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NEES FAST HYBRID TEST SYSTEM AT THE UNIVERSITY OF COLORADO

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SUMMARY

As part of the George E. Brown, Jr. Network for Earthquake Simulation, a Fast Hybrid Test system has been developed and installed at the University of Colorado. The system is based on the pseudodynamic test method, and it combines physical testing with model-based simulation. The system is designed to achieve a rate of loading that is significantly higher than that of a conventional pseudodynamic test approaching the real-time response of a structure subjected to earthquake loads. This paper presents an overview of the system, including the computational method, system hardware and software, and two of the validation tests that were conducted to evaluate the performance of the system. Results of these tests have demonstrated the good performance of the system for real-time multiple-degree-of-freedom tests.

INTRODUCTION

As one of the fifteen equipment sites of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) supported by the US National Science Foundation, the University of Colorado at Boulder has developed and installed a Fast Hybrid Test (FHT) system for the experimental evaluation of seismic performance of structural systems and components. This system is based on the substructure pseudodynamic test concept (Dermitzakis [1], Nakashima [2], and Shing [3]). The main distinction is, however, that the system can deliver a rate of loading that is significantly higher than that in a conventional pseudodynamic test, approaching the real-time response of a structure under earthquake loads. During such a test, the actuators are in continuous motion.

With the FHT system, one can test the most critical structural subassemblage, where severe inelastic deformation or damage is expected to develop, and model the rest of the structure in a computer. In general, the method can be applied to full-scale structural systems and subassemblages depending on the size and capacities of the reaction-wall facility and the high-speed, high-performance hydraulic actuators available. Furthermore, with a slower rate, it can be used to conduct geographically distributed tests, where different components and subassemblages of a structure can be tested in different laboratories with the synchronization and data exchange controlled by a computational model of the entire structure via the Internet.

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While real-time pseudodynamic test methods have been developed by a number of researchers (e.g., Nakashima [4], Magonette [5], and Darby [6]), the FHT system developed here has several unique features. It has a flexible system architecture and incorporates a general finite element analysis framework OpenSees (McKenna [7]) for nonlinear substructure analysis. It is also the first real-time pseudodynamic test system that is based on an unconditionally stable implicit time integration scheme that provides a robust computational environment for large-scale structural response simulations.

The FHT system employs high-performance servo-hydraulic loading apparatus, modern digital control technologies, and the state-of-the-art model-based simulation techniques to allow a most realistic and efficient assessment of the performance of large-scale structural systems, subassemblages, and components, and response mitigation devices under earthquake loads. The system is accessible by remote users through a high-performance information network, the NEESgrid, for teleparticipation in experiments.

This paper presents the main features of the FHT system, including the system hardware and architecture, computational method, and simulation software. The performance of the system is demonstrated by sample validation tests.

SYSTEM OVERVIEW

The FHT system is based on the pseudodynamic test method. A general overview of the test method can be found in Shing [8]. In such a test, the dynamic behavior of the test structure is simulated in a computer using a direct step-by-step time integration technique. In each step of a test, the displacement response computed is imposed on the structural specimen and the resulting structural restoring forces developed are fed back to the computer model to compute the response in the next step. Since the inertia effect is simulated in the computer model, a pseudodynamic test can be carried out at a very slow rate.

The FHT system is to enhance the accuracy of the pseudodynamic test method for cases where the behavior of the structural specimen is sensitive to the rate of loading. This is very desirable for structural testing in general as the behavior of most structural materials is strain-rate sensitive to a certain extent. Moreover, the method can be used to evaluate the performance of passive and active structural control devices, where the rate of loading is a governing factor. A simplified schematic of the system, showing the essential components, is shown in Figure 1. The computation module is implemented in a real-time machine for on-the-fly numerical simulations. The numerical computation, involving step-by-step integration, is carried out with a Simulink program or OpenSees [7]. The latter is used to model an analytical substructure that is not physically tested. The displacement commands generated in each time step are sent to a digital servo-controller to control the deformation of the structural specimen with high-speed actuators. The displacements, velocities, accelerations, and forces measured from the structural specimen are collected by a data-acquisition system and fed back to the simulation program. All communications between the simulation computer and the digital processor used for digital control and data acquisition are through a high-speed memory-sharing network called SCRAMNet. The details of the system architecture will be described later on.

The FHT system can also allow the testing of multiple structural components and subassemblages of a single structure in geographically distributed laboratories that are linked by a single simulation program through the Internet. This is an extension of the substructure test method and is referred to as a multi-site test in this paper. As shown in Figure 1, multi-site tests can be set up by linking the simulation computer to actuator controllers and data-acquisition systems in remote laboratories via the Internet. Furthermore, like other NEES facilities, the system has tele-participation capabilities for researchers at remote locations to participate in experiments via the Internet. To this end, the system is equipped with data and audio/video servers to stream live data to remote participants through the NEESgrid.

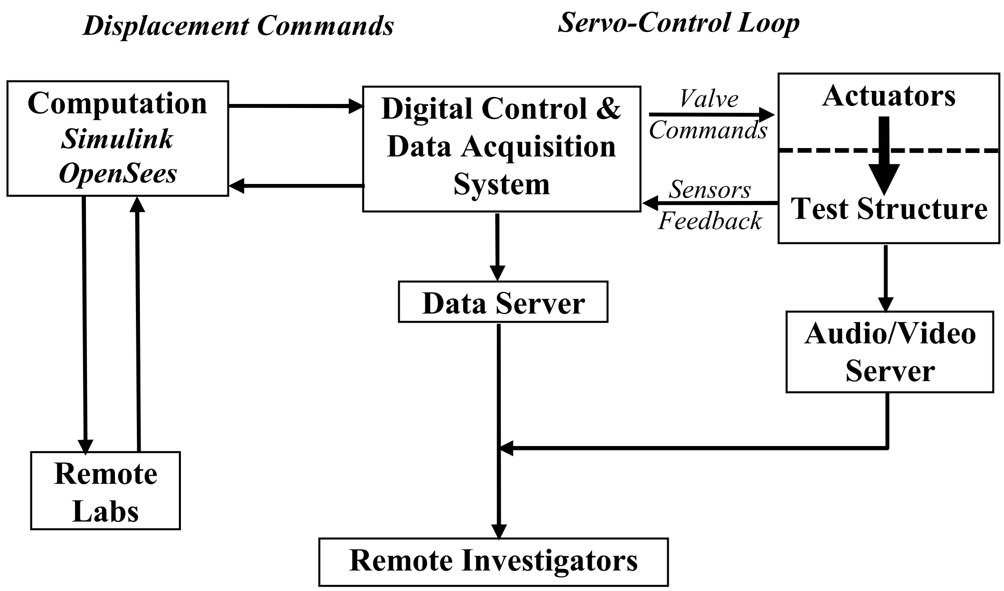


Figure 1 – Basic Configuration of the FHT System

COMPUTATIONAL SCHEME

For pseudodynamic testing with substructuring, an unconditionally stable implicit time integration method is desirable because of the additional degrees of freedom introduced by the analytical substructure. Furthermore, an experimental substructure can have high-frequency modes introduced by the rotational degrees of freedom at its interface with the analytical substructure. For this reason, the unconditionally stable α-method (Hughes [9]) is adopted for time integration. This integration method has been successfully adapted for conventional pseudodynamic tests (Shing [10,3]). However, for nonlinear structures, implicit methods normally require Newton-type iterative corrections, which are not suitable for high-speed testing where actuators have to move continuously and reach the converged solution within a fixed time interval. Therefore, a special iterative correction scheme has to be developed here for fast hybrid tests. The details of this scheme are given below.

For a multiple-degree-of-freedom structure, the α-method can be expressed as follows.

$$\mathbf{M}\mathbf{a}_{i+1} + (1+\alpha)\mathbf{C}\mathbf{v}_{i+1} - \alpha\mathbf{C}\mathbf{v}_i + (1+\alpha)\mathbf{r}_{i+1} - \alpha\mathbf{r}_i = (1+\alpha)\mathbf{f}_{i+1} - \alpha\mathbf{f}_i \quad (1)$$

$$\mathbf{d}_{i+1} = \mathbf{d}_i + \Delta t\mathbf{v}_i + \Delta t^2\left[(1/2-\beta)\mathbf{a}_i + \beta\mathbf{a}_{i+1}\right] \quad (2)$$

$$\mathbf{v}_{i+1} = \mathbf{v}_i + \Delta t\left[(1-\gamma)\mathbf{a}_i + \gamma\mathbf{a}_{i+1}\right] \quad (3)$$

in which $\mathbf{d}_i$, $\mathbf{v}_i$, and $\mathbf{a}_i$ are the displacement, velocity, and acceleration vectors of the structure at time step *i*; $\mathbf{r}_i$ is restoring force vector that is in general a nonlinear function of the structural displacements and their histories; $\mathbf{f}_i$ is the external force vector due to earthquake ground motions or other dynamic excitations; Δt is the integration time interval; $\mathbf{M}$ and $\mathbf{C}$ are the mass and damping matrices of the structure; and α, β, and γ are parameters of the integration scheme governed by the following relations.

$$-1/3 \le \alpha \le 0 \tag{4}$$

$$\gamma = \frac{1}{2}(1 - 2\alpha) \tag{5}$$

$$\beta = \frac{1}{4}(1 - \alpha)^2 \tag{6}$$

For a nonlinear structure, the above equations need to be solved in an iterative manner. The residual error in each iteration k is given as

$$\mathbf{R}_{i+1}^{(k)} = \bar{\mathbf{M}}\hat{\mathbf{d}}_{i+1} - \bar{\mathbf{M}}\mathbf{d}_{i+1}^{(k)} - \Delta t^2 \beta(1+\alpha)\mathbf{r}_{i+1}^{(k)} \tag{7}$$

where

$$\bar{\mathbf{M}}\hat{\mathbf{d}}_{i+1} = \bar{\mathbf{M}}\tilde{\mathbf{d}}_{i+1} + \Delta t^2 \beta\left[(1+\alpha)\mathbf{f}_{i+1} - \alpha\mathbf{f}_i - \mathbf{C}\mathbf{v}_i - (1+\alpha)(1-\gamma)\Delta t\mathbf{C}\mathbf{a}_i + \alpha\mathbf{r}_i\right] \tag{8}$$

$$\tilde{\mathbf{d}}_{i+1} = \mathbf{d}_i + \Delta t\mathbf{v}_i + \Delta t^2\left(1/2 - \beta\right)\mathbf{a}_i \tag{9}$$

$$\overline{\mathbf{M}} = \mathbf{M} + \left(1+\alpha\right)\gamma\Delta t\mathbf{C} \tag{10}$$

The incremental correction $\Delta\mathbf{d}_{i+1}^{(k)}$ is obtained by solving the following equation.

$$\mathbf{K}^*\Delta\mathbf{d}_{i+1}^{(k)} = \mathbf{R}_{i+1}^{(k)} \tag{11}$$

where

$$\mathbf{K}^* = \bar{\mathbf{M}} + \Delta t^2 \beta(1+\alpha)\mathbf{K} \tag{12}$$

In a pseudodynamic test, the updated displacements $\mathbf{d}_{i+1}^{(k+1)} = \mathbf{d}_{i+1}^{(k)} + \Delta\mathbf{d}_{i+1}^{(k)}$ are calculated and imposed on the structural specimen. The restoring forces $\mathbf{r}_{i+1}^{(k+1)}$ are then measured and the iterative correction is repeated. In this approach, if $\mathbf{K}$ is the tangent stiffness of the structure, we have a Newton iterative scheme. Nevertheless, we normally do not know the tangent stiffness of the structural specimen during a test. Hence, a modified Newton method has to be used, with $\mathbf{K}$ being the initial stiffness of the structure. It has been found that the modified Newton method leads to a smooth convergence and desirable numerical properties to suppress experimental-error propagation. This method has been successfully used for conventional pseudodynamic tests where actuators move slowly and stop at the end of each time step (Shing [10]).

In the above algorithm, the number of iterations required is not known at the beginning of a time step Δt, and the incremental correction will decrease as the solution approaches convergence. This presents a problem for high-speed tests where actuators have to move continuously and attain the converged displacements within a fixed time interval. To circumvent the uncertainty problem and allow the actuators to move in a continuous and smooth fashion, a special iterative scheme with repeated interpolations is proposed. The scheme adopts a fixed number of iterations in each time step. The displacements updated in each iteration are used to generate displacement commands by interpolation.

The interpolation scheme is illustrated in Figure 2. For the purpose of the following discussion, let t stand for the time frame of the earthquake, and τ denote the time frame in which a test is actually conducted. Hence, $\Delta\tau/\Delta t$ is the time scaling factor used in a test, which is one when a real-time hybrid test is performed. In a slow test, this factor could be in the range of 100 to 1,000. As shown in Figure 2, in each iteration, a quadratic function is constructed for the actuator displacement using the end displacement commands, d_{i-1}^c and d_i^c, generated in the previous two time steps and the newly updated displacement $d_{i+1}^{(k+1)}$. A displacement command for the next increment is then generated by interpolation using the quadratic function. The number of interpolation points in each time step Δt is so selected that commands are continuously received by the controller at its sampling frequency. The controller used in this system has a sampling frequency of 1024 Hz. This results in a sampling interval $\delta\tau$ of approximately 1 ms. Hence, for a real-time test with $\Delta t = \Delta\tau = 0.01$ sec, we have 10 interpolation points in each time step. The number of sampling points will increase as the rate of a test decreases. The displacement updates can be carried out at every sampling point or every several points depending on the sampling frequency of the controller and the number of iterations desired. The same interpolation curve is used to generate subsequent displacement commands until a new displacement update is calculated in the next iteration. It has been found that with an integration time step of 0.01 sec, 10 iterations are more than sufficient even for a highly nonlinear structure.

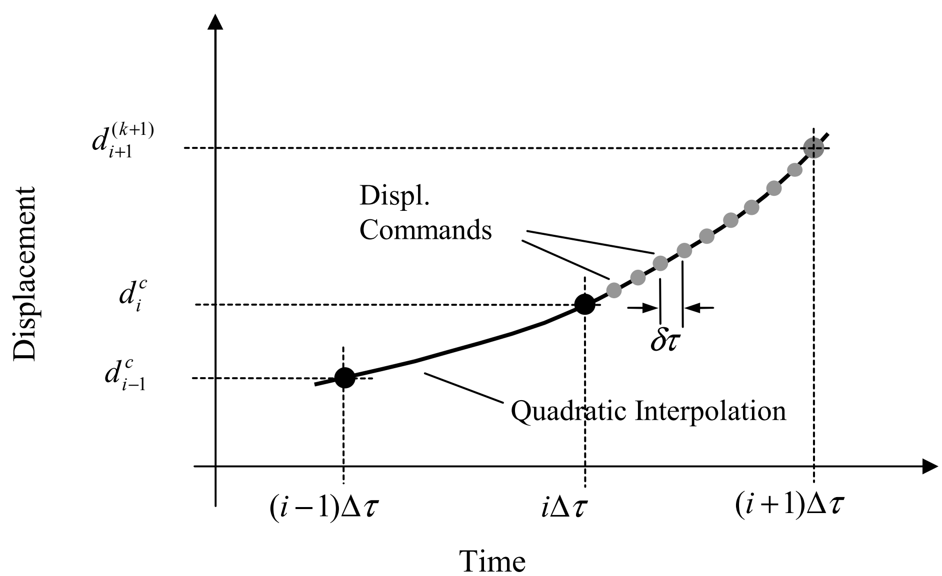


Figure 2 - Iterative Correction

In a fast hybrid test, the displacements attained in a structural specimen at each sampling point often differ from the displacements calculated by the numerical scheme for a number of reasons. First, because the reaction frame supporting the actuators has a finite stiffness, the actual structural displacements attained tend to be less than the actuator displacements when the servo-control loop is based on the displacement transducers mounted within the actuators. Second, there is a couple of milli-seconds of delay between sending the displacement command from the computer and the execution of the command by the controller. This is an inherent property of a digital control system. Third, there is always a time lag in actuator response caused by the dynamics of the servo-hydraulic actuator. This delay could be as large as 10 ms. Several compensation schemes have been implemented to account for the delays. One is a feed-forward control scheme to supplement PID control. This is implemented by MTS in the digital servo-controller. The other is a discrete feed-back compensation method developed in this project. In this method, instead of using $d_{i+1}^{(k+1)}$ directly in the interpolation, an adjusted displacement update $d_{i+1}^{a(k+1)} = d_{i+1}^{(k+1)} + \lambda \delta d_{i+1}$ is used, where δd_{i+1} is the difference between the calculated and measured displacements at the end of the previous time step *i*, and λ is a scaling factor which is normally less than or equal to one. The measured displacements can be the displacements obtained from the specimen with external transducers, which are not affected by the deformation of the reaction frame.

SYSTEM CONFIGURATION

The FHT system has three basic components: (I) hydraulic equipment; (II) instrumentation package; (III) control, computation, data-acquisition, and networking systems. It integrates the high-performance hydraulic actuators with a custom real-time digital control and simulation system. The major hardware components are summarized in Table 1. The system is located in the 12-m-by-21-m (40-ft.-by-70-ft.) strong floor area of the Structures Laboratory.

Table 1 – Major Hardware Components

Equipment	**Description**
Hydraulic power supply	682 lpm (180-gpm) silent pump
One 100-ton (220-kip) double acting actuator	±152-mm (6-in.) stroke; 947-lpm (250-gpm) three-stage servo-valve; maximum velocity of 254 mm/sec (10 in./sec); furnished with internal LVDT
Two 50-ton (110-Kip) double acting actuators	±127-mm (5-in.) stroke; 682-lpm (180-gpm) three-stage servo-valve; maximum velocity of 500 mm/sec (20 in./sec); furnished with internal LVDT
Integrated digital control and data-acquisition system	63 analog/digital channels; 15 channels for command, load, stroke, valve command, and delta-p for each of the 3 actuators; 26 channels for general purpose load/strain inputs with programmable excitation and gain; 10 channels for AC LVDTs; 6 channels for preconditioned analog inputs; 3 channels for high-resolution digital linear-encoders; 3 channels for accelerometers; all input/output channels have a maximum sampling rate of 1024 Hz with 16-bit resolution

Hydraulic Actuators and Power Supplies

There are three high-performance dynamic actuators in the FHT system. As summarized in Table 1, two of the actuators have a static load capacity of 50 tons (110 Kips) and a stroke of +/-127 mm (5 inches). The third actuator has a static load capacity of 100 tons and a stroke of +/-152 mm (6 inches). The 100-ton actuator can deliver a maximum velocity of about 254 mm/sec (10 in./sec) in seismic tests, while the 50-ton actuators have a maximum velocity of 500 mm/sec (20 in./sec). The maximum velocity actually attainable in a test depends on the load developed in the actuator. In general, it is necessary that the maximum load developed does not exceed 2/3 of the static load capacity to attain a high velocity.

The system is powered by a 21 MPa (3,000 psi), 682 lpm (180-gpm) quiet pump. In addition, the laboratory has two 265 lpm (70 GPM) hydraulic pumps, which can also be used when needed. These pumps are connected to a separate hydraulic power supply line. The pumps can be activated individually or together to provide a maximum flow of 530 lpm (140 gpm). Supplemental oil flow is provided by accumulator banks for high-speed tests. The total capacity of the pressure accumulator banks is 227 liters (60 gallons), and is provided in four separate units.

Digital Control and Data-Acquisition System

An integrated digital control, data-acquisition, and signal-conditioning system manufactured by MTS is used, as described in Table 1. The system can be reconfigured to accommodate different combinations of LVDT and strain-gage channels as needed. All input/output channels have a maximum sampling rate of 1024 Hz. Optional analog filters are provided with a fixed 300 Hz cut-off filter. A programmable digital low-pass filter with stop ending at 1/2 of the digital sample rate is also provided. The data-acquisition system allows the data to be time and date stamped between channels with exact synchronization for each channel of data. The system is equipped with application software for graphic display and viewing of data at a host computer. Standard Windows operating protocols are used for the storage and transfer of data files from the system.

The controller has displacement and load control capabilities and allows the switching of the two during a test while the actuators are still in power. Furthermore, the controller has a remote control console that allows the control and positioning of individual actuators at the test location.

Instrumentation Package

In addition to the three LVDTs and three load cells that are integral to the hydraulic actuators, the instrumentation package includes three accelerometers, ten LVDTs, and three Heidenhain optical linear position encoders that can provide accurate displacement feedback for numerical computation in a fast hybrid test.

Networking and Real-time Simulation and Testing

The local area network is designed to suit the fast hybrid testing needs and for easy connection to the wide area network for teleparticipitation and teleobservation by remote users. Figure 3 shows that the local area network consists of two fundamentally distinct networks. First, a conventional Ethernet network which utilizes two high-performance Cisco switches, and second, a high-speed fiber optic network built upon a Shared Common RAM Network (SCRAMNet).

The conventional Ethernet network consists of Intel processor based computers which run Microsoft Windows, Red Hat Linux, or one of two real-time operating systems. The three computers shown at the top of Figure 3 all run on Linux operating systems. The NEES Point of Presence (NEESpop) performs an assortment of tasks primarily involving the integration of the local equipment into the nationwide network of NEES resources through the NEESgrid. The NEES Tele-Presence Server also ties into the NEESgrid and completes the remaining tasks to fully integrate the University of Colorado site into the national network. Tasks such as video streaming and the electronic notebook are part of the functionality of the NEES Tele-Presence Server.

The third Linux based computer, shown at the top-right of Figure 3, is the data-storage computer (also called the local data repository). As the name implies, experimental data is stored here on a temporary basis. Ultimately all the data, including metadata, is sent to and archived at the NEES central data repository.

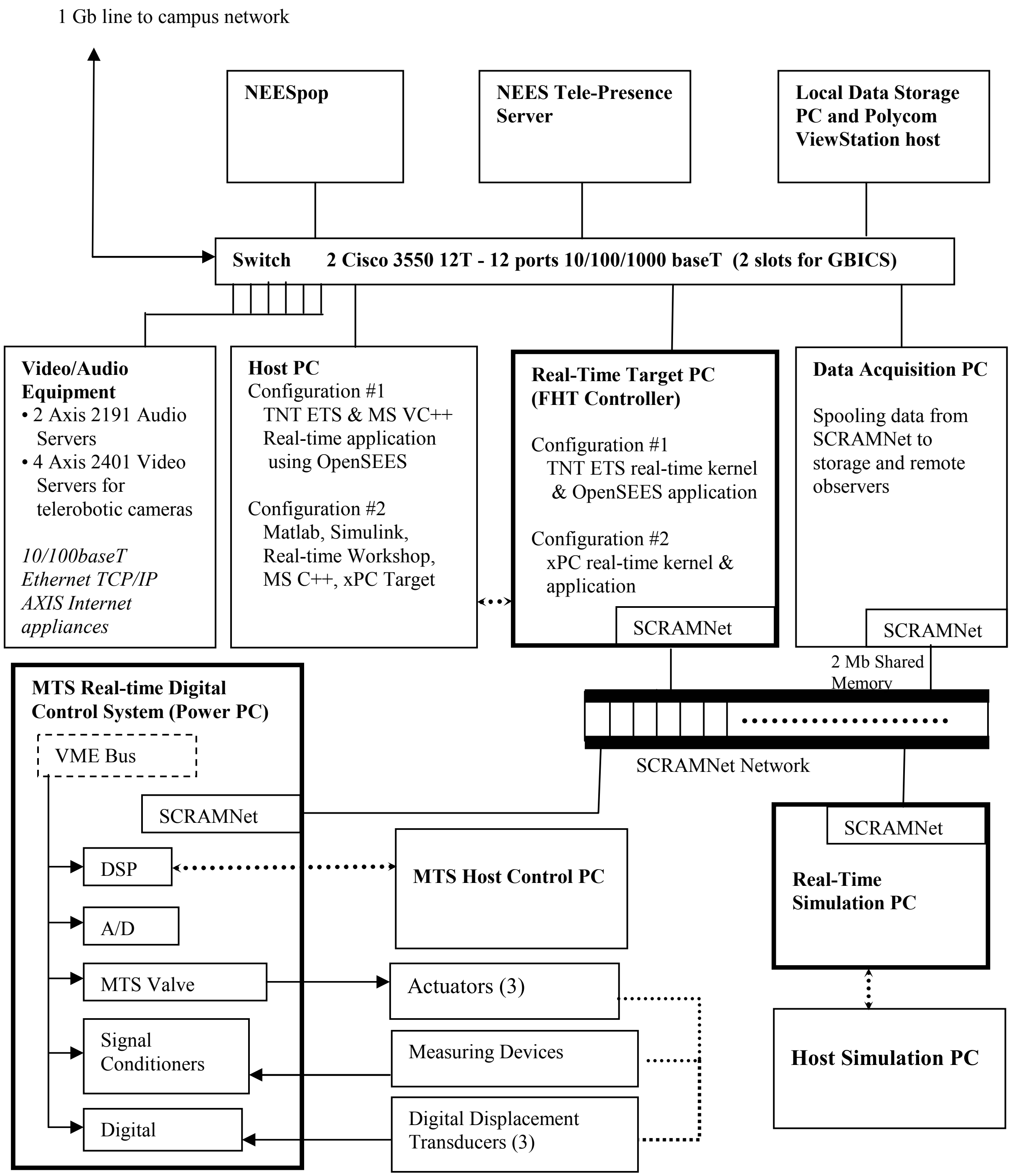


Figure 3 - FHT System Architecture

As shown in Figure 3, the basic computational component of the FHT system consists of two PCs. One is a host PC for program development and input preparation, and the other is a target PC is for real-time computation, which includes solving the equations of motion for the test structure, analyzing the analytical substructure, and actuator command generation using OpenSees or Simulink programs. The software tools available include Mathworks' Matlab, Simulink, Real-time Workshop, xPC-Target, State Flow, and State-Flow coder, Venturcom's TNT, and a C++ compiler. The computational scheme presented in the previous section has been implemented in Simulink programs for real-time pseudodynamic testing without substructuring. The substructuring capability is provided by the OpenSees framework which is adapted to run in Venturcom's TNT real-time environment.

The system provides the capability for simulating a virtual fast hybrid test without using actuators. For this purpose, as shown in Figure 3, another set of host-target machines are available for real-time simulation of the dynamics of the actuators, reaction frame, and structural specimen. The target machine is linked via the SCRAMNet to the MTS controller and the other real-time target PC that serves as the FHT controller for a realistic simulation of a virtual fast hybrid test.

The use of SCRAMNet provides the flexibility for future upgrade and expansion of the system. Additional data-acquisition units can be added to the SCRAMNet loop and synchronized with the MTS controller and data-acquisition unit as the need arises.

ANALYTICAL SUBSTRUCTURING CAPABILITY

The FHT system combines real-time simulation with testing. A test structure may be composed of an experimental substructure and an analytical substructure. OpenSees, which is an open source, object oriented structural analysis framework developed at the University of California at Berkeley (McKenna [7]) and supported by the Pacific Earthquake Engineering Research (PEER) Center, has been modified to work with the FHT system for substructure tests. The interaction and interfacing of the experimental and analytical structures is built into the real-time control and simulation platform as shown in Figure 4. Real-time capabilities have been added to the OpenSees program making the program suitable for FHT. In so doing, the user has full and deterministic control over all of the control and computational resources. The importance of this capability is highlighted by the fact that less then one milli-second is available for processing each successive set of actuator command signals and integrating the governing equations of motion.

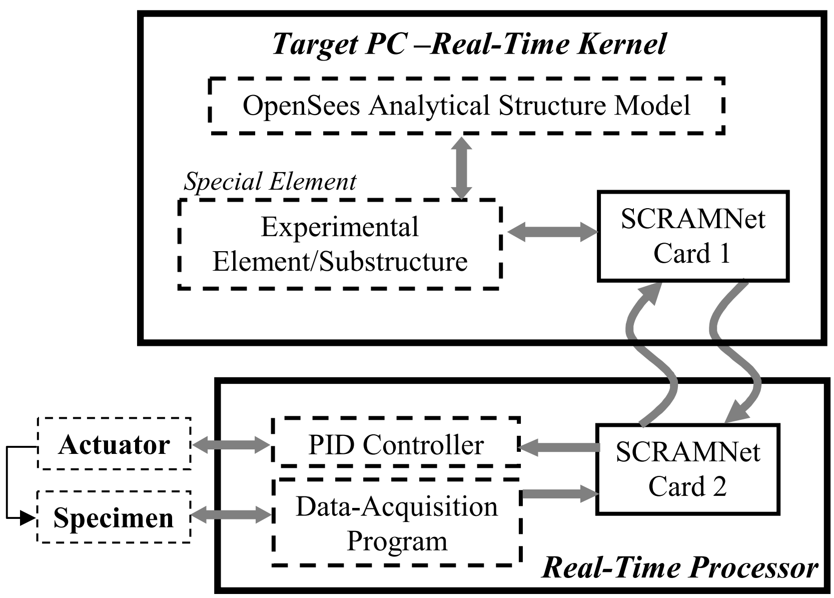


Figure 4 – Real-Time Substructure Tests with OpenSees

OpenSees is capable of performing nonlinear dynamic analysis of structural systems with various direct time integration schemes. The user may select a particular scheme by creating a class object corresponding to that integration technique. These objects are derived from the class object *Integrator* provided by the software framework. To implement the aforementioned computational scheme in OpenSees for FHT, a new class, called *FHT_Integrator*, is created. An object of this class provides methods to compute the system residual or unbalanced loads according to the α-method. In addition, it is in charge of the command interpolation during each iteration and is responsible for initiating the data communication between the target PC and the servo-controller according to interrupt signals sent by the controller. The actual task of data communication is, however, carried out by another class object created to numerically represent the experimental substructure in the computer model. It is derived from the class *Element*. This object takes displacement commands and directs them to memory locations on the SCRAMNet card corresponding to each actuator. It is also responsible for correcting the measured restoring forces for any actuator delay and passing the response measurements back to the system of equations.

Currently, the aforementioned objects can handle a test substructure with a maximum of three actuators attached to a maximum of three structural nodes. These class objects perform their individual tasks managed by the class object *FHT_Algorithm* to execute a complete iteration cycle of the computational scheme. Figure 5 shows the class structure of the analysis part of OpenSees with the modifications for FHT. New class objects implemented for FHT are highlighted in bold face. From the figure, we can see that the structural model, which is represented by the *Domain* object, is associated with the *FHT_Analysis* object. The *Analysis* is an aggregation of class objects for analyzing the status of the structure at the current time step.

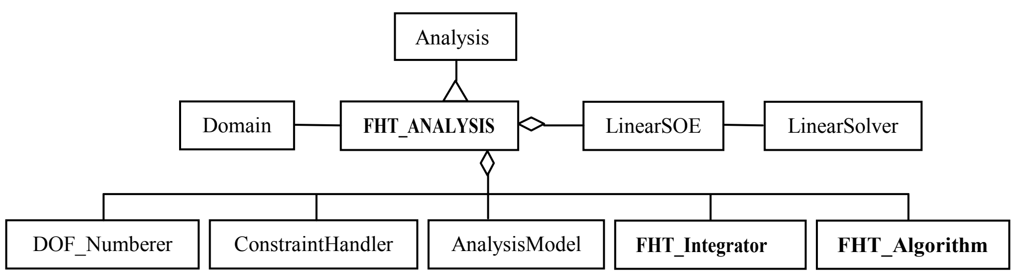


Figure 5 – Implementation of the FHT Scheme in OpenSees

With the current software, a Pentium-4, 2-GHz target PC is capable of handling a structural model in real-time with up to 15 beam-column elements and 35 degrees of freedoms. Currently, an adaptive interpolation scheme is being developed to handle the situation when a large structural model is being evaluated and the computer needs more than one milli-second to solve the equations of motion. This new scheme will be implemented in a separate target PC and will slow down or speed up the actuator motion accordingly to adapt to the prevailing computation speed of OpenSees.

VALIDATION TESTS

Two-Degree-of-Freedom Test

A two-degree-of-freedom test was conducted to evaluate the performance of the FHT system. In this test, the computation was carried out by a Simulink program executed in a real-time xPC-Target environment. The structure was a scaled model of a two-story steel frame with simple beam-to-column connections as shown in Figure 6. To take advantage of the structural symmetry, only a single column was tested with two actuators as shown in the figure. Figure 7 shows that the column was supported horizontally with the actuators in a vertical orientation. Prior to the real-time pseudodynamic test, the stiffness of the column was measured with a static test by moving the actuators slowly one at a time. The measured stiffness properties are shown in Table 2. They include the flexibility of the supporting frame. Table 2 also shows the assumed story mass carried by the column and the resulting natural frequencies. For the real-time pseudodynamic test, the NS component of the 1940 El Centro ground motion was used with the peak ground acceleration scaled to 0.3g. The response of the column remained in the linearly elastic range so that the results could be assessed with numerical simulations. The integration time step was 0.01 sec and ten iterations were used per time step. To compensate for the various delays in the control system and actuator response, a feed-forward control was used to supplement the PID control.

Table 2 - Structural Properties for the Two-Degree-of-Freedom Test
(1 Kip = 4.45 kN; 1 lb = 4.45 N; in. = 25.4 mm)

Stiffness (Kip/in.)	Mass (lb-sec^2/in.)	Frequencies (Hz)
$\begin{bmatrix} 432.6 & -201.6 \\ -201.6 & 115.6 \end{bmatrix}$	$\begin{bmatrix} 97.0 & 0.0 \\ 0.0 & 97.0 \end{bmatrix}$	$\begin{bmatrix} 2.1 \\ 11.8 \end{bmatrix}$

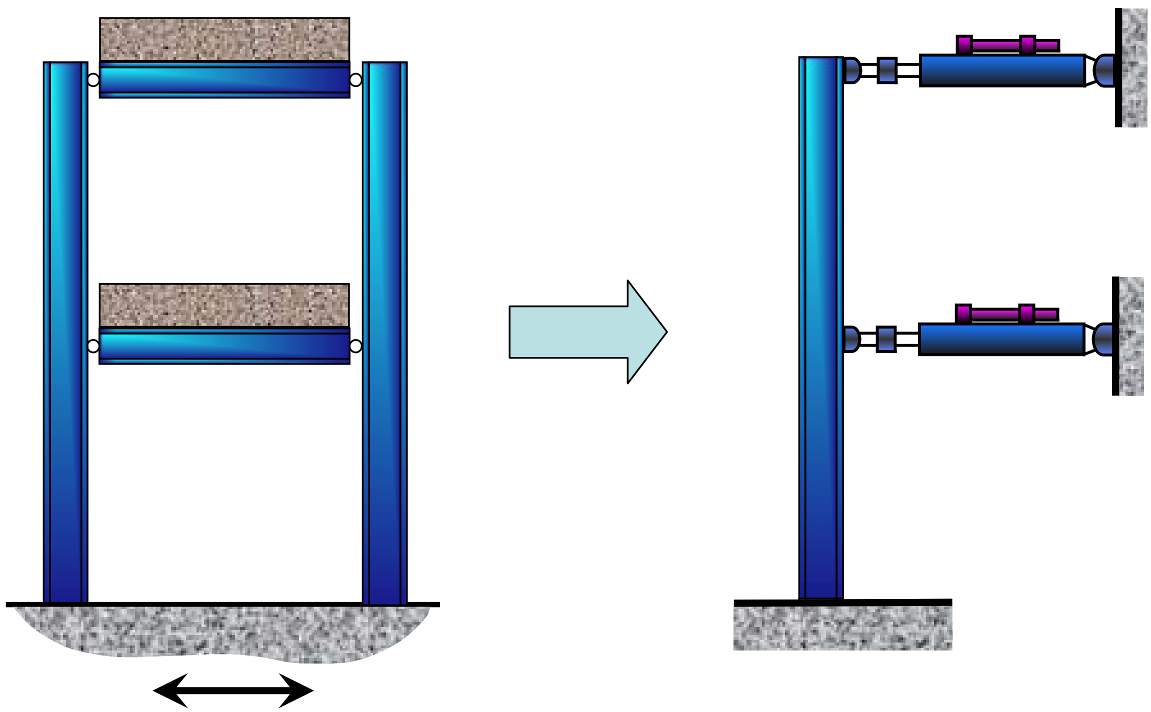


Figure 6 – Structural Model for the Two-Degree-of-Freedom Test

The displacement responses obtained from the test are compared to the exact numerical solution and results of a real-time simulation in Figure 8. The exact numerical solution was obtained by a pure simulation using the measured stiffness shown in Table 2 with no actuators involved, while the real-time simulation was conducted with actuator models considering the actual dynamics of the actuators and test specimen and with the actual servo-controller using the system configuration described in a previous section. In the real-time test and simulation, damping was assumed to be 4% of the critical for each mode. However, for the exact numerical solution, damping in each mode was assumed to be 6% of the critical. The difference in damping is to account for the additional damping effect introduced by the test specimen. It can be seen from Figure 8 that the results obtained from the three cases are all very close to each other, while the real-time simulation results show a little bit more damping. This is probably due to fact that the damping assumed for the specimen model for the real-time simulation was a little too high.

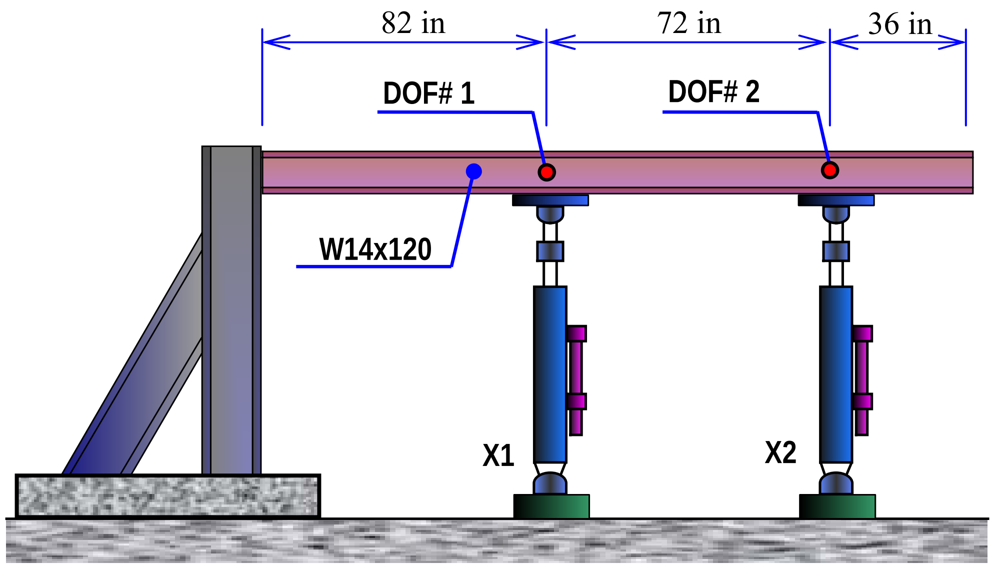
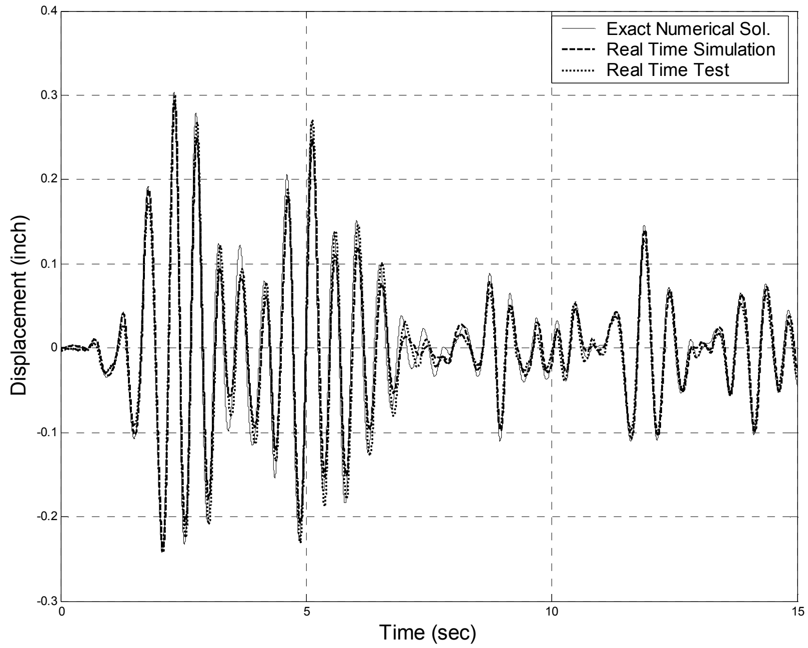


Figure 7 – Schematic of the Test Setup (1 in. = 25.4 mm)

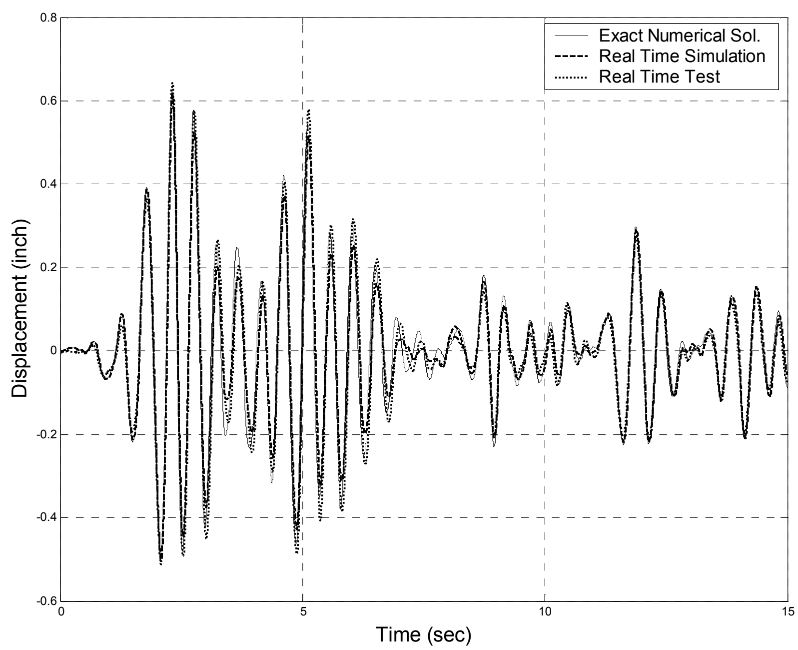
Substructure Test

A substructure test was conducted with OpenSees using the same column that was used in the previous test but with a single actuator. The structural model is shown in Figure 9. The design of the structure was largely governed by the available test column, actuator capacity, and test setup. For simplicity, all the members were assumed to be W14×120. Grade 50 steel was used. The actual yield strength of the steel was, however, 379 MPa (55 ksi) according to mill report. This structure had a floor mass of 4.2×10^4 kg (0.24 kip-sec^2/in.) and a roof mass of 2.1×10^4 kg (0.12 kip-sec^2/in.). The dashed line in Figure 9 represents the experimental specimen to be tested physically. The rest of the structure was defined as the analytical substructure. A flexibility-based nonlinear beam-column element model was used to model the analytical part. Since only one actuator was used during this test to control the horizontal displacement of the test column at its connection with the first floor, a hinge was introduced at this connection to release the moment reaction of the column. All other connections in the structure were modeled as rigid. An analytical truss element was also created to account for the axial restoring force of the test column. As a result of this model, the column was tested as a cantilever. The initial stiffness of the test column including the flexible support was measured to be 2.28 kN/mm (13 kips/in.).

A model of the entire structure was developed and analyzed with OpenSees for comparison purpose. In this model, a rotational spring was introduced at the support of the test column to account for the flexible support. The calculated stiffness of the cantilever column on a fixed base is 3.0 kN/mm (17.25) kips/in. Hence, the rotational stiffness of the flexible support was estimated to be 2.15×10^5 kN-m/ rad. (19×10^5 kips-in/rad.). The frequencies of the first 3 modes were calculated to be 14.33, 41.47, and 241.1 rad./sec, respectively. Rayleigh damping was used, with the damping for the first two modes set to 2% of the critical for both the test and the numerical simulation. The parameter α of the integration scheme was set to zero, resulting in the trapezoidal method, and the time step was 0.01 sec. The structure was subject to the NS component of the 1940 El Centro with the peak acceleration scaled to 0.25g. The magnitude of the ground motion was selected so that the structural response remained linearly elastic. Results from the real-time FHT test are compared to the numerical simulation in Figure 10.



(a) Displacement Response at 1st Story



(b) Displacement Response at 2nd Story

Figure 8 - Displacement Responses from Real-Time Test and Simulations (1 in. = 25.4 mm)

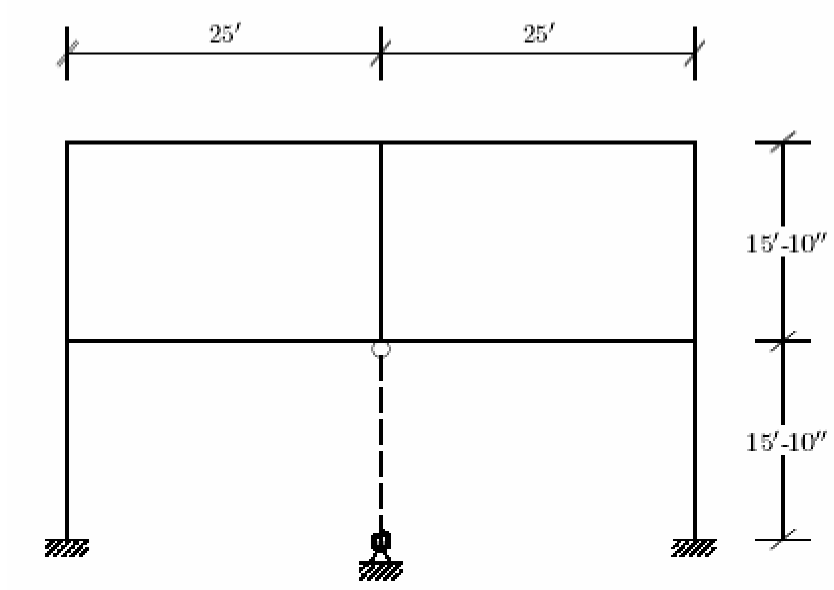


Figure 9 – Structural Model for the Substructure Test

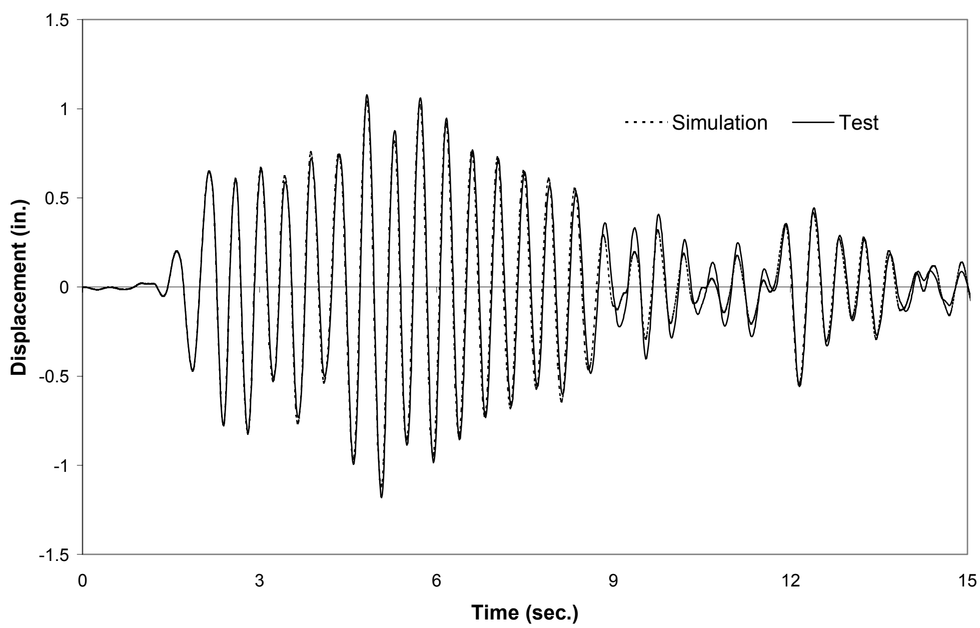


Figure 10 – Displacement Time History from the Substructure Test

CONCLUSIONS

The key features and functionality of the Fast Hybrid Test system developed at the University of Colorado as part of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) are presented in this paper. The system is based on the pseudodynamic test method but can achieve a loading rate that approaches the real-time response of a structure under earthquake excitation. The FHT system presented here has several unique features. It has a flexible system architecture and incorporates a general finite element analysis framework OpenSees for nonlinear substructure analysis. It is also the first real-time pseudodynamic test system that is based on an unconditionally stable implicit time integration scheme that provides a robust computational environmental for large-scale structural response simulations. The reliability and performance of the system have been demonstrated with validation tests conducted on a linearly elastic steel column. Currently, the multi-site testing capability is still under development.

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REFERENCES

1. Dermitzakis SN, Mahin SA. “Development of substructuring techniques for on-line computer controlled testing.” UBC/EERC-85/04, Earthquake Engineering Research Center, University of California, Berkeley, CA, 1985.
2. Nakashima M, et al. “Integration techniques for substructure pseudodynamic test.” Proceedings of the Fourth U.S. National Conference on Earthquake Engineering, Vol. II, Palm Springs, CA, 1990: 515-524.
3. Shing PB, Bursi OS, Vannan MT. “Pseudodynamic tests of a concentrically braced frame using substructuring techniques.” Journal of Constructional Steel Research, Vol. 29, 1994: 121-148.
4. Nakashima M, Masaoka N. “Real-time on-line test for MDOF systems.” Earthquake Engineering and Structural Dynamics, Vol. 28, 1999: 393-420.
5. Magonette G, Pegon P, Molina FJ, Buchet P. “Development of fast continuous pseudodynamic substructuring tests.” Proceedings of the Second World Conference on Structural Control, Kyoto, Japan, 1998.
6. Darby AP, Blakeborough A, Williams MS. “Real-time substructure tests using hydraulic actuators.” Journal of Engineering Mechanics, ASCE, Vol. 125 (10), 1999: 1133-1139.
7. McKenna FT. “Object-oriented finite element programming: frameworks for analysis, algorithms and parallel computing.” Ph.D. Dissertation, University of California, Berkeley, CA, 1997.
8. Shing PB, Nakashima M, Bursi O. “Application of pseudodynamic test method to structural research.” Earthquake Spectra, Vol. 12 (1), 1996: 29-56.
9. Hughes TJR. “Analysis for transient algorithms with particular reference to stability behavior.” Belyschko T, Hughes TJR, Editors. Computational methods for transient analysis. Amsterdam: North-Holland, 1983.
10. Shing PB, Vannan MT, Carter E, "Implicit time integration for pseudodynamic tests," Earthquake Engineering and Structural Dynamics, Vol. 20(6), 1991: 551-576.