
Figure 1. Typical test at the National Center for Research on Earthquake Engineering in Taiwan

Variations in Physical Test Equipment and Computer Simulation Tools for Civil Structural Hybrid Simulation

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ABSTRACT: For the two primary types of hybrid simulation in civil-structural and seismic engineering, real-time and quasi-static, there is a large variation in the requirements for physical test equipment and computer simulation tools. The variations in the physical test equipment are most evident in the size and capacity of the hydraulic actuation system. The differences in computer simulation relate to the speed for which the models are solved and information is communicated to the physical test system. This paper will review the conventional techniques currently employed to physically test full civil structures; describe how hybrid simulation combines computer simulation with these physical techniques to effectively characterize the properties of substructures; and finally explore the basic system architectures of the two types of hybrid simulation that have been successfully deployed by leading universities with the help of MTS Systems.

1 INTRODUCTION

1.1 HYBRID SIMULATION TECHNOLOGY

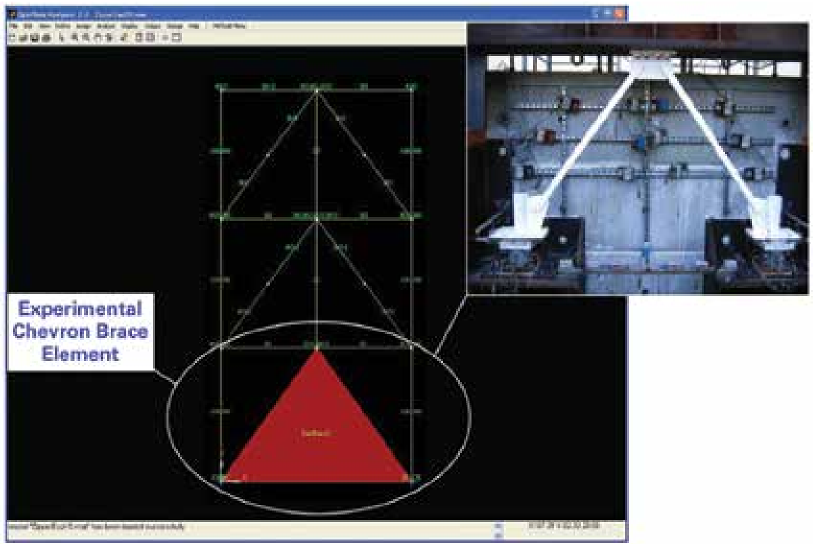
By simultaneously combining physical testing of substructures with computer models of the remainder of the structure, hybrid simulation technology provides a complete picture of how events such as earthquakes can affect large structures such as buildings and bridges without having to physically test the entire structure.

Hybrid simulation technology brings a new level of reality to civil engineering laboratory tests. By integrating computer simulation and physical testing, hybrid simulation more accurately captures the effects that a substructure has on the overall structure, while subjecting the substructure to the forces and motions it would experience if it were in-place within the complete structure.

1.2 LABORATORY TEST EQUIPMENT TECHNOLOGY

Most civil-structural and seismic test laboratories have the equipment needed to perform tests ranging from basic material characterizations to full structural evaluations. A typical laboratory tool-set includes hydraulic actuators, control systems, hydraulic pumps, load cells, displacement transducers, connections (swivels or tables) and reaction structures.

Because of cost constraints, most laboratories have equipment designed to perform slower, or quasi-static, tests. The equipment needed to perform dynamic tests, however, requires a large amount of hydraulic power – larger pumps supply large amounts of fluid to actuators with oversized servovalves. Additionally, these tests require an array of dynamic load and displacement measurement devices and advanced controllers capable of running more sophisticated techniques to effectively control and monitor multiple states of motion.

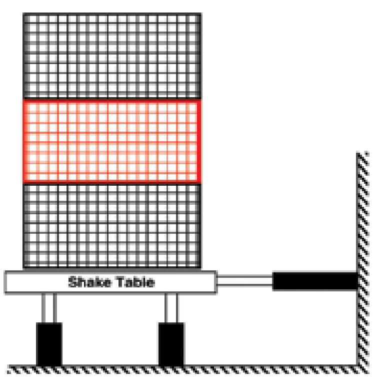


Depiction of the Experimental Element Concept (Schellenberg)

2 CONVENTIONAL CIVIL-STRUCTURAL AND SEISMIC TESTING TECHNIQUES

2.1 FULL DYNAMIC TESTING

Full dynamic testing is performed by subjecting a civil-structural specimen to the simulated motions of an earthquake event using a seismic simulator, or shake table (see the three-story building diagram below). These tests are conducted in real-time so that the true dynamics of the earthquake are imparted to the structure. The primary challenge of such a test lies in achieving the degree of system control necessary to ensure accurate reproduction of the exact motions of the ground under the test specimen.



Typical Seismic Simulator Physical Test (Reinhorn)

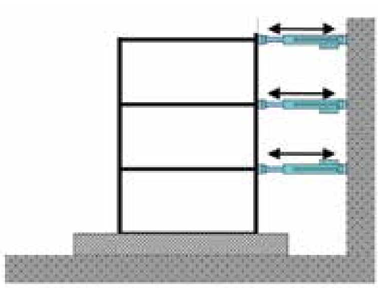
Earthquake	Peak Ground Acceleration (PGA)	Peak Ground Velocity (PGV)	Peak Ground Displacement (PGD)
Chi-Chi, Taiwan 20-Sep-1999	0.364 g	0.554 m/s	256 mm
Kobe, Japan Kobe 16-Jan-1995	0.821 g	0.813 m/s	177 mm
Northridge, CA 17-Jan-1994	0.617 g	0.408 m/s	85.7 mm

Typical Earthquake Ground Motion Characteristics (PEER)

The characteristics of the motions generated by the shake table are unique to civil structural and seismic testing as shown in the above figure. The peak displacements are much greater than the vibrations induced in an aerospace or ground vehicle environment.

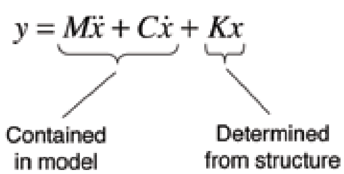
2.2 PSEUDODYNAMIC TESTING

The pseudodynamic test method combines well-established structural dynamics analytical techniques with experimental testing. It is a reliable, economic and efficient method for evaluating large-scale structures that are too large or massive to be tested with a shake table. The base of the structure is fixed in the laboratory and the motions of the earthquake are applied via hydraulic actuators at significant locations throughout the structure.


Typical Pseudodynamic Physical Test (Reinhorn)

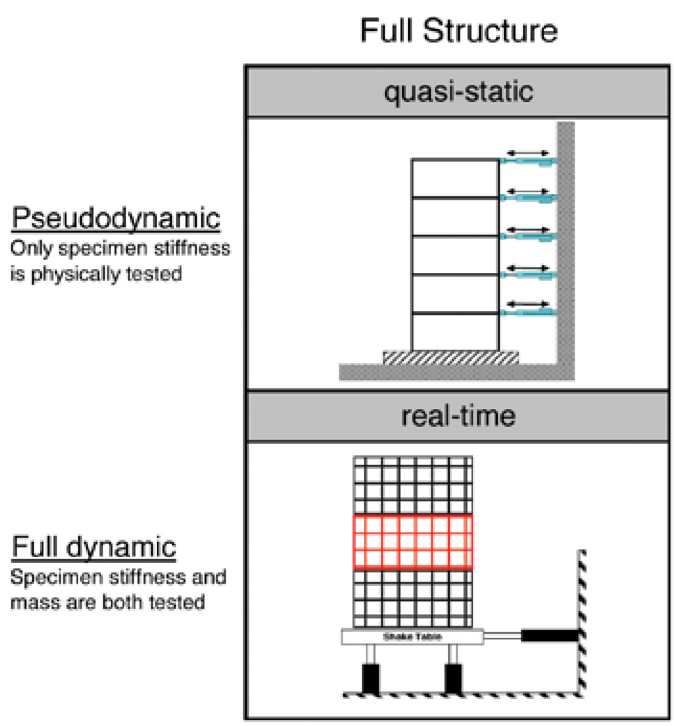
In pseudodynamic testing the complete test structure is first idealized as a discrete-parameter system, so that the motion of the system can be described by ordinary second-order differential equations.

Secondly, assumptions are made for the inertial and viscous damping characteristics of the system according to the figure below. The structural restoring forces, on the other hand, are directly measured during an initial test where force is applied to the structure at a slow, or quasi-static, rate. A step-by-step numerical integration method is used to gather and append these experimental values to the system equations. Once the equations have been determined by the first experiment, a simulated earthquake excitation is imposed on the test structure with results from the model. Thus, the quasi-statically imposed displacements of the test structure will resemble those that would be generated if the structure were tested dynamically.



Equation of Motion Separation for Pseudodynamic Technique

The following diagram shows the differences between the two conventional testing methods.



Comparison of Conventional Testing Techniques

3 CIVIL HYBRID SIMULATION

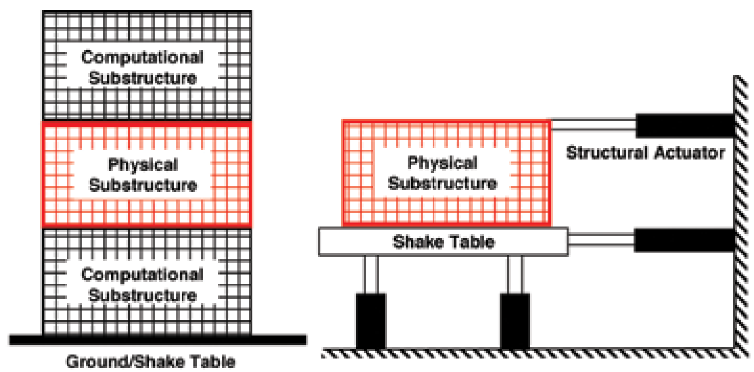
3.1 HYBRID SIMULATION

Hybrid simulation, which can be used to perform both full dynamic and pseudodynamic testing, is defined by the concept of substructuring. The full dynamic and pseudodynamic test methods described above involve the testing of complete structures. The hybrid simulation method includes a physical test of a portion of the structure and the rest of the structure is modeled in a computer simulation. The computer simulation is generally performed with finite elements that will most accurately represent the dynamic properties of the simulated structure.

The physical test recreates the boundary conditions within the computer model. In the above example, the shake table represents the interface between the first and second floor of the building and the structural actuator represents the interface between the second and third floors of the building.

Hybrid simulation can also be broken into the categories of dynamic and pseudodynamic. The above is an example of a full dynamic hybrid simulation with all of the mass being included in the test article. A variation of this simulation can also be conducted with the removal of the nonstructural components, or mass components of the physical test specimen. This simulation is called real-time pseudodynamic where the damping properties of the test specimen remain a part of the physical specimen according to the following equation.

The full spectrum of civil structural techniques is shown in the following chart. This chart illustrates the differences between conventional and hybrid simulation (sub-structuring) and the contrast between pseudodynamic and dynamic simulation as well.



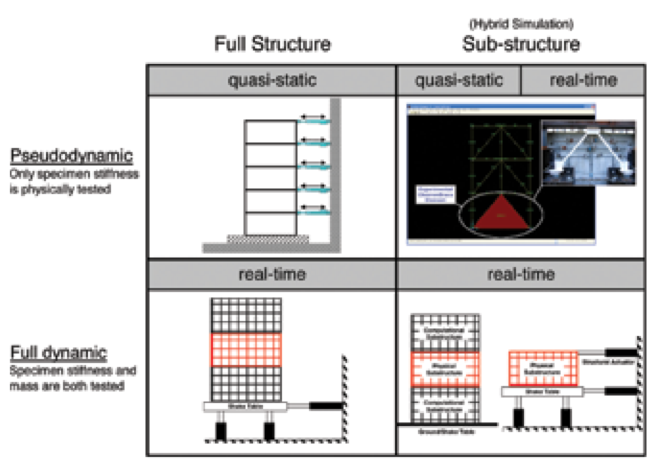
Hybrid Simulation Example (Reinhorn)

4 QUASI-STATIC HYBRID SIMULATION

4.1 MOTIVATION

Quasi-static hybrid simulation is used to evaluate substructures that predominantly contribute stiffness and strength to the complete structure. The forces and motions in a quasi-static simulation are applied at an artificially slow rate to allow for a more detailed study of a structure and to accommodate the limited capacity of the hydraulic actuators and pumping systems of most civil engineering laboratories.

The typical system set-up for a quasi-static hybrid simulation includes a computer simulation PC which runs the finite element model. Commands for the physical



Comparison of Conventional and Hybrid Simulation Testing Techniques test are communicated to the test PC via an ethernet (TCP/IP) connection. The test PC interprets the commands and sends a signal to the servocontroller which in turn activates a closed-loop control algorithm to move the actuator to the desired location. The resulting state from the computer simulation command is then communicated back up the same chain to the computer simulation PC.

4.2 PHYSICAL TEST EQUIPMENT

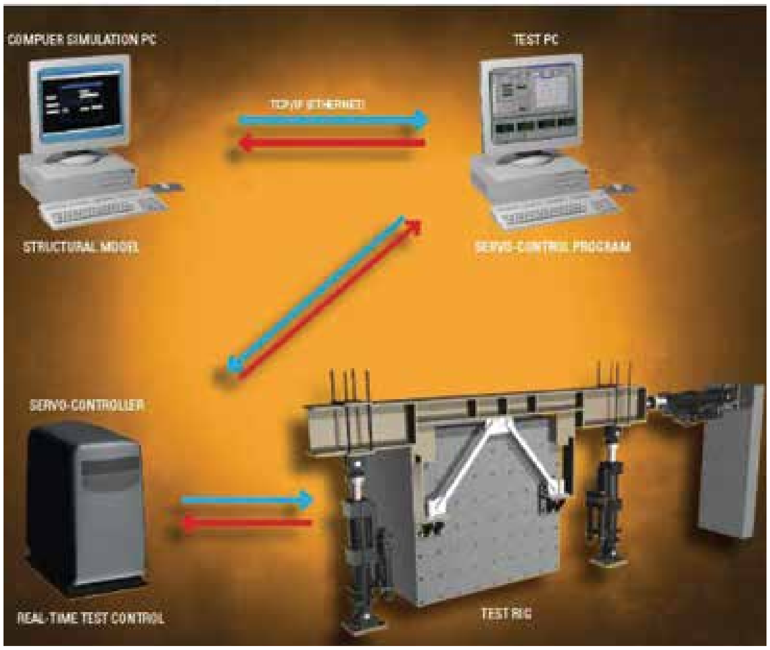
The physical test equipment required for a quasi-static hybrid simulation is more typically found in a civil structural laboratory and is also used to perform more conventional tests. Hydraulic actuators are designed for slow cycles (maximum 1-2 Hz), and the requirement of hydraulic fluid flow to each of the actuators is typically in the range of 115 to 230 liters per minute. The operation of three or four of these actuators simultaneously in a hybrid simulation is achievable with the pumping systems found in most civil structural laboratories.

Displacement and force measurement transducers must also measure relatively slow changes in position and load. A magneto-strictive linear-position transducer is typically used for displacement measurement, and a load cell is typically used for force measurement.

4.3 COMPUTER SIMULATION TOOLS

There is a wide choice of computer simulation tools based in finite elements that are typically used for the analysis of civil structures. The implementation of hybrid simulation is dependent on the ability to create a new experimental element in the finite element code. The speed of a hybrid simulation is highly dependent on the speed at which the finite element code can perform the calculations to change the state of the model from current to future time steps.

To bridge between the computer simulation and physical test environments, a communication framework is needed to exchange command and feedback signals. Most typically the signals are sent between computers via a TCP/IP connection which can be within the same laboratory or geographically distributed. Another important function of the framework is to map the control points and degrees of freedom in the computer simulation to the actuator control channels in the physical test equipment.

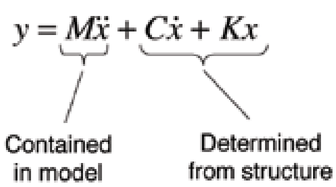


Quasi-static Hybrid Simulation System Diagram

5 REAL-TIME HYBRID SIMULATION

5.1 SCOPE OF THE SIMULATION

Real-time hybrid simulation is used to evaluate substructure or components that contribute damping or inertia effects to the complete structure. A real-time hybrid simulation requires high-force, dynamic structural actuators and large hydraulic power units to evaluate all dynamic properties (mass, damping and stiffness) of the substructure. Real-time hybrid simulation also means that the computer simulation is performed in real-time. The computer model is developed in a tool such as Simulink® and downloaded to a real-time target PC. A special high-speed connection is made directly to the real-time test controller via SCRAMNet® reflective memory.



Equation of Motion Separation for Real-time Pseudodynamic Technique

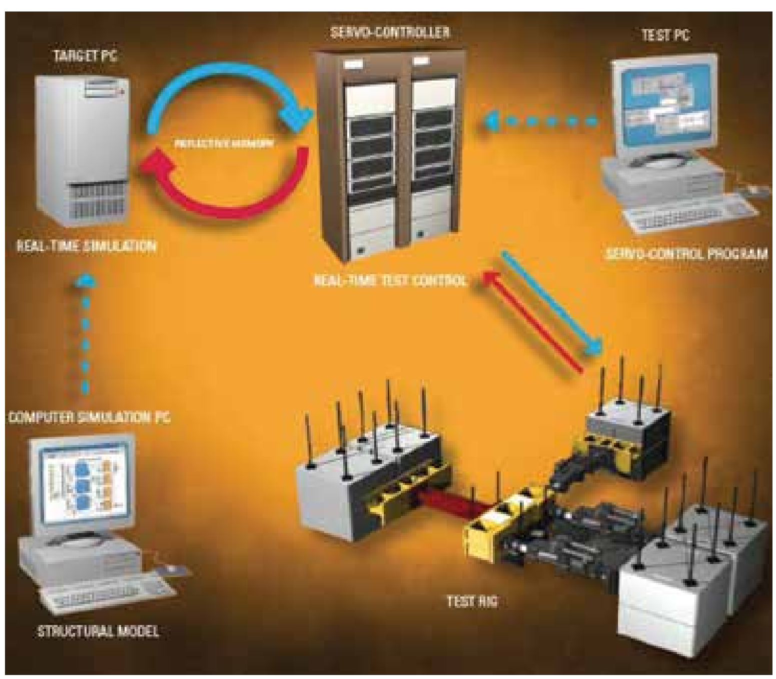
The difficulty of accurately controlling the physical test escalates when performing a real-time hybrid simulation. The test controller must react instantly to the computer simulation while maintaining three parameters of motion (displacement, velocity and acceleration).

5.2 PHYSICAL TEST EQUIPMENT

Real-time requires high-speed, high-force hydraulic actuators along with a large amount of hydraulic pump capacity to deliver appropriate forces and motions. A real-time hybrid simulation requires high-force, dynamic structural actuators and large hydraulic power units to evaluate all dynamic properties (mass, damping & stiffness) of the substructure. Actuation is achieved with actuators designed for high-frequency, high-speed fatigue tests. Displacement and load measurements are provided by LVDTs and delta-pressure cells, respectively.

5.3 COMPUTER SIMULATION TOOLS

The system's Computer Simulation PC features real-time dynamic modeling software, such as Simulink, which can run in real-time when downloaded to the system's xPC Target® PC. Simulink is a general purpose dataflow programming environment, widely used in universities and industry worldwide. After developing a Simulink model on the Computer Simulation PC, Real-Time Workshop® can be used to download it to the xPC Target PC where a connection is established to the real-time test controller via reflective memory. The xPC Target PC runs a kernel



Real-time Hybrid Simulation System Diagram that provides deterministic performance on PC hardware for running real-time models. High performance is achieved by booting the kernel rather than DOS or Windows. The xPC Target kernel is tuned for minimal overhead and maximum performance with published sample rates approaching 100 kHz.

6 CONCLUSIONS

The two approaches to hybrid simulation require significantly different physical test equipment and computer simulation tools. Quasi-static hybrid simulation leverages physical test equipment and computer simulation tools that are commonly found in civil structural laboratories. Real-time hybrid simulation requires specialized tools for both physical teat equipment and computer simulation that are focused on providing maximum speed.

Most civil engineering research institutions will benefit from some degree of hybrid simulation technology. By integrating computer analysis and physical testing, hybrid simulation enables them to efficiently model a significant portion of a structure on a computer, while simultaneously conducting physical tests on critical substructures or components, thus eliminating the need to perform expensive large-scale physical tests on full structures using multi-degree-of-freedom seismic simulators. Only a handful of labs, however, have the resources to set-up and maintain effective hybrid simulation facilities on their own. To realize the full benefits of hybrid simulation, the rest require more user-friendly solutions that minimize IT requirements and maximize their lab's research potential by facilitating the sharing of test data across projects and peer institutions.

Through the collaboration of leading universities in the NEES Program – including the University of California Berkeley, State University of New York Buffalo, the University of Colorado Boulder, the University of Nevada-Reno – and industry partners such as MTS, an array of affordable, high-performance hybrid simulation solutions is available to meet the technical and budgetary requirements of a wide range of civil engineering labs.

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