There are several types of standards that could be considered, depending on the goals of the standard. In the realm of software, there are essentially two types of standard: the formal specification, and the functional specification. A complete standard that fully encompasses interoperability between NEES sites would likely include both types.

In light of the fact that such framework software is already available but not broadly known to the user/potential user community (at least based on some of the recent survey responses), the following steps are suggested: (1) organize a community-based effort to assess the capabilities and user friendliness of existing tools for hybrid simulation, and to collect documentation available on the protocols used; (2) develop a set of typical domain-driven use-cases based on current and planned hybrid simulations that will drive the development of standards and interoperability requirements for the users; (3) identify the desired capabilities and features regarding interoperability that are not available currently; (4) allocate necessary resources to support further development of standards and implementation of interoperability; (5) allocate appropriate resources for user training and support; and (6) involve software engineers to develop and document robust and user friendly components (e.g., APIs, middleware, etc), and secure and efficient data exchange protocols over the Internet, all based on the standards that have been established for the community.

Next steps:

Near-term recommendations to establish standards for interoperability for hybrid simulation:

- Establish a working group to provide input and user perspectives to this process.
- Organize a community-based effort to assess the capabilities and user friendliness of OpenFresco and SIMCOR, and any other tools identified that should be considered.
- Develop realistic use-cases that would drive the development of the standards for interoperability.
- Create a set of formal specifications that outlines the major components of a "standard" HS/RTHS system along with the major requirements placed upon each component. These specifications declare what a component should do, but not how it should do it.
- Create a set of functional specifications to support the formal specification. For each component, specify the specific way (interfaces, protocols, and data formats) that allows for interoperability.

Long-term recommendations to establish standards for interoperability for hybrid simulation:

- Provide appropriate user training.
- Ensure that the standards are appropriately documented and posted for the community to employ in their testing and tool development.
- Develop new APIs or middleware as new products, tools or hardware become available.
- Develop a best practices document to capture the lessons learned and inform future decisions regarding maintenance and development.

WORKING GROUP 5: DATA EXCHANGES / CYBERSECURITY

The group started the discussion by addressing the following questions:

- What steps (computational and experimental) need communication protocols in hybrid simulation?
- What communication protocols are used? What data formats are used, and what data need to be exchanged?
- What are the limitations of these? What are the cybersecurity concerns?
- Are we using the latest technologies here?
- How will more security precautions impact our tests? Timing? Difficulty?
- At what steps are we most vulnerable to a cyber attack, and what are the potential impacts of an incident?

Summary of Discussions

The first question addressed by the breakout group was: What steps (computational and experimental) need communication protocols in hybrid simulation? We discussed both hybrid simulation as well as real-time hybrid simulation. The group discussed the impact of timing on both real-time and non-real-time hybrid simulation. The obvious need for real-time hybrid simulation is for fast-acting, time-based communications protocols that have very little overhead and low latency. When the network diameter is within a local site, the delays caused by the speed of light over communications networks does not pose a significant problem. However, for distributed real-time hybrid simulation beyond the laboratory, network loss, latency, and jitter become a matter of concern. To address this, one approach that was discussed was to use techniques such as a Smith Predictor to help pre-generate and buffer information to help overcome some of the networking constraints that impact real-time hybrid simulation. The downside of this approach, however, is the need closely monitor and manage the stability and accuracy of the models. Moreover, nonlinear specimens may be difficult to accurately model for the purposes of prediction. The other area, non-real-time hybrid simulation, also involves time constraints. One problem mentioned in the group was the need for a smooth and continuous flow of data to avoid the problems arising for force relaxations.

The group also discussed the specifics involved in hybrid testing and possible approaches to overcoming some of the communications limitations. One of these is: before starting the test, the software should first estimate how long each step will take, and then adjust the loading rate of the actuator so that force relaxation will not occur during the time waiting for the next step of the simulation. The communications and control approaches described in the group involved the separation of monitoring and control into a control plane and a data plane. Safety rules and policies can be embedded within the control plane to ensure the necessary safety and security of the testing process.

The second set of questions considered by the group was the following: What *communication protocols* are used? What data formats are used, and what data need to be exchanged? The group discussed the issue of determining the criteria needed to select the correct communications protocol(s) to be used for hybrid testing. Some of these criteria include: whether we should be bound to a single communication protocol; the security capabilities available as a part of the protocol; and the stability and reliability of the protocol and network infrastructure. On an application level, the issues involved in the protocols for sharing information are the need for agreed-upon data schemas and formats and the need for application level protocols for establishing and maintaining a control and data plane to define how data are exchanged between simulations and physical experiments.

The third set of questions addressed was the following: What are the *limitations* of these approaches? What are the cybersecurity concerns? The group discussed the need for resiliency and fault tolerance in the cyberinfrastructure. UIUC mentioned an approach they employed to test the cyberinfrastructure for several days before conducting the experiment to ensure that no unforeseen issues would affect the physical experiment. Another site mentioned the need to halt and delay a test due to unexpected load from competing networking traffic that significantly slowed the network connection. Many campuses and sites have deployed firewalls to protect their computing infrastructure. However, one of the attendees mentioned that they observed that a firewall on their network path added 30 to 40 ms of additional delay. Attendees discussed the possible use of other technologies such as open source Virtual Private Networks to create secure and predictable network paths between computational and physical simulation resources.

Another question discussed was: Are we using the latest *technologies*? Attendees agreed that although the existing approaches basically are working, there is a serious need to survey the suite of new technologies to determine if these new approaches could help to address the problems identified by the group.
The final question was: At what steps are we most vulnerable, and what are the potential impacts of an incident? Although attendees thought that their tests were not particularly vulnerable to attacks, in reality there are daily cyberattacks on systems connected to the Internet. As a consequence of this activity, the group discussed the need for logical checks on the data to ensure that it has not been corrupted or compromised. One of the possible problems is updates or patches applied to a system. How can we ensure the integrity of these? What is the best way to protect the system? The group members encouraged NEES to share the practices they have developed over the years with IT staff and other researchers in the community.

Next steps:

Near-term recommendations to enhance cybersecurity and the exchange of data:

- Collect information to document current practices used now for exchange of data and cybersecurity during a test. Identify potential gaps.
- Survey the suite of new technologies to assess the use of new approaches to address existing challenges identified by the group, such as communication delays.
- Use of technologies such as open source Virtual Private Networks to create secure and predictable network paths between computational and physical simulation resources.

Long-term recommendations to enhance cybersecurity and the exchange of data:

- Document the best practices developed over the years to share with the community. For instance, safety checks are an important part of any hybrid simulation and should be documented.
- The network should also work to identify ways to ensure the integrity of patches or updates prior to installation to avoid potential cybersecurity risks or added communication delays.

WORKING GROUP 6: NEEShub / VISUALIZATION NEEDS

The group started the discussion by addressing the following questions:

- How can the NEEShub enable advances and broader participation in hybrid simulation methods?
- User requirements: What information would be helpful to the users for learning and implementing hybrid simulation methods?
- What hybrid simulation tools/services would be helpful to the users for research and education?
- How could NEES disseminate information more effectively about the hybrid simulation tools and services available?

Summary of Discussions

The participants agreed that NEEShub should be the central place for finding support documents regarding hybrid simulation tools and resources. In this group, attendees believed that, currently, the Project Warehouse is suitable for existing users but that the Project Warehouse could be improved to help users new to hybrid simulation with getting started. In terms of helping new users, the proposed action items are as follows:

- Publishing some new guides including downloadable hybrid simulation models and the lessons learned.
- Developing interactive online demonstrations that provide user experiences.
- Using grand challenges as an incentive.

With respect to resources available in the NEEShub, the group categorized its suggestions into three divisions, (i) people, (ii) sites, and (iii) high performance computing.

- People: this group suggested to have a pool of people that can answer hybrid simulation questions and to appoint a contact person for NEES who could guide new users to a specific person from the pool who is knowledgeable.
- Sites: the main suggestions were that the NEEShub should provide a link to the sites that do hybrid tests; that there be a contact person at these sites who can help users; and that a compatibility matrix outlining the sites and equipment be made available. Furthermore, the group raised a question about whether the NEEShub should add a hybrid simulation category to https://nees.org/sites.
- High Performance Computing: the group discussed that, although the NEEShub advertises HPC for simulations, the NEEShub should advertise computational models for hybrid simulation as well.

With regards to tools, the group discussed the capabilities of the available tools, such as OpenSees, OpenFresco, UI-SIMCOR, OpenSeesNavigator, RT-Frame2D (for Real Time Hybrid), and ExVis which is a visualization tool that the University of Illinois at Urbana-Champaign is developing. Furthermore, the group discussed (i) the need to develop software to enable existing tools to be interoperable and (ii) the opportunities to write proposals for users to access MATHWORKS tools.

Finally, the group talked over different ways to effectively disseminate information. The group suggested that graduate students, based on a two-page proposal, should be given opportunities to spend time at sites currently using hybrid simulation techniques. Perhaps the students would be expected to contribute information about what they learn to the NEEShub resources for new users. Also, the group opined that hybrid simulation data in the Project Warehouse should be integrated in a more effective way.

Next steps:

Near-term recommendations to add NEEShub capabilities to support hybrid simulation:

- Explore ways to make the NEEShub more accessible for users new to hybrid simulation.
- Add some hybrid simulation users to the RAAS committee.
- Add a hybrid simulation section to the list of sites.
- Create user group that might answer questions for each other regarding getting started with hybrid simulation.
- Provide funding for graduate students to learn about hybrid simulation by spending some time visiting sites conducting tests.
- Provide better descriptions of the hardware and software available at each NEES site for running hybrid simulations, and a compatibility matrix outlining the sites and equipment.
- Support travel for (external) graduate students to spend time at the NEES sites during hybrid simulation experiments based on a short proposal. Perhaps the students would be expected to contribute information they learn to the NEEShub resources for new users.

Long-term recommendations to add NEEShub capabilities to support hybrid simulation:

- Establish capability to integrate experimental and analytical data for visualization of a hybrid simulation and animate the structure, existing tools or new tools
- Provide training materials targeted to the potential users, researchers, site users, and students.
- Provide downloadable hybrid simulation examples on the NEEShub, both as packages of files suitable for downloading and as files that can be executed in the NEEShub, as well as lessons learned.
- Currently, the NEEShub advertises HPC for simulations. It should advertise computational models for hybrid simulation as well.

CONCLUSIONS

Empowering the broader earthquake engineering community to successfully employ hybrid simulation methods is going to require significant effort beyond this workshop. However, as documented in several reports on the future of earthquake engineering in the US, hybrid simulation is certain to play a significant role in that future. Rapid progress is needed enable the community to harness the power of these techniques. Implementing the future steps identified in these discussions must be a priority for the NEES community, and thus a roadmap for the community based on these discussions will be established for the future of hybrid simulation. A task group will be formed to plan and initiate these activities, but involving the community-at-large will be critical for accelerating progress toward improving seismic resilience in the US.

Dissemination of information about the importance of this method is especially critical. With limited budgets and limited access to large-scale equipment, the community needs to become more efficient in its experimentation. We need to become more adept at employing component testing with realistic boundary conditions to explore global system behaviors, while reserving large-scale testing for validation of the most effective new designs or models.

Attracting and training users new to hybrid simulation is a high priority. The task group will need to develop a general user guide and dictionary for hybrid simulation, create a plan for a series of example problems and benchmark problems, and provide information on existing hybrid simulation setups. These activities will provide new users with the tools to successfully learn to use these techniques.

To facilitate improvement of the existing methods for hybrid simulation, access to the published data from the prior successful (and even unsuccessful) experiments is important. Completing and documenting the data, simplifying the procedures to use the hybrid data model, and enabling visualization of the integrated data (both virtual and experimental) during and after a hybrid simulation experiment is performed will require support from NEES headquarters as well as the NEES equipment sites.

Providing the tools and services that enable users to effectively employ these methods must also be a priority. For example, visualization of the integrated data, establishing standards for interoperability, and developing criteria for evaluating the performance of a hybrid simulation (before, during and after) are essential for standardizing these methods, building acceptance in the broader community and communicating the outcomes of a simulation with to the broader community.

There is a real sense from the community engaged at this workshop that hybrid simulation is a viable testing technique that has come a very far way in the past number of years and is well-poised to play a significant role in the development of technologies to improving seismic resilience in the US. This community is eager to establish a roadmap to provide better and broader understanding and acceptance of hybrid simulation and looks forward to the opportunity to work within the NEES framework to achieve these goals.