Ninth Canadian Conference on
Earthquake Engineering
Ottawa, Ontario, Canada
26-29 June 2007

UI-SIMCOR : A GLOBAL PLATFORM FOR HYBRID DISTRIBUTED SIMULATION

O. Kwon[1], A.S. Elnashai[2], B.F. Spencer, Jr.[3], and K. Park[4]

ABSTRACT

Assessment of complex systems under extreme loads continues to be a formidable challenge that hampers development of effective mitigation, response and recovery measures. Neither modern laboratory testing nor advanced computer simulations are able on their own to respond to this challenge. Laboratory testing is restricted by issues of scale (e.g., a long bridge) whilst computer simulation is inadequate in representing certain important failure modes (e.g., shear in concrete). Moreover, within the testing community, it is recognized that not one single laboratory has the features of all others, while the computer simulation community recognizes the relative merits of different analysis software packages. A new framework has been established at the University of Illinois for combining seamlessly any number of testing sites with an unlimited number of analysis software packages in one single integrated hybrid (testing-analysis) distributed (different geographical locations) simulation of complex systems. The framework, UI-SimCor, communicates with sites and programs through application program interfaces to integrate contributions from the various components of a complex system, such as a dam with fluid, buttresses and soil, or a bridge with abutments, piles and soil. The paper outlines the concept underlying UI-SimCor, its communication mechanisms and scope of application. Two application examples are given. The first is a three-site hybrid simulation conducted to verify the applicability of the developed framework on multiple sites. The second example is a hybrid simulation of large scale bridge piers at University of Illinois and at Lehigh University. The hybrid simulation experiments proved versatilities and potential of the developed framework. The UI-SimCor is freely available for use without restrictions and is effective in detailed and advanced assessment of complex systems under static and dynamic loading conditions.

Introduction

Analytically-oriented researchers have been developing applications to predict structural response based on principles of mechanics and/or observational-empirical data utilizing readily accessible computational resources. The ensuing analytical platforms are diverse in nature and have excellent problem-solving

[1]Graduate Research Assistant, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801. okwon2@uiuc.edu
[2]Bill and Elaine Hall Endowed Professor, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801. aelnash@uiuc.edu
[3]Nathan M. and Anne M. Newmark Endowed Chair, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801. bfs@uiuc.edu
[4]Post Doctoral Researcher, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801. kspark@uiuc.edu

capabilities. Unfortunately, most or even all of these developments are limited to solving a specific set of relatively narrow problems of components within complex structural systems. An approach that has the minimum assumptions and provides the best available option is to model each component using the most suitable analytical model and integrating the various contributions into a fully interacting system. Whereas in theory the objective of accounting for interacting inelastic components could be achieved within one analysis platform, this possibility is not achievable with any existing package, and is unlikely to happen in the near future. It is indeed a fact that different analysis programs exhibit strengths and weaknesses and that combining programs with no restrictions placed on the selection is the obvious and only way forward.

Laboratory tests are one of the three fundamental sources of knowledge from which understanding of the behavior of structural systems can be attained; the other being field observations and analytical simulations. Due to the dimensions of civil engineering structures, such as buildings, bridges and utility networks, experiments are usually conducted on the most vulnerable components of a system and often at a reduced scale. Currently, the number of full scale complete structure tests is very limited. Examples of full scale system tests are Negro et al. (1996), Molina et al. (1999), Pinho and Elnashai (2000), Chen at al. (2003), and Jeong and Elnashai (2005). Even in the aforementioned cases, the foundations and soil were not modeled. A system by which a number of laboratories could combine their capabilities to undertake a set of integrated component tests of structural and geotechnical elements for example would provide an exceptionally attractive option for assessment of complex interacting systems with neither the assumptions necessary for conducting stable inelastic dynamic analysis, nor the limitations of small scale testing that would be required to fit all components into one laboratory.

The case is made above for distributed analysis, in contrast to using one analytical platform, and distributed testing, in contrast to using one experimental facility. There also exists a combination between the two, once the concept of a distributed representation is accepted. This 'Hybrid Simulation' approach has been subject to extensive research in recent years, (Watanabe et al. 1999, NSF 2000, Tsai et al. 2003, Kwon et al. 2005, Pan et al. 2005, and Takahashi et al. 2006). It has hitherto remained, however, a rather arduous task that requires extensive knowledge of both experimental and analytical tools, their detailed input-output requirements, and necessitates considerable programming effort. The procedures have indeed not been sufficiently robust and had therefore remained in the advanced research domain, not in the persistent application domain.

This paper addresses the above problem and proposes a simple, transparent and fully modular framework that allows the utilization of analytical platforms alongside experimental facilities for the integrated simulation of a large complex system. Whereas the framework presented is simple and intuitive, its impact on structural and geotechnical research is substantial. The approach utilizes pseudo-dynamic (PSD) simulation, distributed analysis and experimentation. It enables the combination of unique analysis applications in various fields and promotes collaboration of nationally and internationally distributed experimental and analytical simulation sites interested in large complex systems. The framework presented in this paper is an extension of the previous development by Kwon et al. (2005). The following section provides brief conceptual background on the framework followed by the architecture and dataflow of the development. There have been several experimental and analytical applications of the developed framework. Among those, two representative experimental examples are introduced with summary of the potential of the framework.

Theoretical Formulation and Implementation

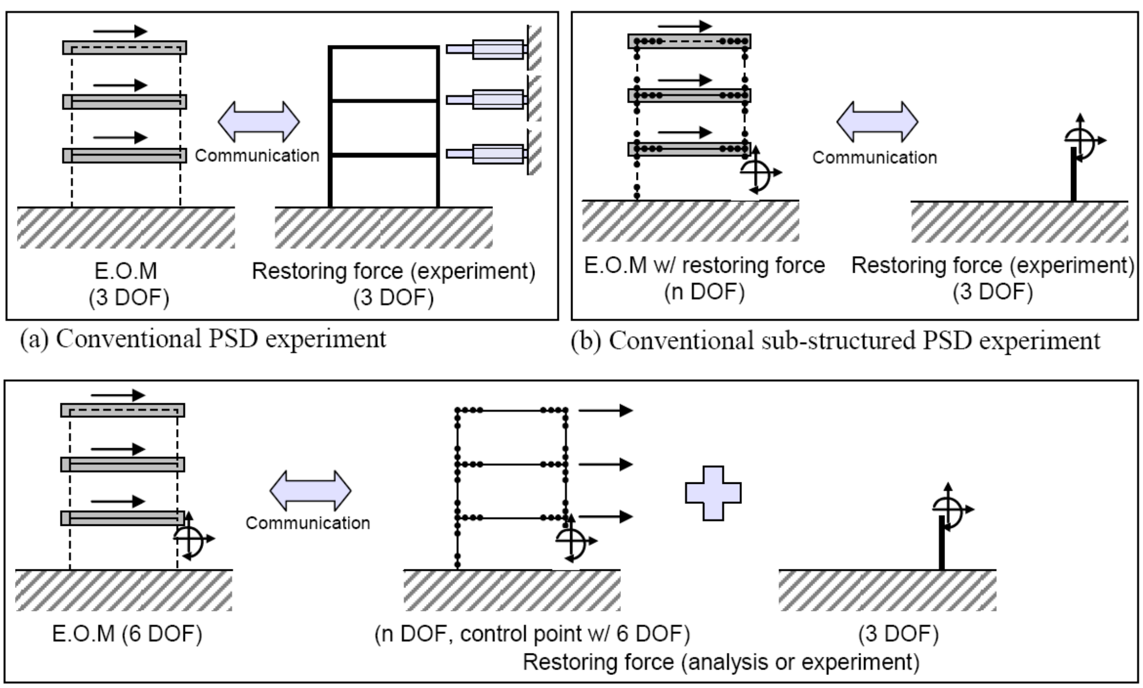
The concept and architecture of a framework for multiplatform hybrid simulation is reviewed in this section. The developed framework is based on PSD simulation which has been conducted in many research institutes in the past. The conventional approaches, however, are limited to a specific experimental setup or to a specific analysis platform for which the PSD simulation is developed. The proposed framework in this study allows generic combination of various analysis platforms and experimental sites by employing widely adopted communication protocols, as well as a transparent and object oriented program architecture.

Conceptual Background

PSD test methods have been investigated by researchers for more than thirty years. One of the earliest developments of the PSD method was by Takanashi et al. (1975), which has evolved toward substructure (Dermitzakis and Mahin 1985) and distributed PSD test (Watanabe et al. 2001). In these conventional PSD methods predicted displacements are imposed and measured restoring forces are used in the time integration scheme. These methods are in mature state in comparison with newly explored PSD test field such as real time testing (Nakashima et al. 1992 and Juan and Spencer 2006), continuous PSD testing (Takanashi and Ohi 1983), and effective force testing (Dimig et al. 1999). The proposed framework adopted conventional PSD testing scheme with its well established theory.

In a conventional PSD test, the structural mass, damping, and inertial forces are defined within a computational module. The predicted structural deformation at the control points is statically applied to a structure to estimate the restoring force vector. In a conventional PSD test of a whole structure, such as the three-storey frame depicted in Fig. 1 (a), degrees of freedom (DOFs) with lumped masses are included in the equations of motion. If the three-story structure is pseudo-dynamically tested, it is assumed that the mass of each floor can be lumped at a single control point, and one actuator per story is normally used to apply inertial forces, for planar structures. Thus the computational module handles the equations of motion with three translational DOFs.

The experimental specimen for the PSD test may also be represented numerically, as shown in Fig. 1 (c). The analytical model may use refined meshes to capture propagation of damage. Hence the model may include a larger number of DOFs than the equations of motion where only the DOFs with lumped masses are used. The predicted displacements at the control points are applied, and the restoring forces at these points are returned to the equations of motion. Where substructuring is required, force equilibrium and displacement compatibility should be satisfied at interfaces between substructured components. Hence, the control points should include nodes at interfaces, as well as nodes with lumped masses. The equations of motion subject to time integration should also include DOFs at lumped masses and interface nodes.



(c) Proposed Sub-structured PSD simulation

Figure 1. Substructuring of PSD Simulation.

When testing a critical element and analyzing the rest of the structure, substructured PSD simulation should be used. In the conventional approaches for substructured PSD simulation, a single analysis platform is combined with a time integration module, as shown in Fig. 1 (b). This approach is adequate if the adopted analysis platform can represent the true structural responses. In most situations, however, the analytical platform is limited to dealing with a simple nonlinear model. By completely separating the restoring force modules from the time integration scheme, and by allowing an unhindered combination of restoring forces from various analytical modules, a complex structural system can be accurately modeled. In the proposed framework, the PSD test algorithm itself is identical to the conventional method. But the way it combines several restoring force modules, whether analytical or experimental, and the communications between modules are the most distinctive characteristics of the development. The architecture of the framework, communication protocols, and simulation procedure are introduced in the following sections.

System Software Architecture

The basic concept of the framework is that analytical models associated with various platforms or experimental specimens are considered as a super-element with many DOFs. Each of these elements are solved on a single computer or on different computers connected through the network. Figure 2 illustrates the overall architecture of the framework, termed UI-SimCor. The main routine shown in the figure enforces equilibrium and conducts dynamic time integration. In this process, the structural model is fully encapsulated as objects of a class. Hence it is straightforward to add new time integration or methods to enforce static equilibrium.

There are two classes in UI-SimCor: MDL_RF (restoring force module) and MDL_AUX (auxiliary module). The objects of MDL_RF class represent structural components. The main functionality of this class is abstraction of the structural components at remote sites. The main routines such as dynamic integration schemes impose displacement onto the structural components and retrieve restoring forces without consideration of communication with remote sites regardless of whether the components are experimental specimens or analytical models. This abstraction allows exceptionally easy implementation of new simulation tools and components.

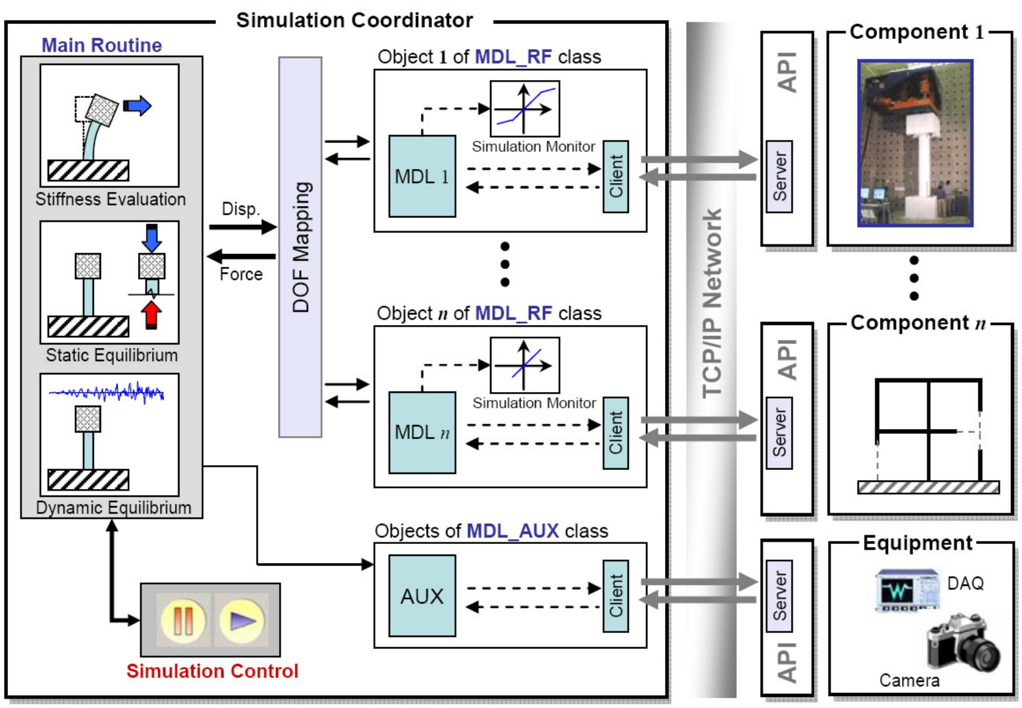


Figure 2. Architecture of proposed framework.

Another important functionality of the MDL_RF class is communication. When the main analysis routines impose a displacement on a structural component represented by an object of MDL_RF class, the object reformats the data for the pre-specified protocol, opens connections to the remote sites, and sends the reformatted data. Six types of communication protocols are implemented in the current release. These are introduced in the following section. MDL_RF class includes other functionalities such as checking force and displacement capacities at every time step. In addition, the object of MDL_RF class shows the communication status and monitors communicated values at each time step. MDL_AUX class is used to control experimental hardware other than actuators. The object of this class has a function to send out pre-specified commands to remote sites. Upon reception of the command, the remote sites can take actions such as taking pictures or triggering data acquisition.

At remote sites, it is necessary to have an Application Program Interface (API) which open ports for connection from main framework, impose displacements to analytical model or experimental specimen, and send measured data. The APIs for analytical platforms have been developed for Zeus-NL (Elnashai et al. 2004), OpenSees (McKenna and Fenves 2001), FedeasLab (Filippou and Constantinides 2004), and ABAQUS (Hibbit et al. 2001). The API for VecTor2 (Vecchio and Wong 2003) is under development.

Simulation Procedure and Data Flow

A typical simulation procedure where three communication layers are labeled as ‘User’, ‘Simulation Framework’, and ‘Remote Sites’ is illustrated in Fig. 3. The user of the hybrid simulation framework initiates the procedure, monitors its current status, and pauses the simulation whenever necessary based on the warning messages. The simulation framework is responsible for initialization, stiffness estimation, time integration, and communication with remote sites. The remote sites are responsible for running analysis or experiments under the commanded displacements and returning the measured resistance. The simulation procedure shown in Fig. 3 is for a configuration with the Network for Earthquake Engineering Simulation (NEES) Telecommunication Control Protocol (NTCP) described in the next section. The data flow shown in Fig. 3 may vary depending on the protocols or simulation configuration used.

Communication Protocols

The communication through the network following standard protocol is one of the most important requirements for geographically distributed hybrid simulations. In the proposed framework, six communication protocols are implemented: NTCP, LabView1, LabView2, TCP/IP, NEES Hybrid Simulation Communications Protocol (NHCP), and a protocol for OpenFresco (Takahashi and Fenves 2006). To promote collaboration of equipment sites across the USA, NEES consortium has developed a standard communication protocol, NTCP (NEESgrid Teleoperation Control Protocol, Pearlman et al. 2004). NTCP allows secure communications between remote sites through the NTCP server. LabView1 and LabView2 protocols are communication protocol for which data are exchanged in ASCII format. The ASCII format data is very practical as all commands and values can be easily interpreted. But the format requires significant overhead as it needs to convert data from binary format to ASCII format at every simulation step. And also the converted data demand much larger network traffic. Thus in addition to these protocols, a binary format communication protocol, referred as TCP/IP in UI-SimCor, is also implemented. In the past few months, NEESit has been developing a NHCP protocol, a successor of NTCP. The earliest version of NHCP is also implemented in UI-SimCor. UI-SimCor can communicate with OpenFresco (Takahashi and Fenves 2006) which provides a versatile interface to control experimental equipments. In addition to these already implemented communication protocols, any other protocols can be easily implemented. These versatilities in communication allow potential involvement of wide range of equipment sites and analysis platforms.

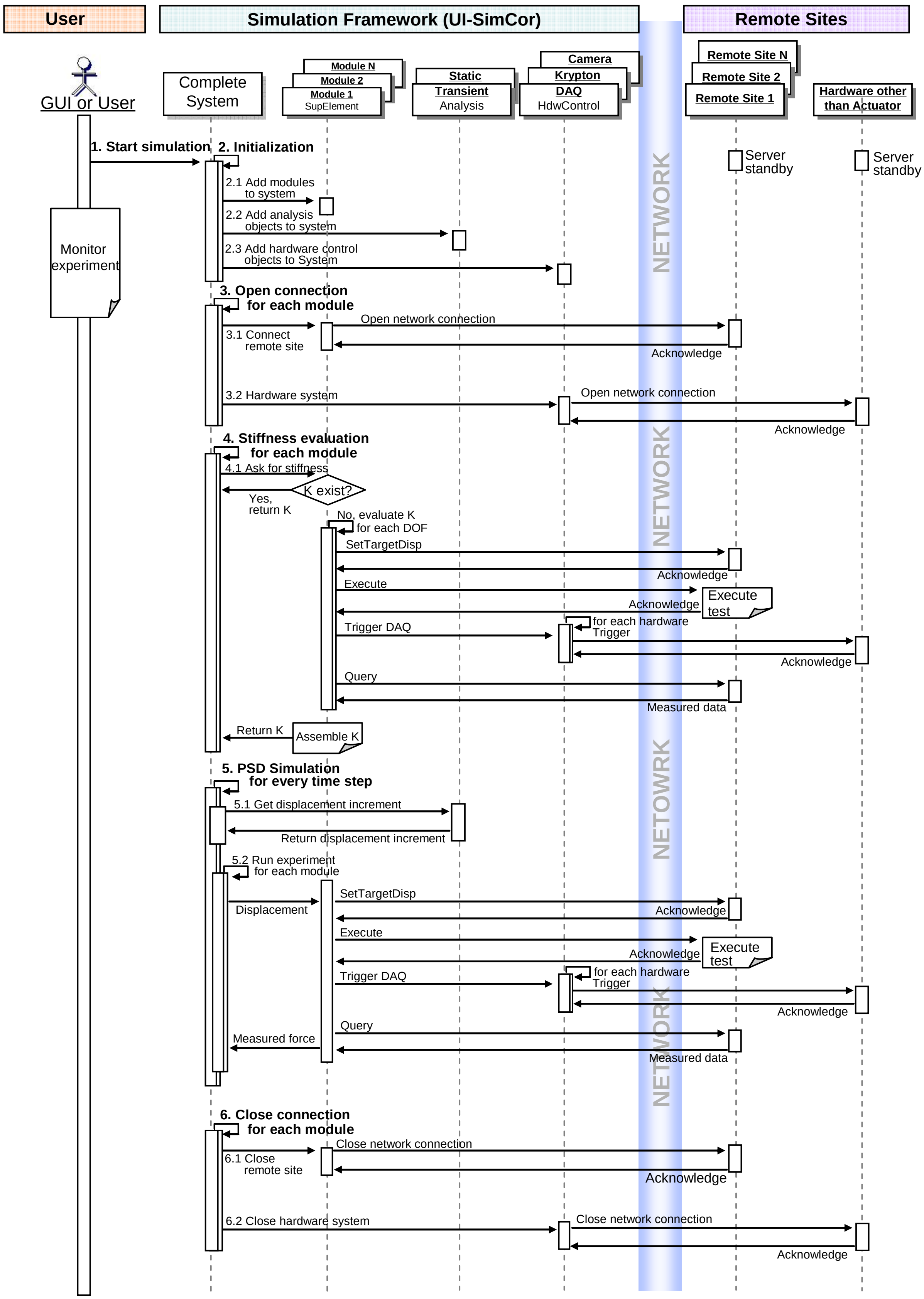


Figure 3. Simulation procedure and data flow.

Framework Validation with Three-Site Hybrid Simulation

The main objective of the three-site hybrid simulation example (NEESit Phase I project) is to verify the proposed framework and checks the compatibility of the framework with other experimental sites. Three sites are involved in this project: University of Illinois at Urbana-Champaign (UIUC), University of California at Berkeley (UCB), and San Diego Supercomputer Center (SDSC). Each experimental site is equipped with a small testing facility developed for the verification of a hybrid simulation; MiniMOST 1 (Gehrig 2004) at UIUC and SDSC, μ-NEES (Schellenberg and Mahin 2006) at UCB. The MiniMOST 1 specimens behave in linear elastic range while the specimen in μ-NEES behaves fully in inelastic range. It is considered that the experimental specimens from three sites represent piers of a bridge. The remaining structural elements are modeled in Zeus-NL, Fig. 4. Simulation was carried out at the rate of 6.5 sec/step. The slow simulation rate is resulted from Mini-MOST 1 at UIUC and SDSC as those equipments consume few seconds to stabilize load cells to get good measurements. Figure 5 compares the responses from three-site experiment and PSD simulation with analytical model of experimental equipments. The experimental result is very close to analytical simulation result. The slight difference is caused by inaccurate representation of inelastic behavior of μ-NEES with hysteretic spring model. This project verified that the proposed framework runs reliably with minimum efforts for customization at each remote site.

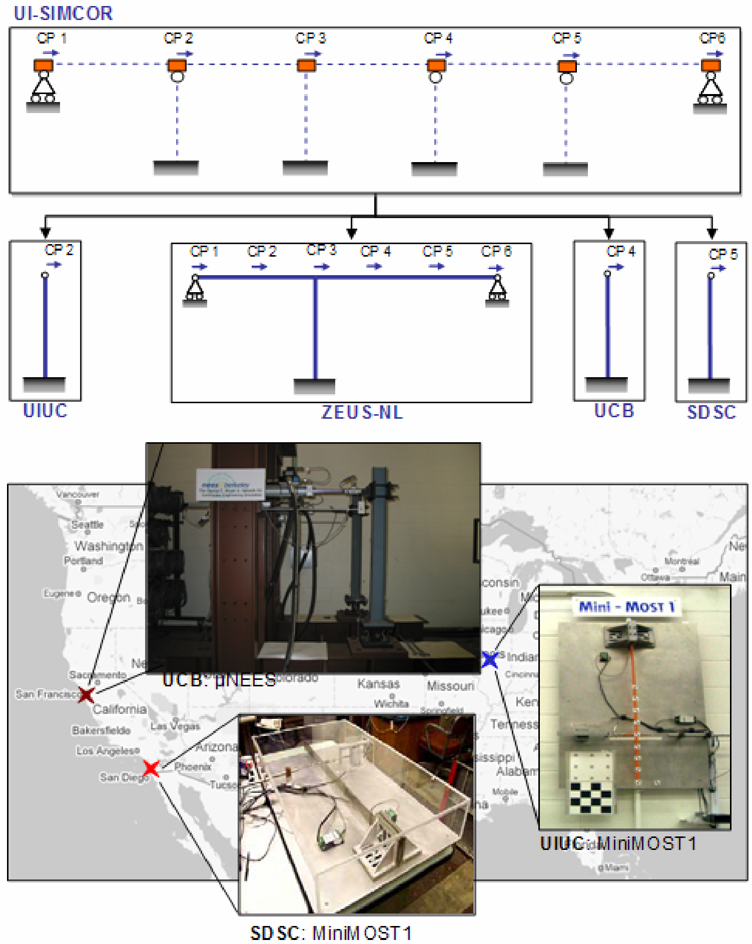


Figure 4. Simulation configuration of three-site experiment.

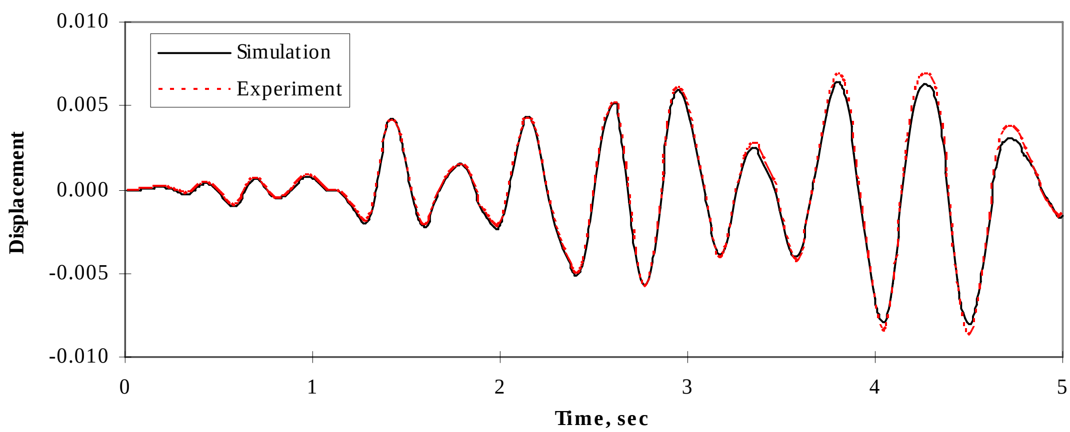


Figure 5. Comparison of analytical and experimental results.

Multi-Site Soil-Structure-Foundation Interaction Test

The main objective of MISST (Multi-Site Soil-Structure-Foundation Interaction, Spencer et al. 2006) project was to demonstrate the potential of NEES to investigate systems that could not be studied before by running on-line hybrid simulation of a structural-geotehcnical system. The tested bridge is based on the Collector-Distributor 36 of the I-10 Santa Monica Freeway that was severely damaged during Northridge Earthquake in 1994. In this experiment, two experimental sites (one pier in UIUC and another pier in Lehigh University, LU) and two analytical models (geotechnical model in Rensselaer Polytechnic Institute, RPI, and structural model in UIUC) are integrated using UI-SimCor. To satisfy capacity limitations of test equipment, a ½ scale model of prototype pier was constructed and tested at UIUC. The diameter of tested specimen was 24 inches with reinforcement ratio of 3.11% and 0.176% for longitudinal and transverse direction. Several hybrid simulations were carried out. These simulations included both small and large amplitude tests. The small amplitude test was intended to verify the functionality of all components and equipment while the large amplitude tests were intended to replicate the observed damage in the prototype structure. Two earthquake records that were captured during the Northridge earthquake of 1994 were employed during these simulations. The first record was strong motion data collected at the Santa Monica City Hall which had a peak ground acceleration (PGA) of 0.37g. The second record was collected at the Newhall Fire Station and had a PGA of 0.58g. In both cases, the acceleration record was applied along the longitudinal direction of to the bridge structure.

The coordination and communication of the three sites, UIUC, Lehigh, and RPI, for the five component hybrid and geographically distributed simulation worked seamlessly. Despite their brittle nature, the simulation was able to continue on well past the initial shear failures observed at both the UIUC and Lehigh sites. Furthermore, the redistribution of forces between the two sites with the bridge piers as either of the two suffered partial failure shows that full interaction was taking place between the distant sites. Thus the simulation system which includes all NEESgrid components, UI-SimCor, the analytical modules, and all experimental equipment and components at both UIUC and Lehigh proved to be quite effective and robust. Moreover, the failure modes obtained are similar to those in the prototype observed following the 1994 Northridge earthquake. Thus, the observed and complex field behavior of a complicated structural system was successfully reproduced. Not only does this create an opportunity to address or propose new design approaches for bridge structures, but also clearly demonstrates how NEES can be applied to address problems which have previously been unapproachable to the earthquake engineering community.

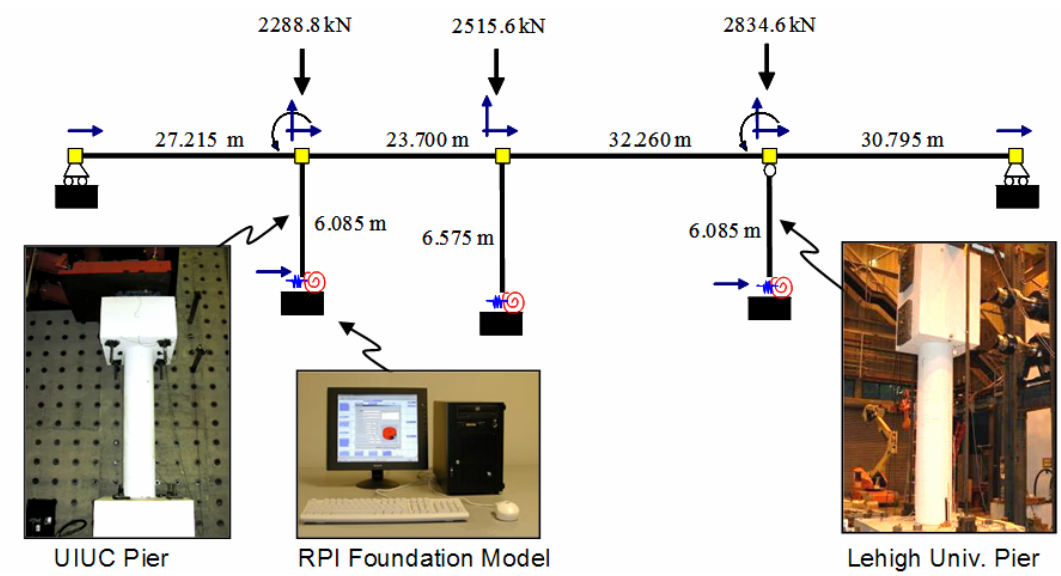


Figure 6. Experiment configuration of MISST project.

Conclusions

In this paper, a framework for multi-platform distributed earthquake simulation is described. The framework allows concurrent utilization of various analysis platforms each of which is deemed the best environment for modeling a specific feature of the complex interacting system. For example, the geotechnical constitutive relationships implemented in OpenSees may be combined with the powerful fiber-based analysis capabilities of Zeus-NL to provide the most appropriate and accurate assessment procedure. The object-oriented program architecture allows extremely simple extension of the framework to new integration schemes or analysis methods. The framework has been verified through various hybrid experimental-analytical studies as well as simulation investigations. In the current paper, two distinct hybrid simulations are introduced to demonstrate the potential of the proposed framework. One of the examples involved three experimental sites distributed across U.S. Each experimental specimen is assumed as a pier of a bridge. Remaining bridge is represented by an analytical model in Zeus-NL. The hybrid simulation proved that the framework can be easily applied to multiple equipment sites. The other example involved large scale piers of Santa Monica Bridge under combined loading condition (shear-flexural-axial load). A system behavior of a bridge with multiple of real piers has not been readily tested in the past. The UI-SimCor easily accommodated two large scale piers distributed in UIUC and Lehigh University. The failure the piers was dominated by shear failure similar to the actual failure mode of Santa Monica Bridge. The developed framework opens up extremely large opportunities for potential collaborative research in analysis, experiment, and hybrid simulation. The proposed framework, UI-SimCor, is available for download from http://neesforge.nees.org/ projects/simcor/.

Acknowledgments

This research was supported by Mid-America Earthquake Center project EE-3, the NEES project at UIUC and NEES Inc. The Mid-America Earthquake Center is an Engineering Re-search Center funded by the National Science Foundation under cooperative agreement reference EEC-9701785. NEES at UIUC is funded by the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) program of the National Science Foundation un-der award reference CMS-0217325 and NEESgird is funded by the same NSF Program, award reference CMS-0117853.

References

Chen, C.-H., Lai, W.-C., Cordova, P., Deierlein, G. G., and Tsai, K.-C., 2003. Pseudo-Dynamic Test of Full-Scale Rcs Frame:Part 1 - Design, Construction and Testing. *Proceedings of International Workshop on Steel and Concrete Composite Constructions*, Taipei, Taiwan, 107-118.

Dermitzakis, S. N., and Mahin, S. A., 1985. Development of substructuring techniques for on-line computer controlled seismic performance testing. *Report UCB/EERC-85/04*, Earthquake Engineering Research Center, University of California, Berkeley.

Dimig, J., Shield, C., French, C., Bailey, F., and Clark, A., 1999. Effective force testing: A method of seis mic simulation for structural testing. *Journal of Structural Engineering*. 125(9): 1028-1037.

Elnashai, A. S., Papanikolaou, V. and Lee, D. H., 2004, Zeus-NL -A System for Inelastic Analysis of Structures" MAE Center CD-Release 04-01.

Filippou, F. C., and Constantinides, M., 2004. FEDEASLab Getting Started Guide and Simulation Examples. Technical Report NEESgrid-2004-22: www.nees-grid.org.

Gehrig, D. 2004. Guide to the NEESgrid Reference Implementation. *NEESgrid TR-2004-04*

Hibbit, Karlsson, and Sorensen., 2001. ABAQUS *theory manual. Version 6.2*.

Jeong, S., and Elnashai, A. S., 2005. Analytical Assessment of an Irregular RC Frame for Full-Scale 3D Pseudo-Dynamic Testing. Part I: Analytical Model Verification. *Journal of Earthquake Engineering*, 9(1), 95-128.

Juan, C., and Spencer, B. F., 2006. Real-Time Hybrid Testing Using Model-Based Delay Compensation. Proceedings of 4th International Conference on Earthquake Engineering, Taipei, Taiwan.

Kwon, O. S., Nakata, N., Elnashai, A. S., and Spencer, B., 2005. A Framework for Multi-Site Distributed Simulation and Application to Complex Structural Systems. *Journal of Earthquake Engineering*, 9(5), 741-753.

McKenna, F., and Fenves, G. L., 2001. The OpenSees command language manual, version 1.2. Pacific Earthquake Engineering Research Center, Univ. of California at Berkeley.

Molina, F. J., Verzeletti, G., Magonette, G., Buchet, P., and Geradin, M., 1999. Bi-Directional Pseudodynamic Test of a Full-Size Three-Storey Building. *Earthquake Engineering and Structural Dynamics*, 28, 1541-1566.

Nakashima, M., Kato, H., and Takaoka, E., 1992. Development of Real-Time Pseudo Dynamic Testing. *Earthquake Engineering and Structural Dynamics*, 21(1), 79-92.

National Science Foundation, 2000. Network for earthquake engineering simulation (NEES): system integration, program solicitation. Report NSC00-7, U.S.A.

Negro, P., Pinto, A. V., Verzeletti, G., and Magonette, G. E., 1996. PsD Test on Four-Story R/C Building Designed According to Eurocodes. *Journal of Structural Engineering*, 122(12), 1409-1471.

Pan, P., Tada, M., and Nakashima, M., 2005. Online hybrid test by internet linkage of distributed test-analysis domains. *Earthquake Engineering and Structural Dynamics*, 34, 1407-1425.

Pearlman, L., D'Arcy, M., Johnson, E., Kesselman, C., and Plaszczak, P., 2004. NEESgrid Teleoperation Control Protocol (NTCP). Technical Report NEESgrid-2004-23.

Pinho, R., and Elnashai, A. S., 2000. Dynamic Collapse Testing of a Full-Scale Four Storey RC Frame. ISET *Journal of Earthquake Technology*, 37(4), 143-163.

Schellenberg, A., and Mahin, S., 2006. Integration of Hybrid Simulation within the General-Purpose Computational Framework OpenSees. 100th Anniversary Earthquake Conference Commemorating the 1906 San Francisco Earthquake.

Spencer Jr., B. F., Elnashai, A., Kuchma, D., Kim, S., Holub, C., and Nakata, N., 2006. Multi-Site Soil-Structure-Foundation Interaction Test (MISST). University of Illinois at Urbana-Champaign.

Takahashi, Y., and Fenves, G. L., 2006. Software framework for distributed experimental-computational simulation of structural systems. *Earthquake Engineering and Structural Dynamics*, 35, 267-291.

Takanashi, K., Udagawa, K., Seki, M., Okada, T., and Tanaka, H., 1975. Nonlinear earthquake response analysis of structures by a computer-actuator on-line system." Bulletin of Earthquake Resistant Structure Research Centre, No. 8, Institute of Industrial Science, University of Tokyo, Japan.

Takanashi , K., and Ohi, K., 1983. Earthquake response analysis of steel structures by rapid computer-actuator online system, (1) a progress report, trial system and dynamic response of steel beams. Bull. Earthquake Resistant Struct. Research Center (ERS), Inst. of Industrial Sci., Univ. of Tokyo, Tokyo, Japan, 16: 103-109.

Tsai, K., Hsieh, S., Yang, Y., Wang, K., Wang, S., Yeh, C., Cheng, W., Hsu, C., and Huang, S., 2003. Network Platform for Structural Experiment and Analysis (I). NCREE-03-021, National Center for Research on Earthquake Engineering, Taiwan.

Vecchio, F. J., and Wong, P., 2003. VecTor2 and FormWorks Manual.

Watanabe, E., Kitada, T., Kunitomo, S., and Nagata, K., 2001. Parallel pseudodynamic seismic loading test on elevated bridge system through the Internet. The Eight East Asia-Pacific Conference on Structural Engineering and Construction, Singapore.

Watanabe, E., Sugiura, K., Nagata, K., Yamaguchi, T., and Niwa, K., 1999. Multi-phase Interaction Testing System by Means of the Internet. Proceedings of 1st International Conference on Advances in Structural Engineering and Mechanics, Seoul, Korea, 43-54.