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# MULTI-AXIAL FULL-SCALE SUB-STRUCTURED TESTING AND SIMULATION (MUST-SIM) FACILITY AT THE UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

**Amr ELNASHAI[1], Bill SPENCER[2], Dan KUCHMA[3], Jamshid GHABOUSSI[4], Youssef HASHASH[5], Quan GAN[6]**

## SUMMARY

Seismic risk assessment is taking a giant leap by virtue of the unprecedented opportunities offered by the George E. Brown Network for Earthquake Engineering Simulations (NEES), comprising state-of-the-art experiment sites networked by the most advanced cyberinfrastructure (NEESgrid) available worldwide. This paper introduces the vision of integrated experimental and computational simulation as articulated by the MUST-SIM team at the University of Illinois. Cases where the distributed simulation vision may be applied to enhance the realism, accuracy and economy of seismic performance assessment are given. The application scenarios presented fully utilize the NEES approach to aid in providing the basis to mitigate the effect of earthquakes on existing infrastructure and furnishing data upon which enhanced design procedures may be derived. The paper closes with the description of the software and hardware components of the MUST-SIM facility and its operational characteristics.

## INTRODUCTION

The investigation tools of earthquake performance assessment are i) testing, ii) analysis, and iii) collecting data from regions hit by destructive earthquakes. Each of the three tools has advantages and drawbacks. Experimental testing is an essential and powerful tool. However, requirements for testing of very large

[1] Willett Professor, Acting Director, Mid-America Earthquake Center, University of Illinois at Urbana Champaign, Urbana, IL, USA. Email: aelnash@uiuc.edu
[2] Nathan M. and Anne M. Newmark Endowed Chair in Civil Engineering and NCSA Senior Center Affiliate, University of Illinois at Urbana Champaign, Urbana, IL, USA. Email: bfs@uiuc.edu
[3] Assistant Professor, University of Illinois at Urbana Champaign, Urbana, IL, USA. Email: kuchma@uiuc.edu
[4] Professor, University of Illinois at Urbana Champaign, Urbana, IL, USA. Email: jghabous@uiuc.edu
[5] Assistant Professor, University of Illinois at Urbana Champaign, Urbana, IL, USA. Email: hashash@uiuc.edu
[6] Post-doctoral Research Associate, University of Illinois at Urbana Champaign, Urbana, IL, USA. Email: quangan@uiuc.edu

structures often exceed the capabilities of a single experimental facility. Analytical modeling also suffers from serious shortcomings, where many important response and failure mechanisms remain beyond the realms of accurate constitutive representation. Finally, field observations are ultimately the most realistic since all aspects of source, path, site, foundation, structural and non-structural components are taken into account. However, field observations, as realistic as they are, suffer from lack of control of the exposed sample, incomplete knowledge of the input motion and uncertainty about the underlying soil properties. Consequently, the data collected is generally regional in nature and cannot be readily applied in a predictable fashion. As a result, only an integrated approach would provide the means to reliably investigate the seismic performance of complex structure-foundation-soil systems.

The NEES experiment sites, integrated through NEESgrid infrastructure, provide a unique opportunity to acquire highly reliable seismic assessment response data for complex systems. The grand challenge facing the earthquake engineering community is how to deploy these unique facilities, how to make full use of the opportunities, and how to breach disciplinary barriers in service of society and contribute to the features of the 'Community of Tomorrow', a community that optimally uses tools at its disposal to improve the quality of life.

In this paper, integrated experimental and computational simulation is discussed and the vision of the MUST-SIM facility as a node of NEES is described. Several examples of possible applications of distributed simulation are presented. Finally, an overview of the NEES MUST-SIM facility and its operational characteristics are presented.

## INTEGRATED EXPERIMENTAL AND COMPUTATIONAL SIMULATIONS

The ideal test for seismic assessment is created by the actual shaking of a number of full-scale model structures constructed on sites with various soil characteristics, where the structure and the soil are heavily instrumented. However, existing facilities cannot provide the capacities to test full-scale structures with soil-foundation-structure interaction (SFSI) effects. There are very few shaking tables around the world that are suited to test full-scale structures and none are able to support the structure with its foundations and a reasonable size soil mass. Therefore, the shaking table suffers from scale and payload limitations, density of instrumentation, short duration of the test and the lack of SSI modeling.

### Soil-foundation-structure interaction

As established in many studies, the increased foundational period due to SFSI would lead to increased rather than reduced response deformations. Such effects are only accounted for empirically in a small sub-set of design codes and guidance documents. The effect of SFSI has been studied analytically but the models used are far too simple to represent the complex kinematic interaction and the effect of soil inertia and soil seismic forces. Well-designed and well-instrumented physical experiments can provide data to calibrate and validate numerical models. Likewise, the results from the numerical analysis can help to determine several factors involved in geotechnical testing, such as the boundary condition. Therefore, integrated structural and geotechnical testing and analysis are needed. The reliable performance limit states that taking into account the structure, foundation and soil characteristics will aid in the accurate assessment of existing structures, as well as in the development of a new generation of performance-based design guidelines.

### Dense instrumentation and data harvesting

Current experimental approaches suffer from two major hindrances. Firstly, conventional instruments can only provide limited information of the structural response for the development, calibration and validation of a comprehensive numerical model. This is because the density of experimental data provided by the strain gauges and displacement transducers is much less than the density of elements in numerical simulation modeling. Analytical models calibration and verification is therefore normally conducted at a macro-scale whereas its accuracy is expected on a micro-scale. Secondly, the analysis of raw experimental data always lags behind testing rather than guides it. It is impractical to suspend tests for the time required to process and infuse experimental results to guide subsequent testing phases. Over the last few years, there has been a tremendous growth in the capabilities of non-contact instrumentation for measuring actions and deformations at many individual points to provide enough detailed information for analytical model reconciliation. Moreover, data harvesting and visualization tools are needed to process measured data in real time, thus making use of the opportunity to adjust and tune subsequent testing phases.

**Assessment of Network Performance**

One of the most exciting and challenging applications of the NEES vision is in transportation and other lifeline networks. Focus is placed hereafter on transportation networks as an example. There are three approaches for seismic assessment and intervention strategies for transportation networks. The Engineering Solution has, thus far, been the main focus of assessment and intervention strategies. It comprises retrofitting the most vulnerable links (e.g. bridges) regardless of its role in the network. In the Transportation Network Solution, the required level of network performance, measured by traffic and commodity flow, is utilized to assign priority for intervention, and possibly types of intervention that would elevate the performance to an adequate level. This approach focuses on retrofitting the structures that cause the most congestion. The Socio-Economic Solution goes much further to investigate the intricate regional inter-relationship between the transportation network, the economic parameters and the societal functions, including public policy, emergency services, educational system, business and cultural participation. Consequential retrofitting of structures that cause the most societal disruption and primary-secondary economic hardship ensues. A framework proposed by the NEES MUST-SIM group is a comprehensive ensemble of 'Engineering', 'Transportation Network', and 'Socio-economic' Solutions. Such a solution would lead to an assessment, prioritization, and retrofit approach that serves all strands of modern and continually functioning society and provides the most effective cost-consequence ratios, thus dictating exactly the research agenda that serves societal needs for an optimum investment.

The possibility of combining different computational and experimental sites furnishes the earthquake engineering community with a comprehensive toolkit for the application of multi-site simulations, employing the NEESgrid cyberinfrastructure. The system to be tested is divided into various sub-structures, including the foundation and the soil. Each sub-structure is to be physically tested or numerically simulated at the same time at different locations. The simulation master controls the overall experiment and communicates with the test sites and simulation computers via the internet. With the telepresence capabilities provided by NEESgrid, it becomes possible to observe experiment and capture data in near real-time. Through the secure and managed grid, the transfer of the experimental data and metadata between repositories and accession by remote users can be achieved in real time or after the experiments.

**Vision for the MUST-SIM facility**

As a node of the NEES system, the MUST-SIM team proposes a vision for a facility which can develop a physical-analytical simulation environment within a network assessment framework. First, the full scale structure-foundation-soil systems subjected to complex loading and boundary conditions can be conducted. Second, the structural response can be captured by state-of-the-art non-contact instrumentation systems and traditional strain gauges and displacement transducers. Third, the experimental data can be presented and visualized, and the numerical simulation model can be updated in real-time. Fourth, by using integrated computational and experimental simulation, the experiment testing of the structural components can be integrated and extended into large-size full-scale structures, and computational simulation modeling can be calibrated and validated accurately. Finally, through NEESgrid, the experimental and computational research can be distributed and shared among the earthquake engineering community.

## APPLICATION SCENARIOS FOR DISTRIBUTED SIMULATION SYSTEMS

This section presents several examples of applications that can utilize the state-of-the-art MUST-SIM facility and deploy the concept of multi-site experimental and computational simulation approach for complex systems.

### Multi-Site Online Simulation Test (MOST)

The Multi-Site Online Simulation Test (MOST) took place on July 30, 2003. The MOST experiment was a large-scale experiment conducted in multiple geographical locations which combined physical experiments with numerical simulation in an interchangeable manner (Figure 1). The partnership between the NEESgrid System Integration (SI) team, the MUST-SIM team at UIUC, and the FHT team at the University of Colorado at Boulder demonstrated the first integration of a prototype implementation of the full NEESgrid system with application software developed by earthquake engineers to support a real domain-specific earthquake engineering experiment.

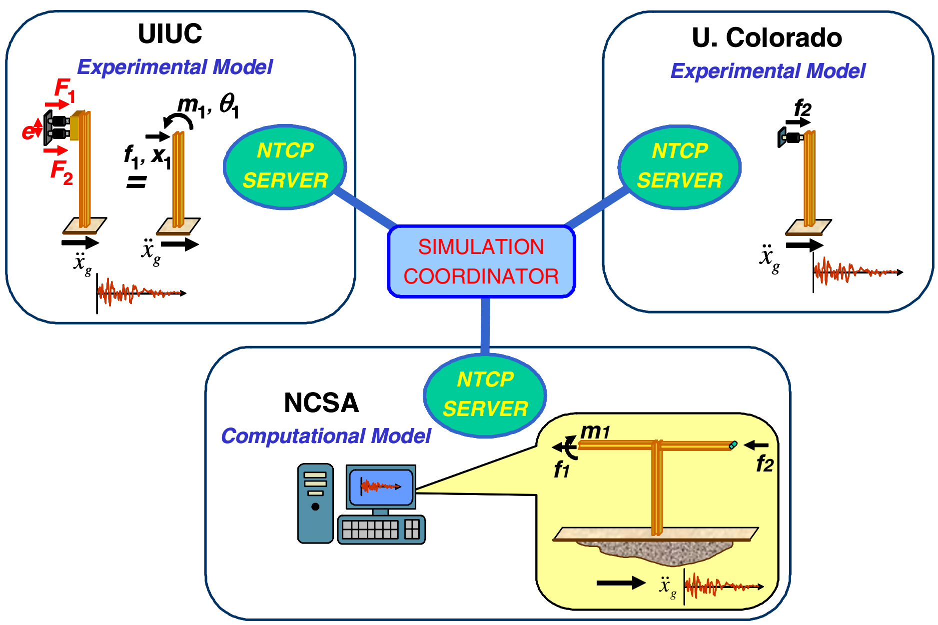



Figure 1 Multi-Site Online Simulation Test (MOST)

### Multi-Site Soil-Structure-Foundation Interaction Test (MISST)

The Multi-Site Soil-Structure-Foundation Interaction Test (MISST), proposed by NEES UIUC team in conjunction with the NEES facilities at RPI and Lehigh, is intended to provide a realistic test bed application with which to verify and extend all components of the NEESgrid as well as all components of the sites taking part in the distributed simulation (Figure 2). Concurrently, it is intended to set the example of excellence for integrated experimental-analytical simulation earthquake engineering. MISST is a unique project and will attract international interest and place the NEES Equipment Sites community at the forefront of earthquake engineering research.

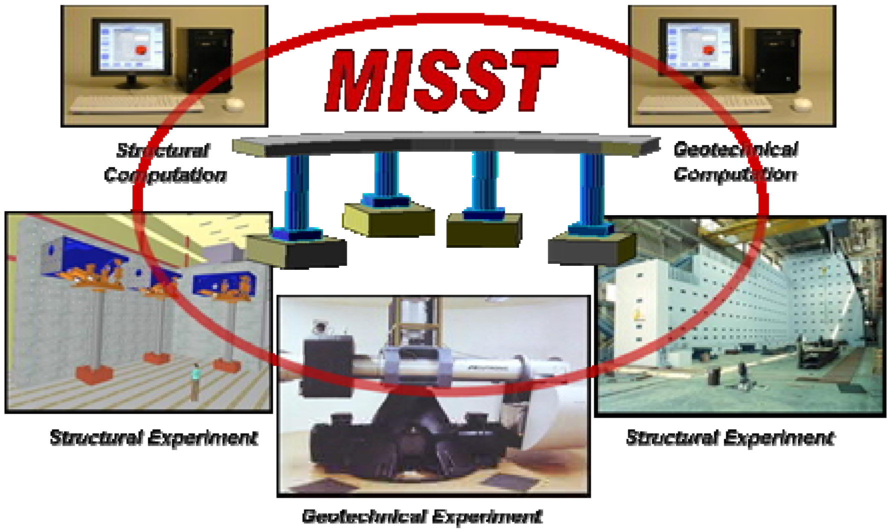



Figure 2 Distribution of Simulation Components

In MISST, two NEES large scale experiment sites (UIUC and Lehigh), one NEES geotechnical experiment site (RPI) and a computational simulation node (NCSA) can be employed. The simulation includes analytical simulation and physical simulation. In analytical simulation, the complete MISST pseudo-dynamic sub-structuring experiment is conducted using computer simulation. The goal of this effort is to support the subsequent experimental implementations required for MISST and to provide a corresponding comparative baseline. In the following physical simulation, first, the computational simulator of the soil is replaced with a corresponding physical experiment at RPI. Second, the computational simulator of one pier is replaced with a corresponding physical experiment at Lehigh using small amplitude shakedown tests. The computational simulator of the rest piers is then replaced with corresponding physical experiments at UIUC using small amplitude shakedown tests. Lastly, the final four-site execution of MISST is performed through NEESgrid.

MISST utilizes four aspects of simulation that will comprise many of the applications of the NEES experimental sites and NEESgrid by including:

- Advanced analytical geotechnical modeling under dynamic loading
- Advanced analytical structural modeling under dynamic loading
- Advanced geotechnical testing using centrifuges
- Advanced structural testing using multi-degrees-of-freedom testing facilities

The earthquake engineering community at large will benefit from MISST by observing that the NEES vision of distributed simulation is finally realized and proven. NEESgrid brings the experiment site facilities together, regardless of geographical location.

**Seismic Performance Evaluation and Retrofit (SPEAR) Test**

One of the leaders in the earthquake simulation field in Europe is the European Laboratory for Structural Assessment (ELSA) within the Institute for Systems, Informatics and Safety at the European Commission Joint Research Center (JRC) in Ispra, Italy. ELSA undertakes pioneering work in full scale Pseudo-Dynamic Sub-structure testing in Europe. The international cooperation between ELSA and UIUC benefits the NEES community, thus encouraging similar developments in Europe and Japan. The international cooperation provides the opportunity to share information to the mutual benefit and in cooperative effort with the broader community. Figure 3 shows the SPEAR test, which is carrying out in ELSA.

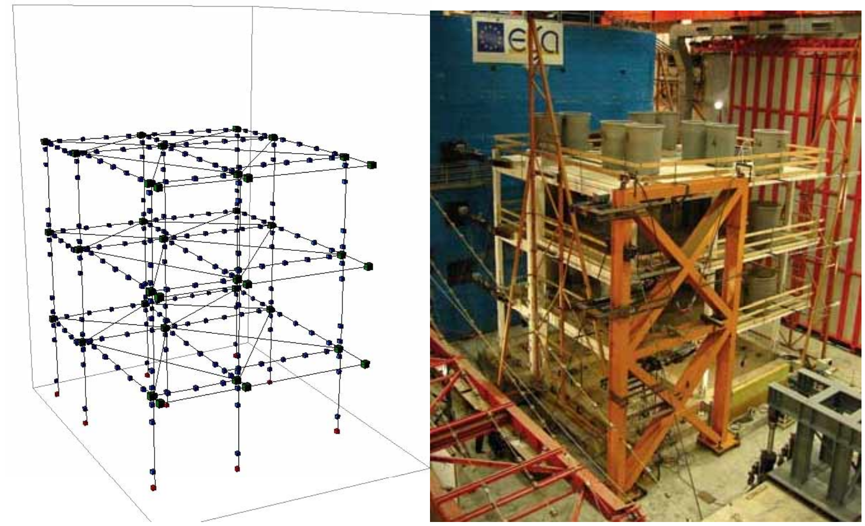


Figure 3 SPEAR Test

As part of the SPEAR project, members of the MUST-SIM team have undertaken extensive pre-test simulations of the shown frame, leading to the selection of the input motion, its direction of application and the scaling factors required to achieve the target limit states (Jeong and Elnashai, 2004). The tests were conducted at JRC, Ispra in January 2004, in the presence of the MUST-SIM/Mid-America Earthquake Center researchers. Whereas the test has taken more than a year to construct, instrument and test, models that are calibrated to replicate its performance execute a full dynamic analysis in a few minutes. In Figure 4 the comparison between the pseudo-dynamic test and the analytical simulation using ZEUS-NL (Elnashai et al, 2002) is shown. Noting that only a few elements of the test structures suffered significant damage, developing retrofit options for this complex structure is a problem well-suited to the application of integrated physical-computational simulation. The members that suffered damage could be tested in the laboratory after the application of a number of retrofitting techniques, whilst the rest of the structure would be analyzed using the model that has been already validated as shown in Figure 4.

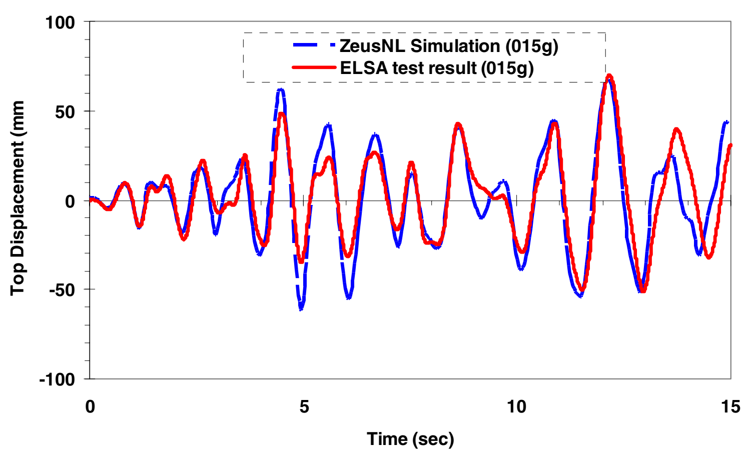



Figure 4 Comparison between PSD Test and ZEUS-NL Analysis

**THE MUST-SIM FACILITY**

The NEES MUST-SIM facility as one of the fifteen NEES experiment sites provides the distributed experimental/computational simulation capabilities to the earthquake engineering community. The details of the components of the MUST-SIM facility and its operational characteristics are presented in this section.

The Multi-Axial Full-Scale Sub-Structured Testing and Simulation facility (MUST-SIM) has the following features: i) 6-DOF load and position control at 3 connection points, ii) Three dense non-contact measurement systems, iii) Advanced geotechnical and structural analysis tools, iv) Data fusion and high-end visualization capabilities, v) A full array of telepresence equipment. The principle components in the MUST-SIM facility are shown in Figure 5.

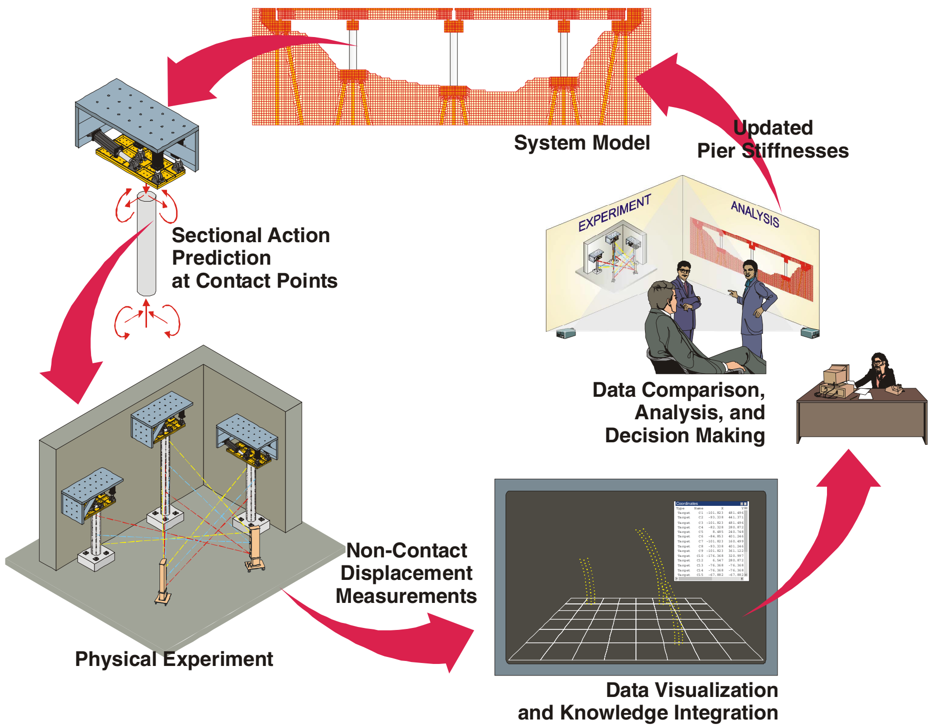



Figure 5 Principle Components in MUST-SIM Facility

**Reaction Wall**
An L-shaped post-tensioned concrete strong wall of 15.2 × 9.1 × 8.5 × 1.5 m (length × width × height × thickness, respectively) enables testing of full scale sub-structures, as is shown in Figure 6.

**Loading and Boundary Condition Boxes (LBCBs)**
Each Load and Boundary Condition Box (LBCB) is a self-reacting assembly of actuators, swivel joints and control software capable of imposing any combination of six actions (forces and moments) and six deformations (displacements and rotations) to test specimens connected to its loading platform, as is shown in Figure 7.

Any of the three faces of the LBCBs could be attached to reaction structures (floor or wall). The LBCBs provide high loading and displacement in six degrees of freedom testing point. The LBCBs can impose motions on the test structures from the results of concurrently running numerical models of the test specimen and the surrounding structure/foundation/soil system employing pseudo-dynamic testing methods. The UIUC NEES Facility comprises three such boxes, which are servo-controlled and connected to finite element analysis software. This makes it possible to perform the distributed simulation of complex structures and their foundations subjected to strong ground motion. The specifications for the LBCBs are presented in Table 1.

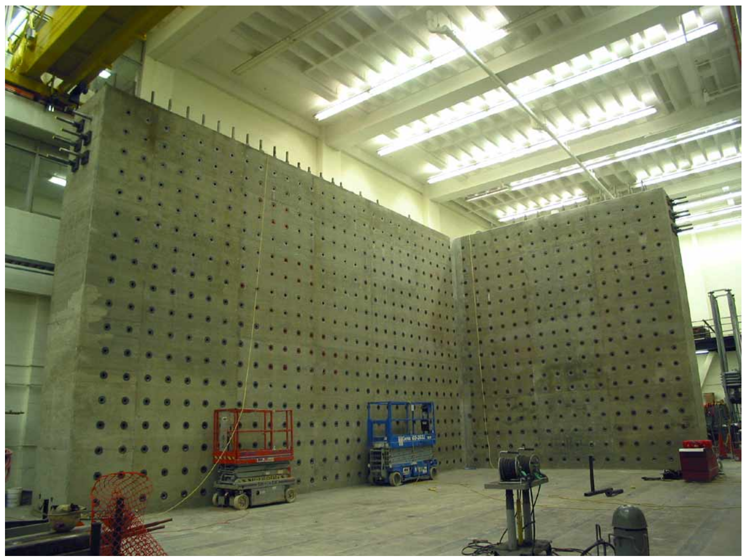


Figure 6 Strong Wall in MUST-SIM Facility

Figure 7 Loading and Boundary Condition Box (LBCB)

**Table 1 LBCBs Specifications**

| | |
|---|---|
| Specifications | Three LBCBs, weighting 33 tons each, post-tensioned to strong floor/wall |
| X-Direction | Force = 1890/2835.6 kN (425/637.5 Kips), Stroke = plus/minus 250 mm (10”) |
| Y-Direction | Force = 960/1459 kN (212.5/318.8 Kips), Stroke = plus/minus 125 mm (5”) |
| Z-Direction | Force = 2882/4377 kN (660/990 Kips), Stroke = plus/minus 125 mm (5”) |
| Theta-X | Moment = 1193 kN.m (880 Kips.ft), Rotational = plus/minus 12 degrees |
| Theta-Y | Moment = 1425 kN.m (1063.3 Kips.ft), Rotation = plus/minus 10 degrees |
| Theta-Z | Moment = 1180 kN.m (850 Kips.ft), Rotation = plus/minus 12 degrees |
| Load Controllers | Three 6-channel Controllers, one for each LBCB |
| Load Control Software | Inner-Loop Load Control program for independent control of load or displacement for each of the 6 degrees-of-freedom for each LBCB; Outer-Loop Load Control for three LBCBs that enables Tele-Operation. |

**Non-contact Instruments**

*Krypton’s K-600 Dynamic Measurement Machine (DMM)*

The Krypton’s DMM is able to measure the position of up to 256 small (8 gram and 8 mm diameter) light emitting diode markers in three-dimensional space to an accuracy of plus/minus 0.02 mm at a sampling rate of up to 3000 individual readings per second (Figure 8). The Krypton system consists of a portable housing containing three 2048 CCD line-element cameras. The camera system has an effective measurement volume of 17 $m^3$. The Krypton system provides a faster, more accurate, more flexible measurement while adding only a few grams of instrumentation mass to the test specimen when compared to traditional mechanical sensors.

Figure 8 Krypton’s K-600 Dynamic Measurement Machine

*Stress Photonics Gray Field Polariscope (GFP-1200)*

The Stress Photonics Gray Field Polariscope (GFP-1200) (Figure 9) is a full field non-contact stress/strain measurement system which is based on the principles of photoelasticity. To use Stress Photonics’ Grey-Field Polariscope, an application of a thin (0.25 mm) plastic coating (photoelastic material/epoxy) is applied to the surface of the test specimen. A light source is then used to emit circular polarized light and a digital camera is used to measure the fringe patterns. Unlike with traditional photoelasticity, the GFP-1200 system measures small variations in patterns of circular light. As a result, reliable sub-fringe level accuracy can be obtained with high resolution in the stress/strain levels being resolved. The typical resolution is 20 microstrain.

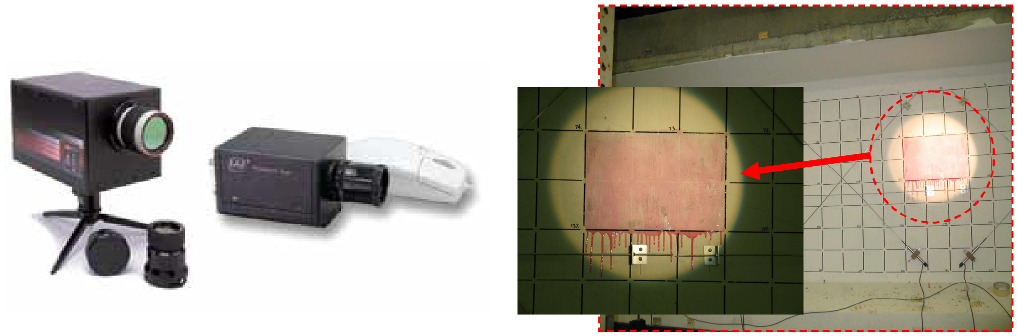


Figure 9 Stress Photonics Grey-Field Polariscope and Application

*Close-Range Digital Photogrammetry*

Close-Range Digital Photogrammetry (Figure 10) is used as a third non-contact measurement methodology. This methodology, widely used in aerial mapping, has recently become increasingly popular for other applications in the field of engineering and solid modeling. In a structural engineering application, the system can be used to measure the movements of targets placed on the surface of the test specimen from which strains, crack widths, and other features can be determined. High accuracies can be obtained by capturing subsequent images through conventional and digital cameras.

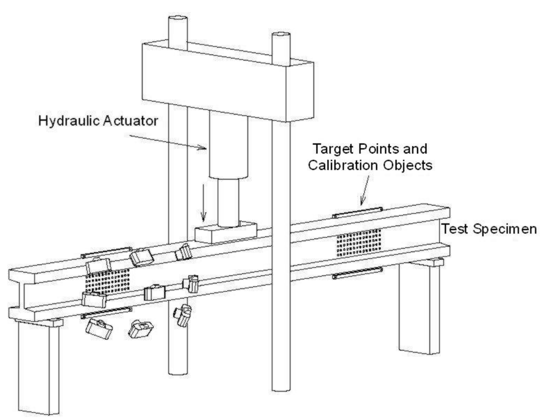


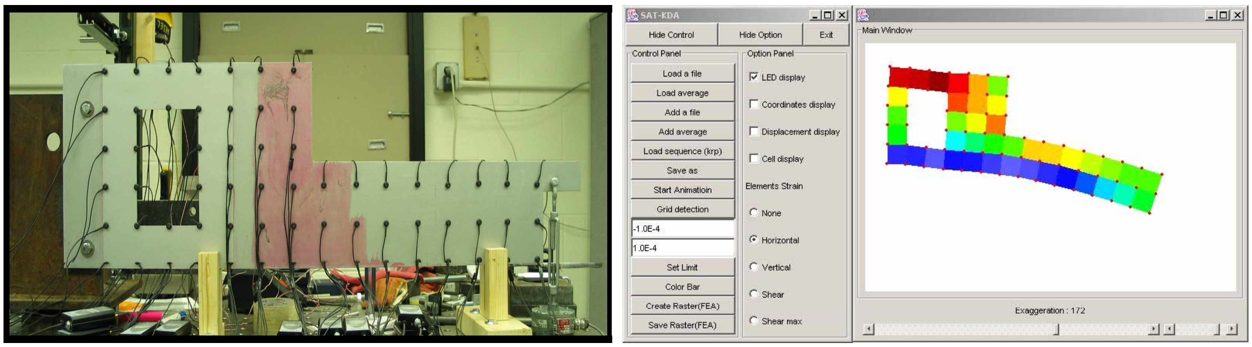

Figure 10 Close-Range Digital Photogrammetric Measurement System

The dense arrays of state-of-the-art, non-contact instrumentations in the MUST-SIM facility will be used to display and analyze the deformations and response of large structures in 3D with unprecedented high spatial resolution and allow near real-time model updating for the model-based simulation.

**Data Fusion and Visualization**

Multi-function data visualization and knowledge interpretation tools are being developed for NEES MUST-SIM with the Automated Learning Group of the National Center for Supercomputing Applications

(NCSA). This will include four stages: visualization, integration and interpretation of multiple-source test data, integration of test and analysis information, and model adjustment and optimization. The Strain Visualization Tool (SVT) can visualize raw data consisting of temporally varying three-dimensional coordinates obtained from non-contact measurement systems (Figure 11). The Strain Analysis Tool (SAT) supports visualization and data fusion tasks performed during structural engineering analysis with data sets acquired from Krypton and Stress Photonics systems.




(a) Specimen with Krypton System (b) Data Visualization Tool

Figure 11 Visualization Tools

**Integrated Computational and Experimental Simulations (ICES) Controller**

One unique feature of the MUST-SIM facility is the ability to test and simulate the entire soil-foundation-structure system at full scale. This is accomplished through the development of a software framework that integrates computational and experimental simulations (ICES) (Figure 12).

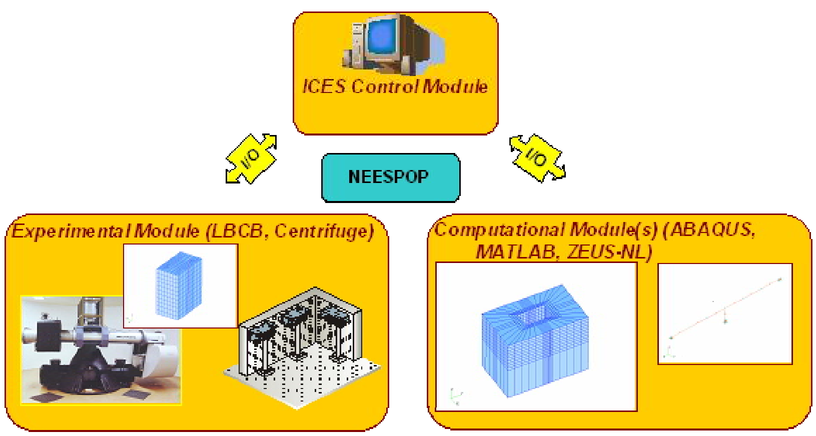



Figure 12 ICES Controller

The ICES framework seamlessly integrates numerical and physical models to simulate a complete bridge structure including its foundations. The framework currently includes two pseudo-dynamic testing procedures: a) α-operator splitting method, and b) a newly developed predictor-corrector method. The framework can use any number of available numerical simulation codes including ABAQUS, ZEUS-NL, MATLAB, and OPEN-SEES. The framework can virtually represent an entire structural system, and the separate modules can represent the components of the structural system. So, this framework can combine physical testing with accurate numerical simulation. In the distributed simulation, each physical test site in various geographical locations can be connected to the ICES controller of the integrated simulation through NEESgrid. A schematic outlining the control system framework is shown in Figure 13.

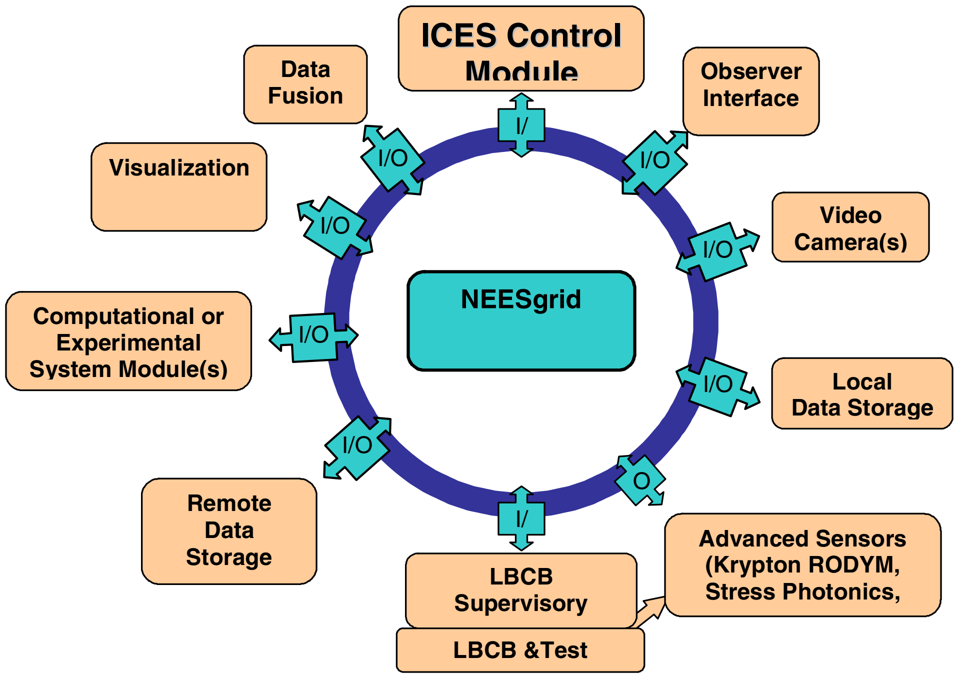
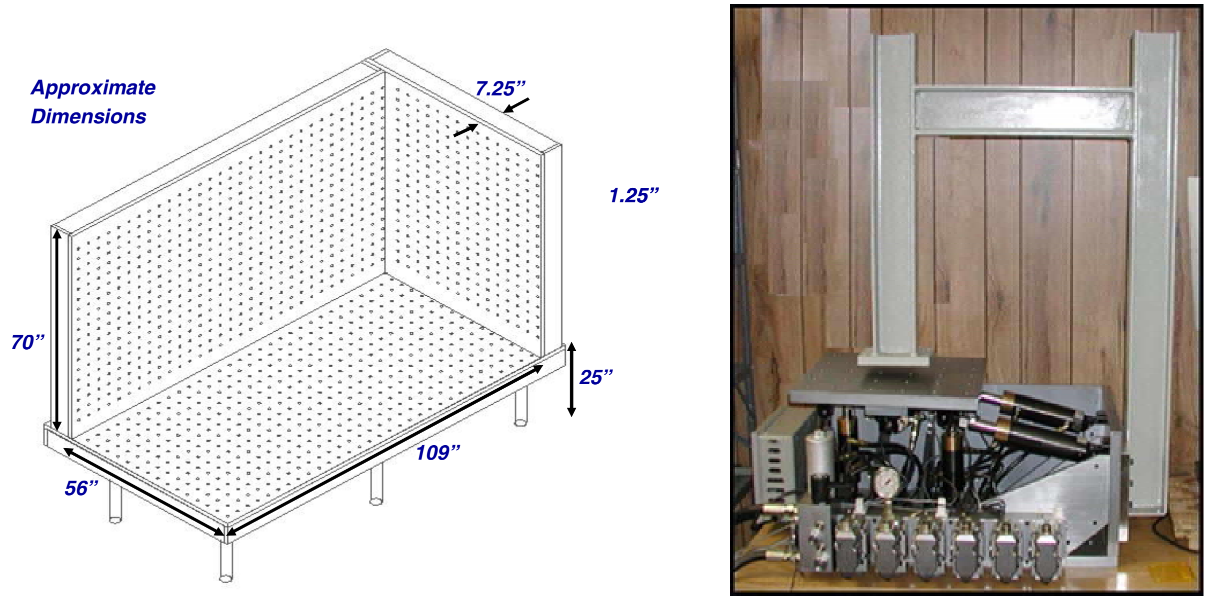



Figure 13 Control Software Framework

**1/5th Scale Laboratory and User Studio**

A fully functional 1/5th scale laboratory includes 1/5th scale reaction structure (Figure 14 (a)) with 1/5th scale LBCBs with Gamma Specimen (Figure 14 (b)) and dedicated load controllers. The 1/5th scale laboratory will allow users with diverse research backgrounds to have full access to the MUST-SIM facility and to understand the capability and limitation of the facility, and train users in use of non-contact measurement systems. Also, the laboratory will provide the pre-test verifications. Various load and deformation scenarios can be tested interactively, and cautionary notes are given to the user if the constraints of the LBCB are encountered. The 1/5th Scale-Model laboratory is located in the User Studio. This 1400 square foot studio is located immediately adjacent to the L-Shaped Strong Wall. It also contains office space for researchers, space for storage of measurement systems, the MUST-SIM load control system, and a data-visualization environment.

Visualization capacity in the User Studio provides advanced data visualization to users of the MUST-SIM facility, enabling video teleconferences with remote participants. The MUST-SIM local area network (LAN) is shown in Figure 15. Such data visualization includes visualization of experimental test data created by the contact and non-contact instrumentation methods, and visualization of the integration and interpretation of multiple experimental test data sets. Equipped with the state-of-the-art technologies of multimedia and remote telerobotic video system, the visualization studio will have extensive abilities of teleoperation and telepresence through the local network and NEESgrid. This will allow for effective communication among researchers in the studio, on the laboratory floor, and participants from other institutions and organizations. It also enables synchronous and asynchronous monitoring of the preparation and construction of tests and test specimens. Through the NEESgrid telepresence mode, the E-Notebook can be used to document and distribute the experimental data and metadata.




(a) 1/5th scale Reaction Structure

(b) 1/5$^{th}$ scale LBCB with Gamma Specimen

Figure 14 1/5$^{th}$-scale Laboratory

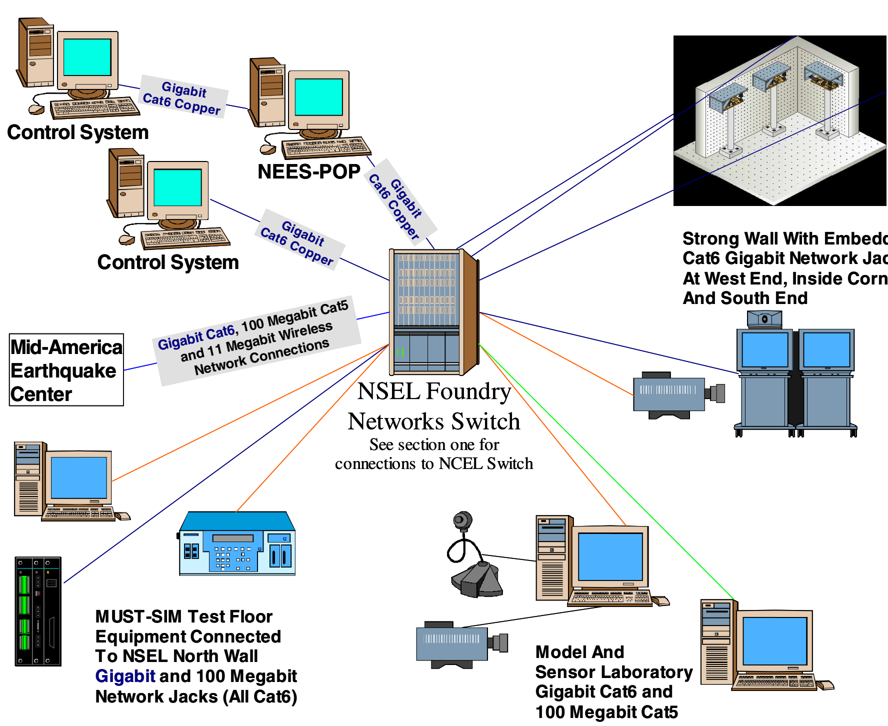



Figure 15 MUST-SIM Facility LAN

**Mini-MOST**

The Mini-MOST is developed and manufactured by NEES System Integration Team at the University of Illinois at Urbana-Champaign. The Mini-MOST is a fully functional scaled-down MOST. It can demonstrate the system integration which combined physical experiments with analytical simulation. It can also deploy the NEESgrid cyberinfrastructure (Figure 16).

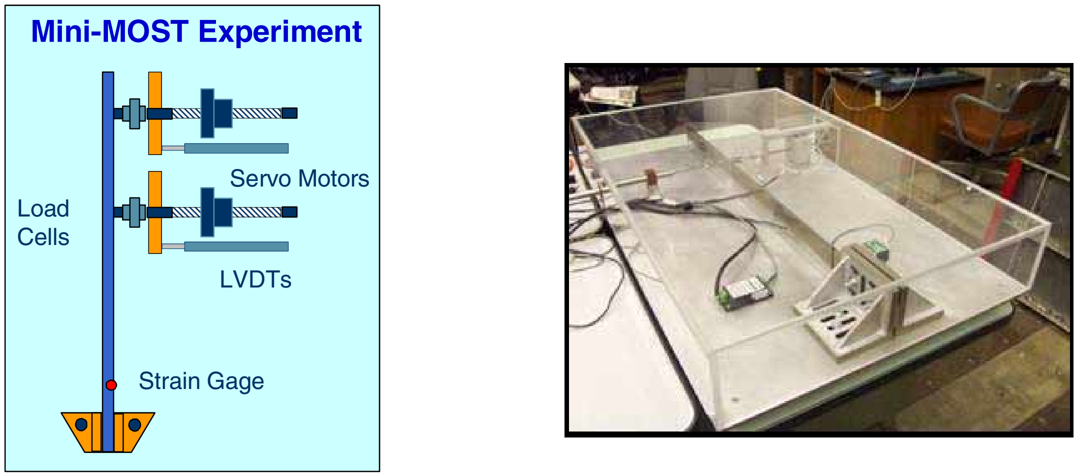



Figure 16 Mini-MOST experiment

After a Mini-MOST demonstration, users can fully understand the multi-site integrated physical-analytical simulations and learn the NEESgrid software. Mini-MOST is much easier to deploy NEESgrid in other NEES equipment sites and among international partners due to its small size. Currently, the effort of deployment of Mini-MOST to Kajima Corporation in Japan is led by the NEESgrid SI team and the NEES MUST-SIM team at UIUC.

## CONCLUSION

As one of the fifteen NEES experiment sites, the MUST-SIM facility will provide a state-of-the-art environment for conducting distributed pseudo-dynamic testing of multi-axial full-scale structural and soil-structure interaction testing with realistic boundary conditions coupled with advanced analysis for sub-structuring of systems and data visualization capabilities. Hence, the facility will stimulate new and unique approaches to address earthquake engineering assessment through a collaborative shared-use testing environment. Several examples of potential applications have been presented in the paper, based on recent developments by the MUST-SIM team on integrating structural and geotechnical analysis and testing. The components of the facility with the operational capabilities and functionalities through NEESgrid lay the groundwork for the research, education and outreach. It offers the opportunity to breach traditional disciplinary barriers and to overcome the logistical and technical complexities of inter-disciplinary research.

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