Hybrid Simulation Commissioning Tests using LHPOST

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Introduction

The NHERI@UCSD Experimental Facility (EF) provides advanced hardware capabilities for real-time hybrid shake-table (RTHST) testing. In RTHST testing, a portion of the structural system (with complex nonlinear behavior difficult to model computationally) is modeled physically while the remaining essential elements of the system are modeled computationally (e.g., using the finite element method) in a computer communicating in real-time with the shake-table controller and possibly the controller of additional actuators acting on the physical specimen tested on the shake table. RTHST has been studied by several researchers [Igarashi et al. 2000, Reinhorn et al. 2003, Zhang et al. 2017] using different integration algorithms and compensators to control the stability and accuracy of the simulation for uniaxial shake tables. Schellenberg et al. [2017] recently verified applications using a 6-DOF shaking table at UC Berkeley. Combining RTHST with dynamic actuators to apply additional boundary conditions has also been explored [Shao et al. 2011]. Notably, the majority of this research has been conducted on small shake tables with scaled experimental substructures. Extending these capabilities to LHPOST can expand the complexity of the large-scale geotechnical and structural systems that can be tested making RTHST an attractive alternative method to evaluate the response of structures under earthquake loads.

The simulator platform of the LHPOST can represent the top surface of a foundation, bridge, or building system that is modelled analytically and would be too large to be tested experimentally in its entirety. Hybrid shake table testing also provides an efficient approach for performing parameter studies, by changing the properties and the behavior of the numerical portion of the hybrid model from test to test. The following tests were carried out to verify the hybrid testing capabilities with LHPOST including shake table performance and compensation of delay.

The capabilities for hybrid testing were verified using LHPOST in a series of commissioning tests in 2017. The computational capabilities utilized include two high performance multicore computers; one computer operating as a real-time digital signal processor programmable through the Matlab/Simulink real-time environment and the second that can be used to run OpenSees/OpenFresco to simulate complex structural analysis models. SCRAMNet, a shared common RAM network, provides high-speed, low-latency communication capabilities between the two new high-performance machines and the existing MTS 469D shake table controller and the MTS STS structural actuator controller for external actuators. During these commissioning tests, it was found that the MTS STS SCRAMNet card was faulty and was replaced to ensure reliable data communication between the real-time computers.

Experimental Setup

A series of experiments demonstrated for the first time the hybrid simulation capabilities of the LHPOST and real-time integration of all hardware components. The experiments were conducted in collaboration with the NHERI SimCenter employing high performance computing models and utilizing data for development and testing of data models in DesignSafe. For these tests, two sets of seismic isolation bearings were obtained including a set of four lead rubber bearings from DIS and four triple pendulum bearings from EPS. Only the friction bearings were tested due to limited availability of the shake table after addressing troubleshooting delays. In addition, we borrowed shear load cells from UC Berkeley to obtain more precise measurements of specimen forces. More importantly, these load cell measurements are being used to evaluate force correction models that are being developed for the shake table. For larger structures, load cells may not be available and the measured base shear of a specimen that will be required for hybrid simulation can be obtained using shake table actuator load cells with correction for inertial and friction forces associated with the platen.

Two different computational drivers were employed to solve the equation of motion for the hybrid numerical and experimental substructure. First, the analytical substructure was modeled entirely in a Simulink environment including the integration algorithm used to solve numerically the equation of motion of the hybrid substructure. This implementation accomplished hard real-time applications using the Simulink Real-Time Target. In the second approach, the analytical substructure was modeled in OpenSees running on a multi-core processor machine. This enables the use of the computational and modeling capabilities of OpenSees but runs in a soft real-time mode because of its nondeterministic execution time. Before using these two methods in an actual hybrid test, a virtual hybrid simulation was conducted for preliminary verification of the accuracy and performance of the hybrid model. In other words, the experimental substructure was numerically modeled separately and coupled to the analytical substructure. The initial verification of the hybrid model consisted of a 2-DOF system as shown in Figure 1. The analytical substructure consisted of a 1-DOF shear frame coupled with a tuned mass damper over 4 isolators. In later applications, the analytical substructure was extended to MDOF shear building models only in the OpenSees application. The mass of the tuned mass damper and the 4 isolators were numerically modeled as a 1-DOF nonlinear element. For the physical tests, the experimental substructure consisted in three blocks of concrete (56 kips) resting on four triple friction pendulum isolators as shown in Figure 2.

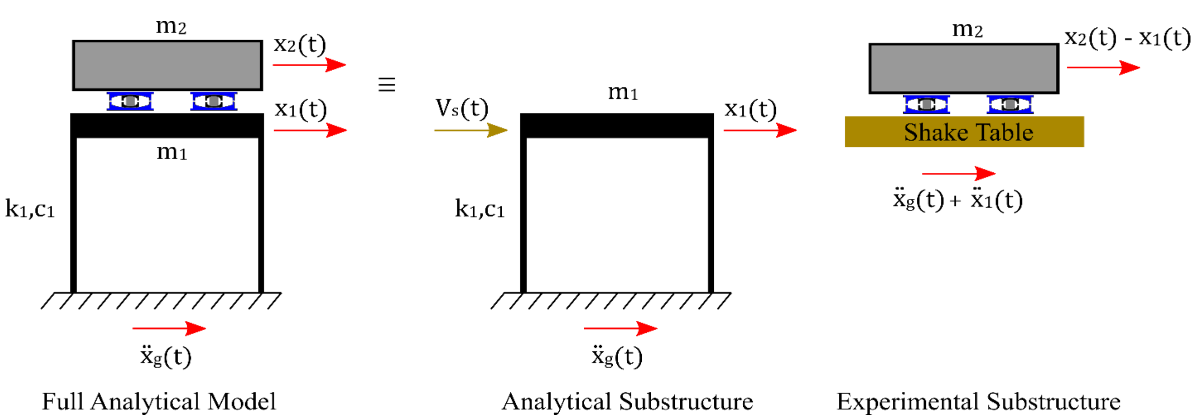

Figure 1: Two DOF hybrid model and substructures

Figure 2: Experimental substructure for hybrid simulations

Hard real-time implementation: A real-time digital signal processor (Simulink Real-Time) is used to create a real-time application from the Simulink model and run it on a dedicated target computer connected via Scramnet through fiber cables to the control system of the shake table. Figure 3 shows a schematic of the coupling between the analytical and experimental substructures.

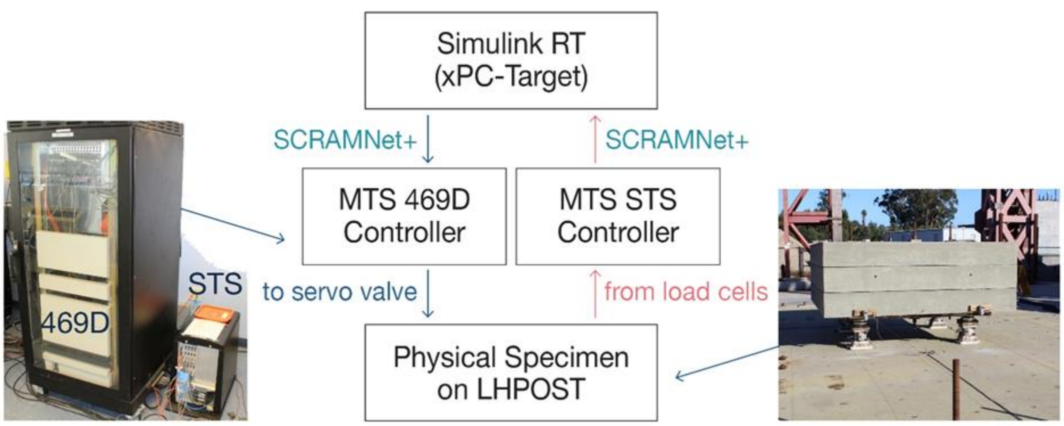

Figure 3: Block diagram of RTHS implementation using Simulink

Soft real-time implementation: The implementation of soft real-time using OpenSees is similar to the previous but requires an extra computer labeled as the host computer, the middleware software OpenFresco, and a predictor corrector algorithm running in the real-time target computer. Figure 4 shows the additional elements needed to use OpenSees in this hybrid test. The main advantage to this approach is the use of advanced computational modeling features available in OpenSees.

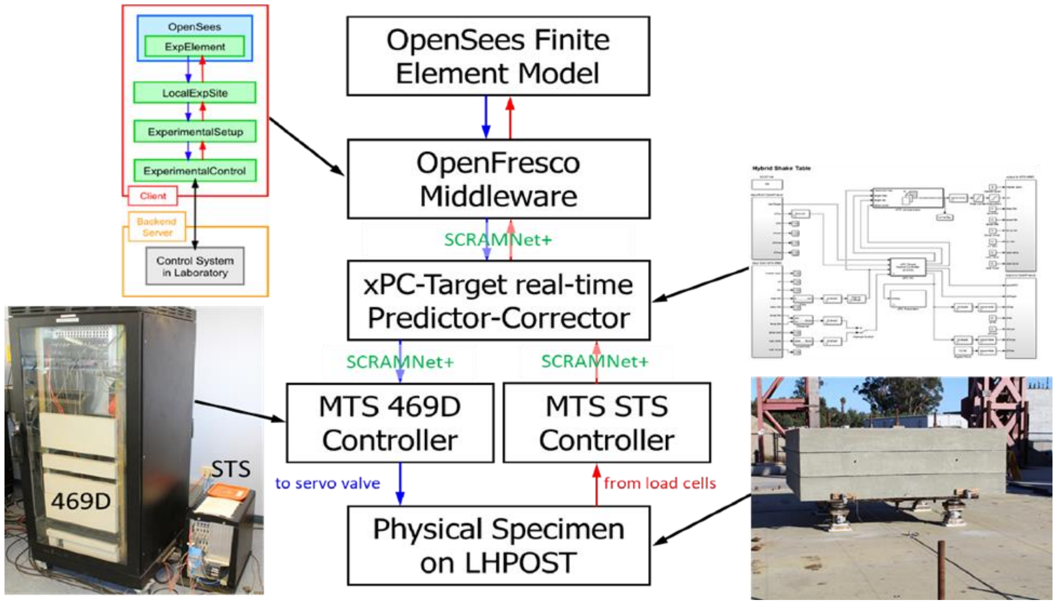

Figure 4: Block diagram of RTHS implementation using OpenSees-OpenFresco

Results

Figure 5 shows the displacement time history of the interface between the experimental and numerical substructures, corresponding to the absolute shake table displacement, for a simulation of a 1 sec period structure subjected to 200% of the 1989 Loma Prieta Earthquake recorded at the Sylmar station. The displacement shown in blue represents the command displacement as predicted by the ATS time-delay compensator [6]. The target displacement shown in yellow and the measured displacement in red demonstrate that the tuning of the shake table controller and the use of delay compensation as applied here can effectively mitigate the 30 msec of delay measured in the shake table and enable reliable hybrid simulations. These results were obtained using Simulink as the computational driver and similar results were obtained with OpenSees/OpenFresco (shown in purple for a separate test). The hysteresis of the experimental substructure base shear is compared in Figure 6 for the full numerical simulation in OpenSees (Full OS) and both applications of hybrid simulation. These results demonstrate that hybrid simulation using the LHOPST can provide accurate results.

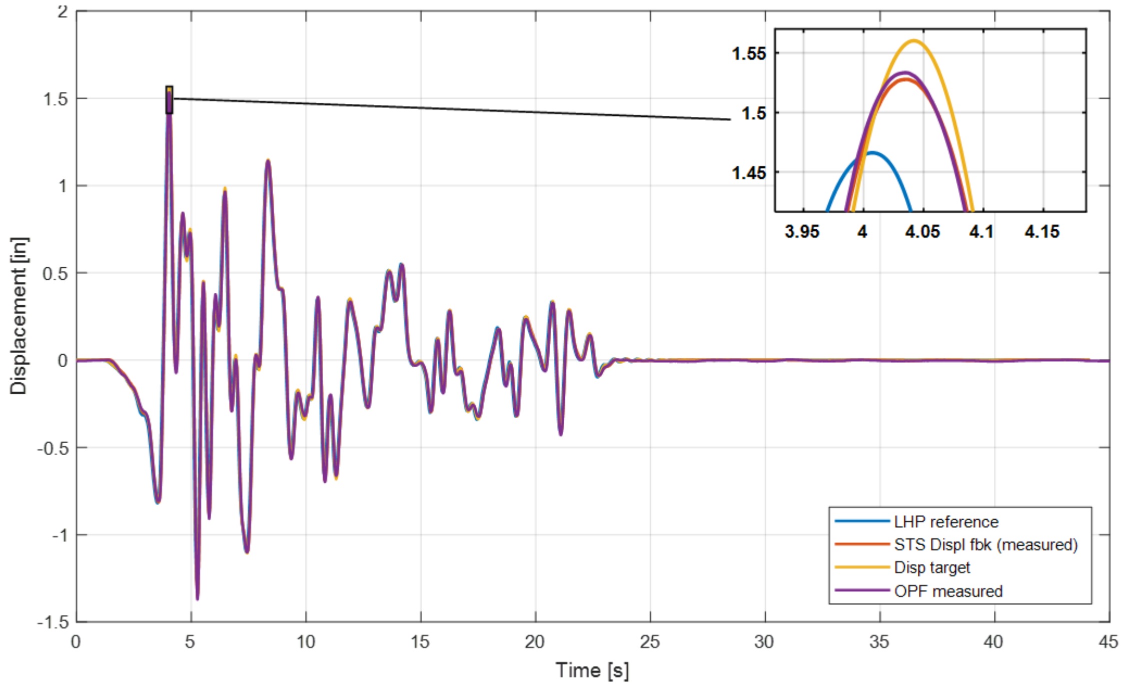

Figure 5: Displacement results at shake table interface from hybrid simulation

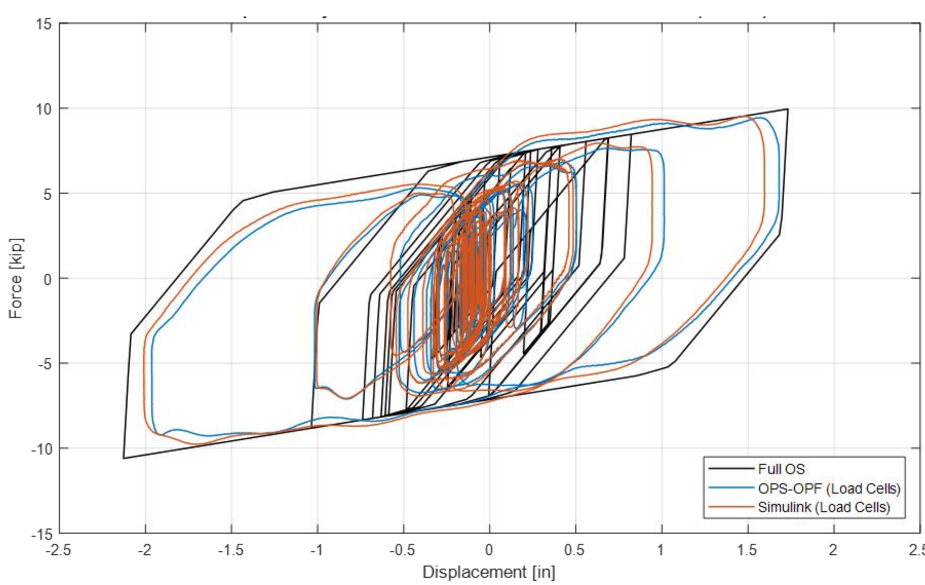

Figure 6: Triple friction pendulum hysteresis for numerical and hybrid simulations

Conclusions

These series of tests verify the hybrid testing capabilities using LHPOST enabling researchers to conduct large scale hybrid simulations. The software for implementation of the Simulink and OpenSees hybrid models is available to users interested in conducting hybrid simulation with LHPOST. The data obtained from these commissioning tests and the software models will be made available as published data in the NEHRI DesignSafe DataDepot.

References

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