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A framework for distributed analytical and hybrid simulations

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Abstract. A framework for multi-platform analytical and multi-component hybrid (testing-analysis) simulations is described in this paper and illustrated with several application examples. The framework allows the integration of various analytical platforms and geographically distributed experimental facilities into a comprehensive pseudo-dynamic hybrid simulation. The object-oriented architecture of the framework enables easy inclusion of new analysis platforms or experimental models, and the addition of a multitude of auxiliary components, such as data acquisition and camera control. Four application examples are given, namely; (i) multi-platform analysis of a bridge with soil and structural models, (ii) multi-platform, multi-resolution analysis of a high-rise building, (iii) three-site small scale frame hybrid simulation, and (iv) three-site large scale bridge hybrid simulation. These simulations serve as illustrative examples of collaborative research among geographically distributed researchers employing different analysis platforms and testing equipment. The versatility of the framework, ease of including additional modules and the wide application potential demonstrated in the paper provide a rich research environment for structural and geotechnical engineering.

Keywords: hybrid simulation; multi-platform analysis; pseudo-dynamic testing.

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1. Introduction and motivation

1.1 The challenge facing earthquake assessment of complex systems

Reliable earthquake response assessment of complex interacting systems remains a major challenge facing researchers and practitioners. Achieving safety by unquantifiable over-design is both uneconomical and irrational. In a risk-aware society, there is a pressing need to achieve a degree of uniformity in design by developing systems with uniform reliability with pre-determined non-catastrophic failure modes. The latter objectives can only be achieved by accurate prediction of action and deformation resistance at a number of response limit states that span from serviceability to collapse.

Analysts aim to duplicate experimental results, assuming that an experiment is 'reality', since they are often not aware of the various issues in the laboratories which may affect experiment result. On the other hand, experimentalists believe that analysts have a relatively straightforward task since they can model whichever features are deemed important by suitable formulations and mechanical representations It is an issue of fundamental importance to appreciate that neither testing nor analysis on its own can provide the best possible system assessment under complex loading such as earthquake ground motion. The situation can be much improved if the best features of each of the two possible approaches of testing and analysis are somehow combined. Moreover, a single analysis platform is unlikely to effectively represent a sufficiently wide range of complex loading, materials and their interaction deep into the inelastic range. Likewise, there is not a single laboratory that can effectively test all types of members, connections and systems under most of the envisioned types of load combinations. It therefore follows that dividing a complex structure into several substructures, representing each substructure with most suitable analytical or experimental model, and integrating these substructures provide an opportunity to understand complex system behavior hence aim to achieve uniformly reliable design against earthquake effects. This line of argument presented herein is expanded upon in subsequent sections of this paper.

1.2 Analysis platforms

Analytically-oriented researchers have been developing applications to predict structural and geotechnical response based on principles of mechanics and/or empirical data utilizing readily accessible computational resources. The ensuing analytical platforms (i.e., various research and commercial finite element, discrete element and infinite element analysis codes, for example) are diverse in nature and have excellent problem-solving capacities. Unfortunately, most or even all of these developments are limited to solving a specific set of problems. For instance, one of the best programs available for the analysis of reinforced concrete panels (Vector; Vecchio and Wong 2003) lacks features to represent steel members, isolation devices or foundation materials. Also, a complex high-rise structure with concrete shear walls and moment frames cannot be modeled using only fiber-based frame elements such as in Zeus-NL (Elnashai *et al.* 2002) or OpenSees (McKenna and Fenves 2001) that do not posses the wide range of concrete constitutive relationships that the program Vector offers. A widely used approach for such complex systems is to use substructuring, static condensation, and back-substitution of stiffness matrices of the various substructures. Because it is based on super-position, the conventional substructuring approach is well suited for large elastic systems and is thus of limited use in inelastic earthquake response analysis. Another often used approach is to evaluate the loading and boundary conditions from a system analysis, then to apply these to the various components in a separate analysis. This approach may be practical and reliable as long as the elements can be fully uncoupled from the system and that the load and boundaries are not affected by changes in stiffness of the constituent components.

An approach that has minimum assumptions and provides a wide range of options is to model each component using the most suitable analytical model and analysis environment, followed by integrating the various contributions into a whole system. This approach is different from conventional substructuring where analysis is undertaken per component independently, followed by a back-substitution step. Herein, substructuring is to analyze the different components in parallel hence all interaction effects are taken into account. Whereas in theory the objective of accounting for interacting inelastic components could be achieved inside one analysis platform, this is not readily achievable with any one existing package. For instance, experts in soil dynamics may develop applications with the state-of-the-art soil material model. But the application would not include capabilities to analyze reinforce concrete or steel structures. It is indeed a fact that different analysis programs exhibit strengths and suffer from weaknesses, and that combining programs with no restrictions placed on the selection widely expands capability of a single program.

1.3 Laboratory testing

Laboratory tests are one of the three fundamental sources of knowledge from which understanding of the behavior of an element or a system can be attained; the others being field observations and analytical modeling. Due to the size of civil infrastructure, such as buildings, bridges, embankments, foundations, and pipeline networks, experiments are usually conducted on the most vulnerable components of a system and often at a reduced scale. Currently, the number of complete full-scale tests is very limited. Examples of full-scale system tests are Negro *et al.* (1996), Molina *et al.* (1999), Pinho and Elnashai (2000), Chen *et al.* (2003), and Jeong and Elnashai (2005). Even in the aforementioned cases, the foundations and soil were not modeled. The most impressive E-Defense shaking table can test large scale multi-story buildings with a load capacity of 1,200 tf and plan dimensions of 20 m by 15 m. But even this shake table cannot manage multi-span bridge with its foundations. It is however noteworthy that load and deformation capabilities of testing equipment around the world has increased very substantially in recent years, rendering testing of full-scale components significantly more accessible than before. This development in testing facilities opens the door for the adoption of an approach similar to the analytical approach described above where different software analysis platforms are combined in a single integrated simulation. A system by which a number of laboratories could combine their capabilities to undertake a set of integrated component tests on structural and geotechnical elements for example would provide an exceptionally attractive option for assessment of complex interacting systems. Current network bandwidth and processing speeds limit distributed testing to slow-rate testing. Moreover, since iterations cannot be performed for the physical test, there is a level of approximation inherent in satisfying force equilibrium and displacement compatibility. Nonetheless, such an approach suffers neither from the serious assumptions necessary for inelastic dynamic analysis, nor from the limitations of small scale testing that would be required to fit all components into one laboratory.

1.4 Integration of analysis and testing

The brief assessment of testing-only at one site, and analysis-only on one software tool provided above points towards the potential significance of using hybrid and multi-platform approaches. There also exists a combination between the two, once the concept of distributed representation is accepted. Using both analysis and testing to represent a complex structural system and its foundation, for example, avails of all the advantages of tests and all those of analytical models. 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 and Nakashima 2005, Takahashi and Fenves 2006, among others). It has hitherto remained, however, a rather arduous task that requires extensive knowledge of both experimental and analytical tools and their detailed background, and necessitates considerable programming effort. The procedures have indeed not been sufficiently robust and have therefore remained in the advanced research domain, not in the persistent application domain.

This paper addresses the above situation 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. As simple and intuitive as the framework is, its impact on structural and geotechnical research is substantial. The approach utilizes pseudo-dynamic (PSD) simulation and distributed analysis and experiments. It enables the combination of unique analysis applications in various fields while still allowing diversity in application development, and promotes collaboration of nationally and internationally distributed experimental sites into simulation of large complex system. There are a few recent investigations on online hybrid simulation. For example, Kwon *et al*. (2005) proposed an feasible approach by connecting remote sites through TCP/IP network and developed an interface for Zeus-NL (Elnashai *et al.* 2002), OpenSees (McKenna and Fenves 2001), and FedeasLab (Filippou and Constantinides 2004). Pan and Nakashima (2005) proposed very similar framework for online hybrid test where shared files and folder are used as means of communication between two sites. Wang *et al*. (2006) used general purpose FE software, ABAQUS (Hibbit *et al.* 2001) as part of the online hybrid simulation. As these methods are based on PSD simulation, there are limitations in applying the approach to test rate-dependent structural system or components. In addition, if there are large amounts of data that need to be transferred at each time step, the communication can limit the applicability of the framework. The potentials and limitations are further elaborated at the end of this paper.

The multi-platform and distributed hybrid simulation framework described in this paper, referred to as UI-SIMCOR, is presented in subsequent sections, including its software architectural features, modularity provisions and four application examples. The examples presented cover both multi-platform analysis and hybrid testing-analysis simulations.

2. Proposed multi-platform hybrid simulation framework

The concept and architecture of the UI-SIMCOR framework for multi-platform analysis and hybrid simulation is introduced in this section. PSD hybrid tests have been conducted by several research groups in the past. The conventional approaches however are limited to a specific experimental setup or to a specific analysis platform for which the PSD test is developed. The framework proposed in this paper allows general and seamless combination of various analysis platforms and experimental sites by implementing transparent and object-oriented programming architecture and employing widely adopted communication protocols. It brings multi-platform analysis and hybrid simulation to a wider audience and refocuses the attention of researchers on the objective of assessment as opposed to ensuring that the simulation mechanics actually work.

2.1 Conceptual background

The proposed framework is based on the concept of PSD test methods which have been a research topic for over thirty years. The early introduction of the PSD method was by Hakuno *et al.* (1969) and Takanashi *et al.* (1975), which evolved into substructured PSD test (Dermitzakis and Mahin, 1985) and distributed PSD test (Watanabe *et al.* 2001). In these conventional PSD methods, predicted displacements are imposed on experimental specimens at each time step and the restoring forces are measured and fed back into the time integreation scheme. This stepwise PSD simulation method has achieved a mature developmental state in comparison with variations of the method such as real time testing (Nakashima *et al.* 1992, Carrion and Spencer 2006), continuous PSD testing (Takanashi and Ohi 1983), and effective force testing (Chen and Ricles 2006), Fig. 1. The framework proposed herein adopts the stepwise PSD testing scheme with its well established theory and extensive applications.

In a conventional PSD test, the lumped mass matrix, **M**, the damping matrix, **C**, and the inertial forces, **f**(*t*), are defined within a computational module. The predicted deformations are statically applied to experimental specimen to estimate restoring forces, **r**(*t*). The measured displacements and forces are fed back into the time integration scheme to correct predicted displacement.

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{r}(t) = \mathbf{f}(t)$$

If a three-storey planar structure is pseudo-dynamically tested, one actuator per storey is commonly used to represent inertial forces, where it is assumed that structural mass at each story can be lumped into a single control point. The equations of motion of three DOFs are solved as one lumped mass is assigned per story as in Fig. 2(a). As an alternative to estimating the restoring force vector from the experimental specimens, it may be obtained from inelastic analysis of numerical model of the specimen. The predicted displacements at control points are applied to the model and

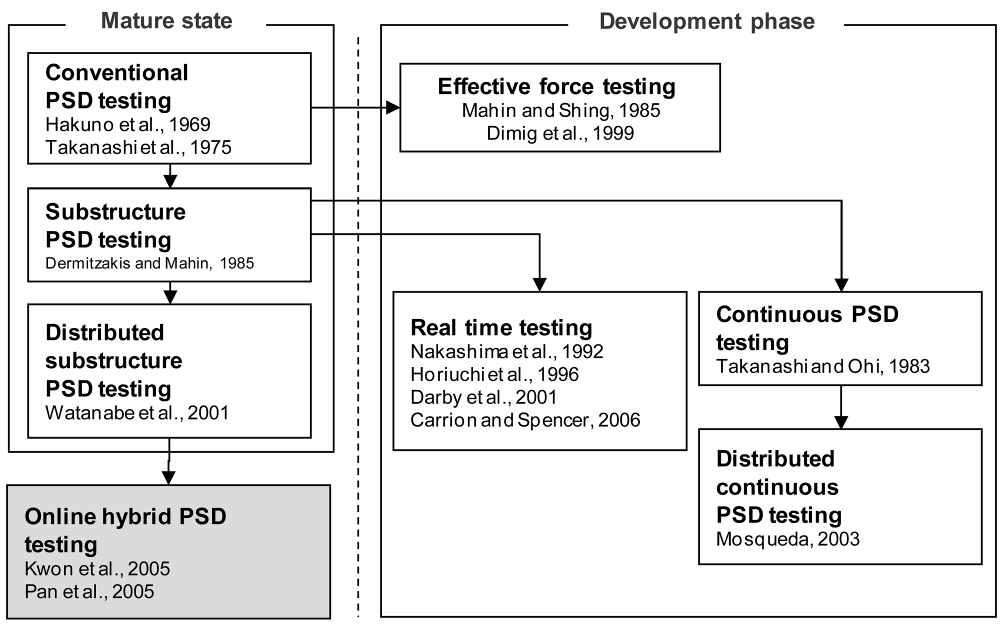
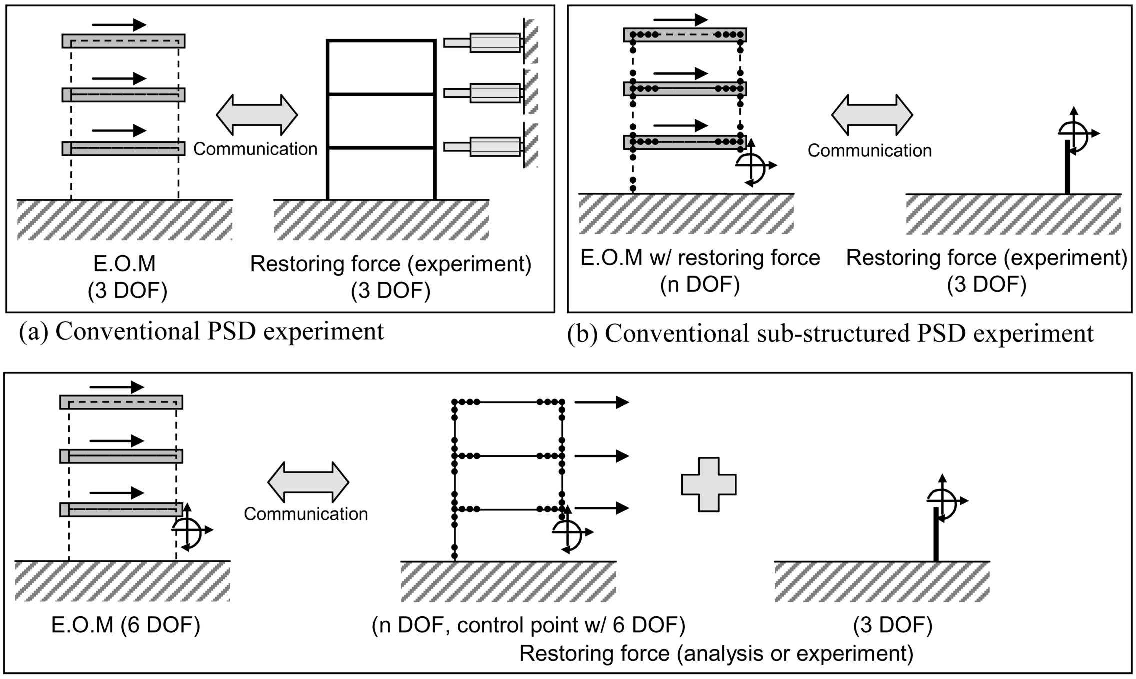


Fig. 1 Backgrounds of PSD test



(a) Conventional PSD experiment

(b) Conventional sub-structured PSD experiment

(c) Proposed sub-structured PSD simulation

Fig. 2 Conventional and proposed configuration of PSD test

restoring forces at these control points are inserted back into the equations of motion. In case it is necessary to divide a structural system into substructures, force equilibrium and displacement compatibility should be satisfied at the substructure interface. Hence, the DOFs at the interface nodes as well as the DOFs with significant inertial forces need to be included in the equation of motion, Fig. 2(b).

In the conventional substructure PSD simulation, a single analysis platform is in charge of solving the equations of motion as well as estimating restoring forces of a substructured analytical model. Restoring forces from substructured experimental model are measured at each step of the simulation. This approach is reliable if the application for FE analysis realistically represents nonlinear response of the part of the structure modeled computationally. In some situations, the adopted analysis platform may be limited to simple nonlinear model or to even elastic model.

A better approach to integrate analytical model of substructure in PSD simulation might be estimating restoring forces with the best available analysis platform and feeding the restoring forces into a solver which runs a time marching scheme. By completely separating the roles of time integration and restoring force estimation, and by allowing the combination of restoring forces from various modules, a complex system can be more appropriately modeled, Fig. 2(c), than modeling all analytical components in a single analysis platform. In the proposed framework, the PSD test algorithm itself is identical to the conventional method. But the ideas of obtaining restoring forces from generic FE analysis platforms or experimental specimen and providing a framework for coordination of these substructure modules are distinctive features of the framework. The adopted PSD scheme and detailed architecture of the framework are introduced in the following sections.

2.2 Pseudo-dynamic integration scheme

Implicit time-step integration schemes have been used for PSD test in two main forms; (i) iterative implicit methods achieving equilibrium at each time step through sub-cycling (Shing *et al.* 1990, 1991), or (ii) linearly implicit and nonlinearly explicit, operator splitting (OS) method (Nakashima *et al.* 1987). Ghaboussi *et al.* (2004) developed a Predictor-Corrector (PC) algorithm which gives better result than the OS scheme when the response of the analyzed system ventures deep into the inelastic range. A study by Combescure and Pegon (1997) showed that the operator splitting method in conjunction with α-modified Newmark scheme (α-OS method) is unconditionally stable when the tested system is softening. With its stability and well established theoretical background, the α-OS method is implemented in the proposed framework. The integration scheme, however, can be easily switched with improved schemes due to highly modular architecture of the framework introduced in next section.

2.3 Software architecture of the proposed framework

In the proposed framework, a structure and/or foundation system is divided into a set of substructures. Each substructure may be represented by either analytical models or experimental specimens. In addition to having the feature of distributing the physical tests over several experimental sites, the framework includes distributing the analytical components over different computers within or outside the local network. Mass, damping, and external forces are defined in the time integration module while restoring forces are obtained from the distributed structural components.

The analysis and experimental inputs-outputs at each step are communicated through the network. The DOFs of each substructure component are mapped onto the global DOFs of the integrated structure. This mapping or local-global assembly procedure is commonly-used in finite element analysis. The major difference between conventional analysis platforms and the proposed framework is that the data from each component, whether they are forces or displacements, are communicated through the network rather than through shared memory within a single process. In addition, as the substructure PSD method does not allow iteration with experimental specimen, there is always certain level of approximation which depends on integration time step. Fig. 3 illustrates the overall architecture of the framework proposed in this paper. The main modules shown in the figure conducts static analysis to apply gravity forces on structure before dynamic stage and runs dynamic time-integration with global DOFs, which is fully independent from the substructured analyses and/or tests. The communication, substructure testing and analysis are completely encapsulated within objects of a class. Hence, it is straightforward to add new schemes for time-step integration in the current framework, due to the separation between components and the symmetry and transparency of handling testing and analysis sub-systems.

There are two classes in the proposed framework UI-SIMCOR. These are MDL_RF (a class for substructures) and MDL_AUX (a class for auxiliary equipment). The objects in the MDL_RF class represent substructures which are either analyzed or physically tested. The main analysis routine in UI-SIMCOR considers these objects as elements with multiple nodes and multiple DOFs. As these objects do not have fixed geometric configuration, a structural model can be constructed with any configuration of these objects. The objects return restoring forces for given displacements. The displacement-force relationships are obtained from analyses or experiments at remote sites. Another crucial functionality of the MDL_RF class is communication, Fig. 3. When the main analysis

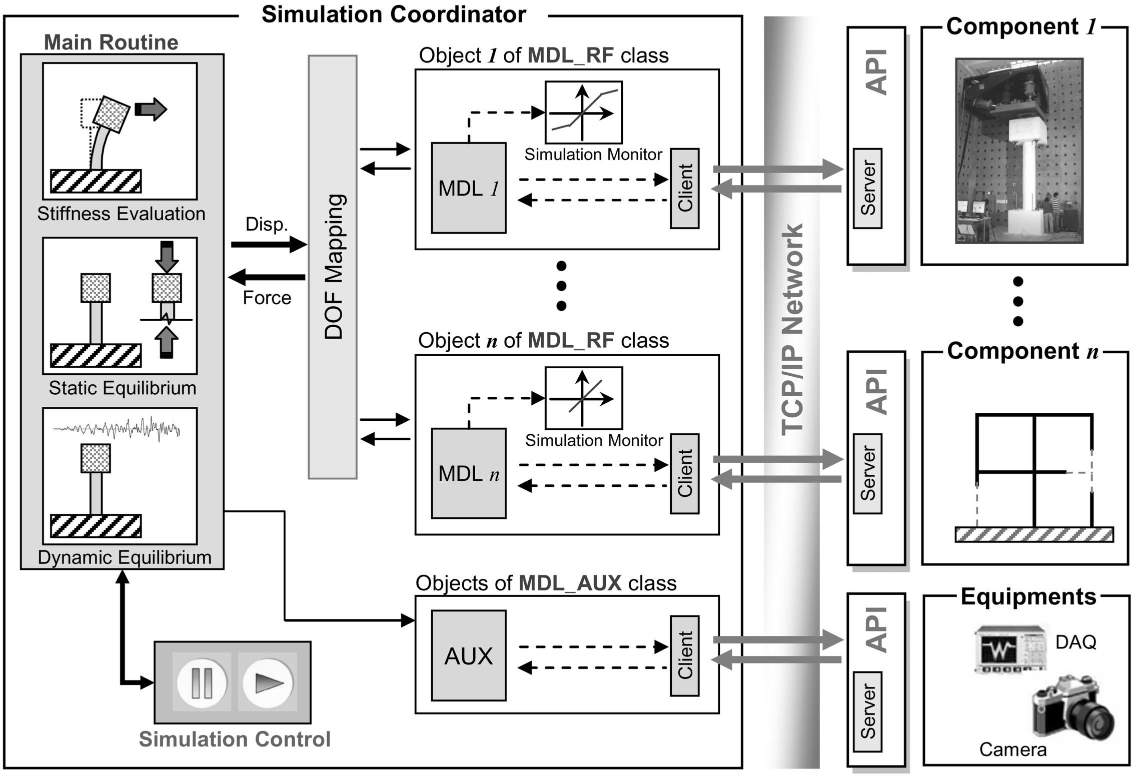


Fig. 3 Architecture of proposed framework

routines impose displacements to substructures represented by objects of the MDL_RF class, the objects reformat the data in a pre-specified protocol, open a network connection to the remote sites, and send the reformatted data. The MDL_RF class includes other functionalities such as checking the force, displacement and relaxation limits for the experimental substructure. Remote sites need interface programs which open ports waiting for connection from main framework, impose displacements to analytical models or experimental specimens, and send the measured responses. The MDL_AUX class is used to trigger experimental hardware other than actuators. The objects in this class can transmit pre-specified commands to remote equipment. Upon receiving the command, the remote equipment executes actions such as taking pictures or triggering data acquisition systems.

By utilizing the proposed framework multi-site hybrid simulation can be easily configured and efficiently coordinated fully utilizing the best features of diverse computational platforms and experimental equipments.

2.4 Simulation procedure and data flow

A typical simulation procedure is illustrated in Fig. 4 where three communication layers are identified as ‘User’, ‘Simulation Framework’, and ‘Remote Sites’. A user of the framework starts the simulation, monitors current status and pauses the simulation whenever necessary based on limit conditions defined by the components and their individual control circumstances. The simulation framework is responsible for initialization, stiffness estimation, time integration, and communication with remote sites. Remote sites are responsible for analyses or experiments to reach predicted displacements. The analysis or test results are sent back to the simulation framework. The simulation procedure shown in Fig. 4 is for the NTCP protocol and HSPTxt v.1 protocol, which will be introduced in the following section.

2.5 Communication Protocols

A multi-site multi-platform simulation requires exchange of data between equipment sites and analysis applications. Hence, communication over the network following standard protocols is one of the most important requirements. In the proposed framework, various communication protocols are implemented for compatibility with a wide range of equipment sites and analysis applications. These are NTCP, ASCII-format based communication protocol (HSPTxt v.1 & v.2), binary-format based communication protocol (HSPBin v.1), and a protocol for OpenFresco (Takahashi and Fenves 2006). To promote collaboration of equipment sites across the U.S.A., NEES (Network for Earthquake Engineering Simulation) consortium has developed a standard communication protocol, NTCP (NEESgrid Teleoperation Control Protocol, Pearlman *et al.* 2004) which allows secured communication between remote sites; this protocol is also implemented.

HSPTxt v.1 and v.2, formerly referred as LabView1 and LabView2, are developed for communication in ASCII codes. Whenever commands are sent to remote sites with the HSPTxt v.1, the remote sites send an acknowledgement back to the UI-SIMCOR to confirm reception of the command, Fig. 4. In the HSPTxt v.2, the acknowledgement steps are removed to reduce time spent in communication. Whenever target displacements are sent to remote sites, remote sites run experiment and send back measured response quantities. Recently NEES has been released an alpha version of NHCP protocol, a successor of NTCP. NHCP is also implemented in UI-SIMCOR.

The ASCII format communication in HSPTxt v.1 and v.2 protocols is efficient to interpret as all commands and values are readable in text format. Hence it can be universally used by many sites as long as the remote site can receive the ASCII format data (text format) and interpret it. But ASCII format communication requires significant overhead as it needs to convert binary data into ASCII format and ASCII format data into binary value. Moreover the size of ASCII format data is usually larger than binary format data. Thus, a binary communication protocol, referred as the HSPBin, is implemented.

OpenFresco provides versatile interfaces to experimental control equipments. OpenFresco can be used to control a number of actuators in diverse actuator configuration. To expand hybrid simulation capabilities to many experimental sites, the communication protocol with OpenFresco is also implemented in UI-SIMCOR. In addition to these already implemented communication protocols, any other protocols can be easily implemented. The wide range of implemented communication protocols allows involvement of numerous equipment sites and analysis platforms.

2.6 Finite element analysis platforms

The main challenge in integrating analysis platforms into multi-platform analysis and PSD hybrid simulation is the development of an interface program which receives data from UI-SIMCOR, executes commands, and returns sub-system response. If the source code of the required analysis platform is available or if the input and output of the analysis platforms can be controlled during simulation, the interface program can be readily developed. Based on their ability to meet these

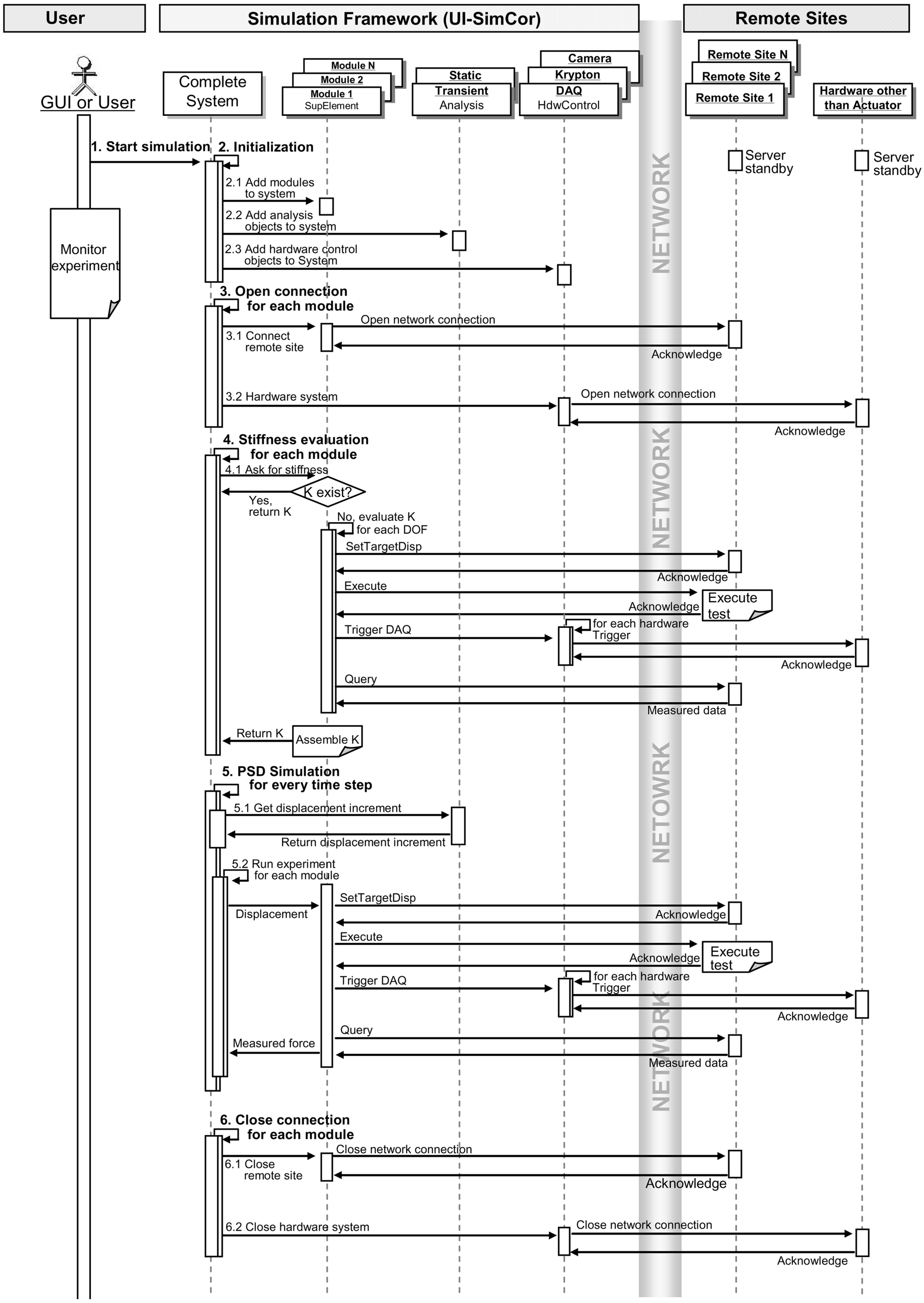


Fig. 4 Simulation procedure and data flow

requirements as well as the necessity for diverse analytical environments to satisfy user needs, interface programs for five analysis platforms are developed. These are ABAQUS (Hibbit *et al.* 2001), FedeasLab (Filippou and Constantinides 2004), OpenSees (McKenna and Fenves 2001), Vecotor2 (Vecchio and Wong 2003), and Zeus-NL (Elnashai *et al.* 2002). The proposed framework alongside various analysis platforms and potential experimental models constitutes an exceptionally versatile tool for research into the response of complex systems under extreme loading conditions.

3. Application examples

The proposed framework has been adopted for several analytical and experimental projects. This section briefly introduces major application of the framework successfully undertaken by the authors and their co-workers.

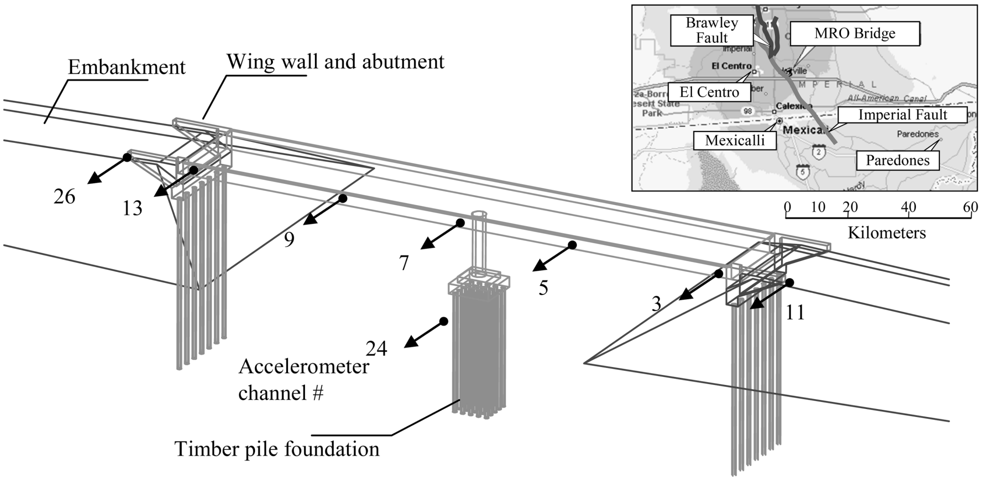
3.1 MRO bridge simulation

The most suitable approach for the analysis of soil-structure interaction (SSI) systems is the detailed modeling of the whole soil domain and structure in a single finite element-infinite element model. Very limited literature, however, is available on such a complete modeling approach. Alternatively, the soil domain can be modeled in a finite element package with the best available soil material models, and the structural components can be modeled on a platform that specializes in structural analysis. The multi-platform simulation framework, UI-SIMCOR, can be utilized to combine these two different analysis platforms, each selected for its superiority in its field. The following example briefly introduces the multi-platform simulation of an SSI system.

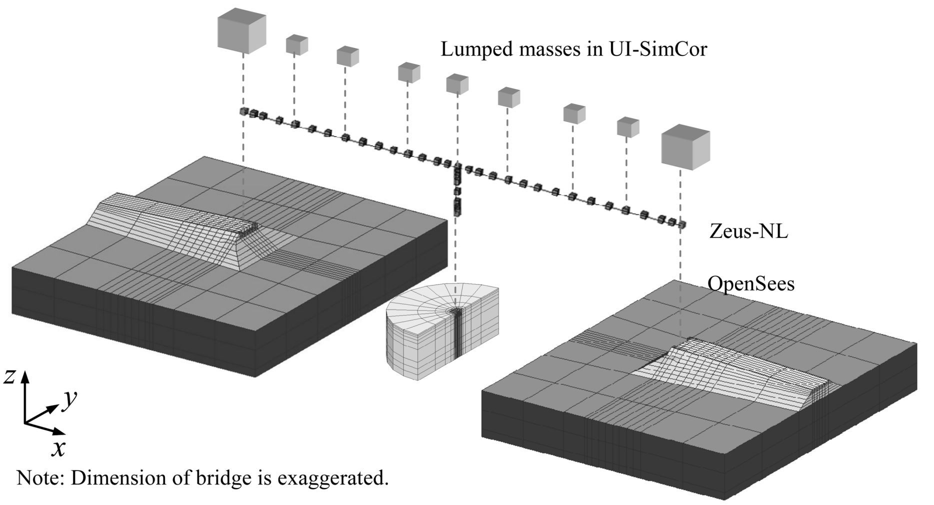
The Meloland Road Overcrossing (MRO) Bridge is chosen as a benchmark, due to the fact that it is heavily instrumented and has been shaken by more than one earthquake. The MRO Bridge was instrumented with 26 accelerometers in 1978. Six additional accelerometers were added in 1992. The 1979 Imperial Valley Earthquake (M_L = 6.6) was the largest recorded event at the site with a peak ground acceleration of 0.3 g. The MRO Bridge is located over Interstate 8 approximately 0.5 km from the fault rupture of the 1979 Imperial Valley earthquake. The bridge consists of two spans of pre-stressed box-girder decks monolithically connected to the center pier. Fig. 5(a) shows the configurations of MRO. Reference can be made to Zhang and Makris (2002) for more information about the MRO Bridge.

The geotechnical components, i.e., the foundations, embankments and abutments, are modeled in OpenSees with hysteretic soil material model. The structural components of the bridge are modeled in Zeus-NL with fiber-based beam-column elements as the application has been extensively verified with experimental results. As the three dimensional soil and foundation system are analyzed in independent processors, the computational load for the analysis of whole system can be distributed. This substructuring is effective especially when substructures share limited number of DOFs. The separate FE models are combined to represent the inelastic stiffness of all components. The individual models are analyzed using different processors coordinated through UI-SIMCOR. The configuration of the simulation model is shown in Fig. 5(b). Inertial forces are represented by lumped masses placed on the bridge and at the abutment-bridge connection.

Response history analyses are conducted with three recorded ground motions. Free-field motions are used as input. Fig. 6 compares analysis results with recorded ground motion at the top of the



(a) Configuration of MRO Bridge



(b) Configuration of multi-platform simulation model

Fig. 5 The configuration of MRO Bridge model

pier. The response history results exhibit good correlation with the recorded motion, in terms of frequency content and peak values.

3.2 Application to multi-resolution dynamic analysis

High-rise buildings are not direct extensions of low- and medium-rise structures. They require special treatment owing to their inherently complex configurations, interaction between a number of dynamic response modes and the requirement to resist much larger loads at the critical lower stories from both horizontal (wind, earthquakes) and vertical (gravity) loads. The following example presents

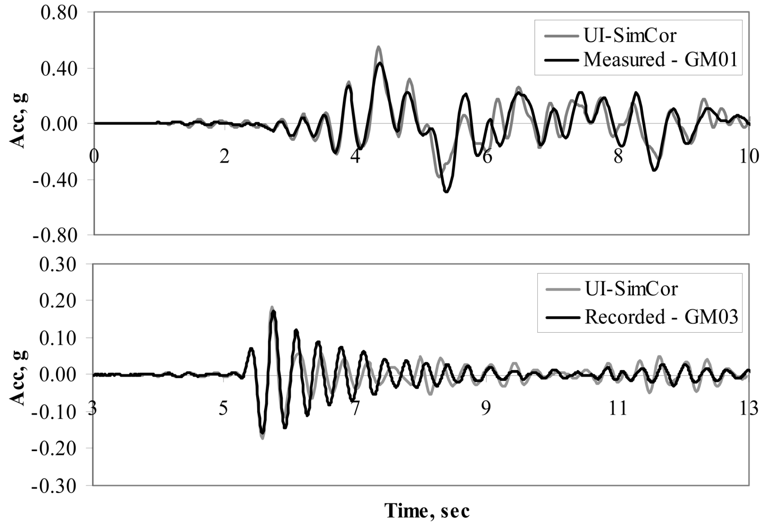


Fig. 6 Comparison of UI-SIMCOR analysis result with measured responses

the application of multi-platform simulation to analyze a complex high-rise structure modeled at two levels of resolution, namely detailed 2D reinforced concrete, and skeletal frame analyses.

An actual RC high-rise building, Tower C03 of the Jumeirah Beach Development, Dubai, United Arab Emirates, is chosen as a representative building because of its well-designed core walls and their interaction with outer frames. The coupled structural system, which includes dual core walls and a frame, is chosen as the reference structure for the simulation. It is assessed using two analysis platforms: VecTor2 and Zeus-NL. The former, VecTor2, is capable of analyzing RC continuua based on the Modified Compression Field Theory (MCFT) by Vecchio and Collins (1986). The latter, Zeus-NL, utilizes fiber-based frame elements, Elnashai *et al.* (2002).

The shear-sensitive lower regions of the walls, 1^{st}~10^{th} story of the building, are modeled as RC continuum elements in VecTor2, while the remaining parts of walls and frame are simulated with fiber-based beam-column elements in Zeus-NL. In UI-SIMCOR, there are control points in the substructured models, with lumped masses and DOFs of relevance to applied loads and response displacements. These control points are defined in order to form the global mass and stiffness matrices necessary in the PSD algorithm, and to serve as the common interfaces between substructures. In each analytical module, these control nodes are associated with other nodes through finite elements. When two analytical modules with different resolutions are combined, it is essential to properly consider DOFs at the boundaries of two modules. For instance, the concrete continuum in VecTor2 is modeled with plane stress element whose nodes have two DOFs while the 2D frame elements in Zeus-NL include three DOFs per node. Thus, to couple these elements with different resolutions and to prevent stress concentration in a module of high resolution, multipoint constraint equations are derived and applied.

The simulation model is shown in Fig. 7. Ground motions are selected considering various magnitudes, epicentral distances and soil conditions. Fig. 8 presents two sets of displacement response histories at two different floor levels (1^{st} and roof stories) using a record from the Hyogoken Nanbu (Kobe, Japan) Earthquake of 1995. The analysis results from multi-platform simulation are compared with those from frame analysis of a skeletal model in Zeus-NL. At lower

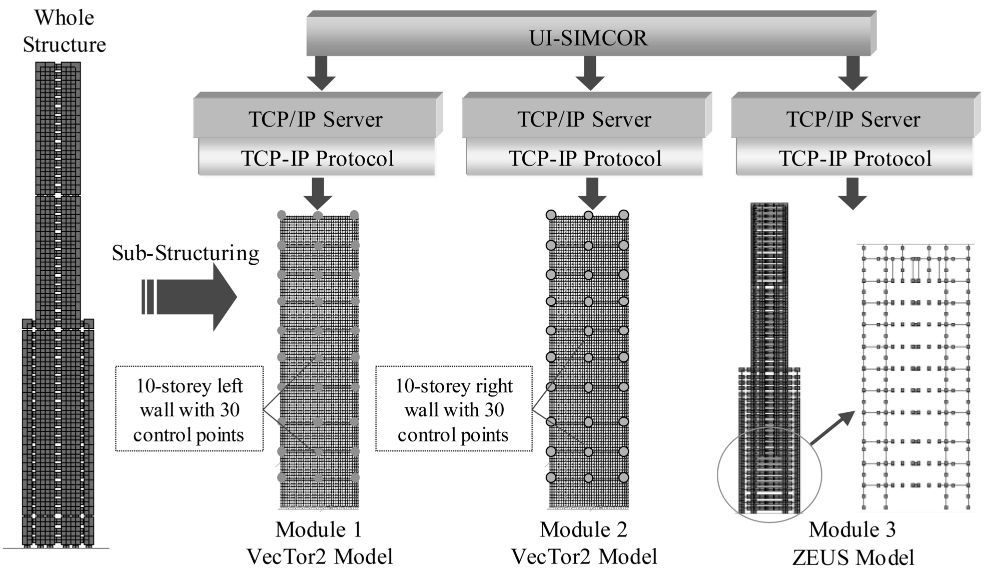


Fig. 7 Multi-platform analysis of high-rise complex structure

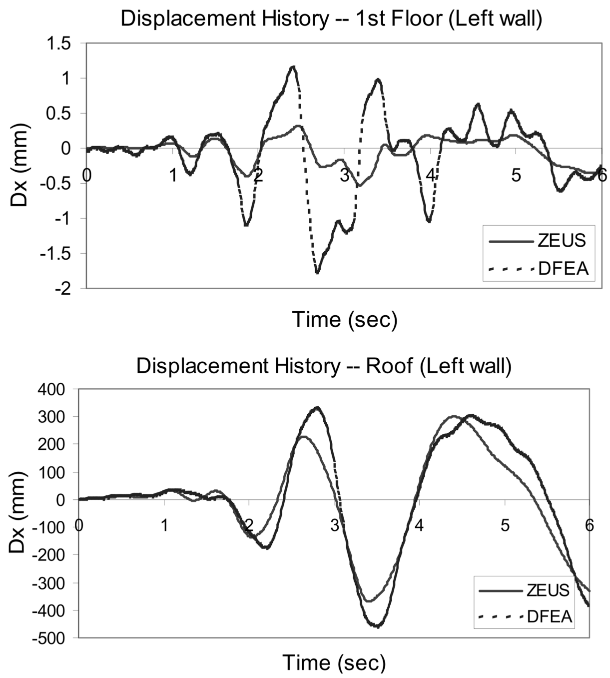


Fig. 8 Sample lateral displacement history comparisons between multi-platform model and Zeus-NL model

levels of the building, the drifts computed from the multi-platform simulation are much larger than those from the single Zeus-NL model, while at the roof level they are close to each other. The large difference at lower level is a consequence of shear deformations considered by the concrete continuum modeling in VecTor2, which is neglected in the skeletal representation of Zeus-NL.

3.3 Three site hybrid test with UI-SIMCOR

The main objective of this three-site hybrid simulation example is to verify the proposed framework and check the compatibility of the framework with other experimental sites. Three experimental 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 hybrid simulation; MiniMOST 1 (Gehrig 2004) at UIUC and SDSC, μNEES (Schellenberg *et al.* 2006) at UCB. The experimental specimen in UIUC and SDSC behaves in linear elastic range while the specimen in μNEES 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. 9. Simulation was carried out at the rate of 6.5 sec/step. The relatively slow simulation rate was due to limitations in the Mini-MOST 1 experiments at UIUC and SDSC. Fig. 10 compares the responses from three-site experiment and analytical simulation. The experimental results are very close to the analytical simulation result. The slight difference is caused by inaccurate analytical

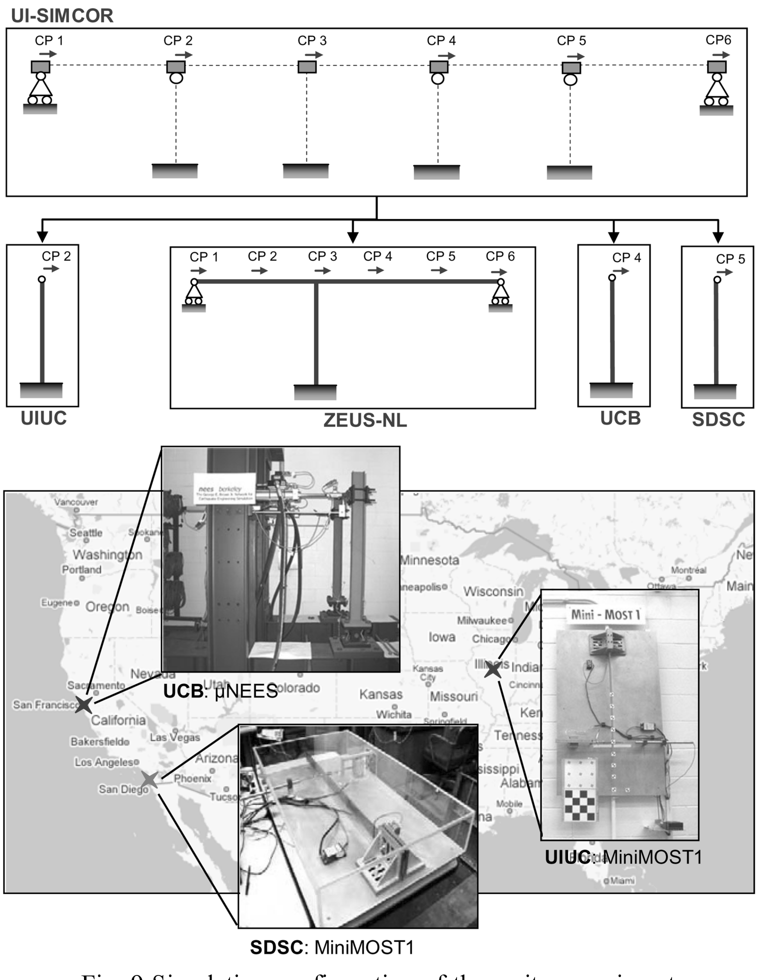


Fig. 9 Simulation configuration of three-site experiment

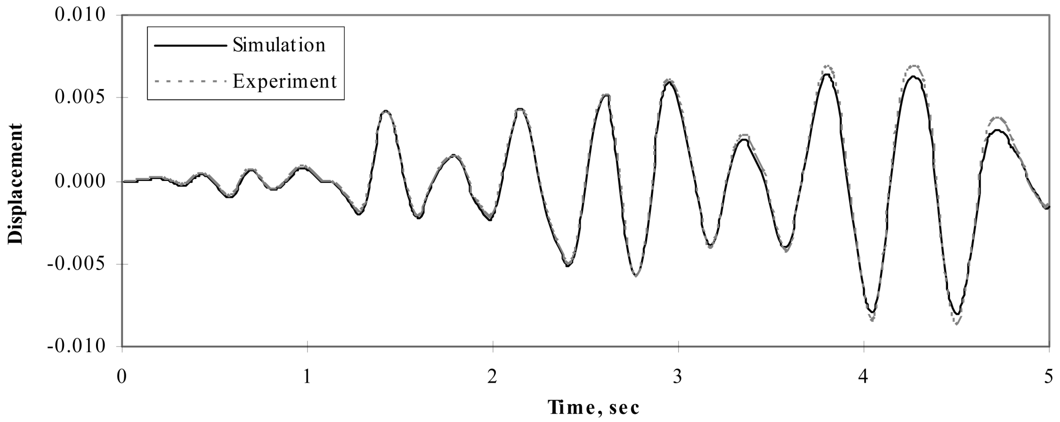


Fig. 10 Comparison of analytical and experimental results

representation of inelastic behavior of μNEES. This project demonstrated that the proposed framework runs reliability with minimum efforts for customization at each remote site.

3.4 MISST project

The MISST project (Multi-Site Soil-Structure-Foundation Interaction, Spencer *et al.* 2006) was undertaken to investigate systems that could not be studied before by running online hybrid simulation of a structural-geotechnical 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 at UIUC and another pier at Lehigh University, LU) and two analytical models (geotechnical model at Rensselaer Polytechnic Institute, RPI, and structural model at UIUC) are integrated using UI-SIMCOR, as shown in Fig. 11. To satisfy capacity limitations of test equipment, a 1/2 scale model of the 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 peak ground acceleration (PGA) of 0.37 g. The second record was collected at the Newhall Fire Station and had a PGA of 0.58 g. 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 remote sites. Thus the simulation system, which includes all NEESgrid components, UI-SIMCOR, the analytical modules, and all experimental equipment and components at both

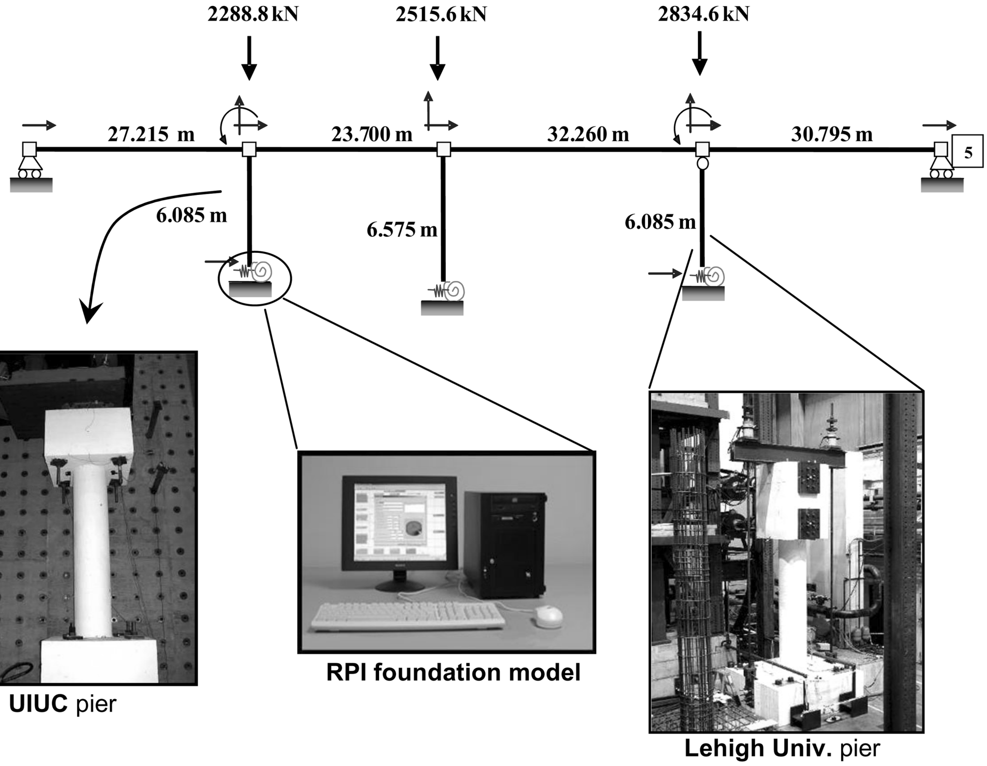


Fig. 11 Experiment configuration of MISST project

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 hybrid simulation can be applied to address problems which have previously been unapproachable to the earthquake engineering community.

4. Potential, limitations, and future challenges

The proposed framework allows the integration of various analysis platforms and physical models which are best suited to represent the sub-system components. These components are connected and coordinated through the network which allows geographical distribution of the individual component, nationally and internationally. The framework described in this paper, UI-SIMCOR allows the distribution of computational resources for large and complex problems with a few coupled DOFs, such as a bridge pile foundation model with tens of thousands of DOFs connected to a pier at a single node. In addition, the object-oriented program architecture and the basic concept of the framework allow exceedingly easy implementation of new analysis algorithm or the inclusion of new analysis platform or experimental sites. UI-SIMCOR therefore achieves two overarching objectives. These are (i) rendering complex multi-platform, multi-resolution analysis and hybrid simulation accessible to a very wide range of potential users, and (ii) providing an ideal environment for collaboration not only between geographically distributed research groups, but also groups from different sub-disciplines, such as structural and geotechnical engineering.

The proposed framework however has limitation. As the stepwise PSD method is adopted as time integration scheme, rate sensitive structures and components cannot be tested. This limitation can be relieved if continuous or fast PSD methods, which are still immature state for distributed testing, are implemented in the current program architecture. As the forces and displacements at all DOFs should be transferred through the network, the demands on communication can be high for a system with many coupled DOFs. This limitation will, however, be overcome with advances and expansion of network capacity and speed. Moreover, in the current state of practice and research, very few PSD simulations involve large numbers of coupled DOFs. The aforementioned limitation becomes much more significant when inertial interaction between different sub-systems is important. In which case, dynamic analysis of sub-systems is required, and all degrees of freedom associated with masses will have to be communicated back and forth, thus taxing the network and slowing down the integration of the components into a whole. This limitation is also subject to being alleviated by increased network bandwidth and speed. Iterations cannot be applied to an experimental model. As a consequence, a level of approximation is inherent in the procedure with regard to achieving force equilibrium and displacement compatibility. The implemented integration scheme, α-OS method, is applicable to softening system with an acceptable level of error. Improved methods of time-integration can be easily implemented in the framework when they become available.

5. Conclusions

A hybrid simulation framework is proposed which allows collaboration of various analytical platforms and experimental sites into a simulation of a large, complex and interacting system. The framework is implemented in an objected-oriented paradigm so that it can be easily extended for new analysis algorithms, platforms and testing sites. Currently four analysis platforms (Abaqus, FedeasLab, OpenSees, and Zeus-NL) are implemented into a versatile multi-platform analysis tool. Two analytical examples and two experimental examples of the proposed framework are introduced. The examples cover multi-platform simulations of a bridge with soil structure interaction and a complex high rise building, and distributed PSD simulation of bridges in small and large scale test equipment. These examples demonstrate the potential of the framework by combining the best features of analysis platforms and experimental sites. The framework UI-SIMCOR is open-source (http://neesforge.nees.org/projects/simcor/), is not system-specific, uses a number of widely used communication protocols and has been extensively verified and documented. It therefore achieves the two overarching objectives of bringing multi-platform multi-site distributed and hybrid simulation to a wide range of users, and providing an ideal collaboration environment for researchers from different regions and sub-disciplines of civil engineering.

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