Chapter 2
Background

Abstract This chapter presents the technical background and literature review on the development of hybrid simulation in the fields of substructuring techniques, integration schemes, continuous and real-time hybrid testing, local and geographically distributed hybrid testing, and experimental and numerical errors in hybrid testing.

Keywords Hybrid simulation · Substructuring · Integration schemes · Continuous testing · Geographically distributed testing · Experimental and numerical errors

2.1 Introduction

The original idea of obtaining the seismic response of a system through a hybrid numerical and experimental model dates back to the late 1960s, when it was first proposed in a Japanese paper by Hakuno et al. (1969). A single-degree-of-freedom (SDOF) cantilever beam was analyzed under seismic loadings using an analog computer in order to solve the equation of motion in combination with an electromagnetic actuator to impose the load on the structure. In order to improve the accuracy of the simulation, the authors suggested using digital computers.

The first major step in the use of digital computers and discrete systems was first taken in the mid-1970s. Takanashi et al. (1975) established the hybrid simulation method in its present form by studying the structural system as a discrete spring-mass system within the time domain. This allowed hybrid simulation to work with typical quasi-static loading systems and provided the necessary foundation to apply hybrid simulation to structural engineering.

Advancements in the development of faster and more reliable testing and computational hardware paved the way for the researchers to expand the capabilities and validation of the hybrid simulation test method. During the late 1970s, 1980s and early 1990s, efforts in Japan and the USA were undertaken in this regard

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that are outlined in Mahin and Shing (1985), Takanashi and Nakashima (1987), Mahin et al. (1989) and Shing et al. (1996). A comprehensive review of the developments in the fields of efficiency, accuracy and performance of hybrid simulation methods can be found in Saouma and Sivaselvan (2008).

2.2 Substructuring Techniques in Hybrid Simulation

Before the mid-1980s, most applications of hybrid simulation required testing of the complete structural system. Consequently, these tests were expensive and required a large-scale testing facility. However, the damage in a structure due to seismic loads could be located within a few critical regions, and as a result, in many cases, it is not necessary to test the entire structural system.

The concept of substructuring, which is similar to the concept of domain decomposition employment in finite-element analysis, is based on splitting the domain of the structure into experimental and numerical substructures and conducting separate analyses on each part, while ensuring the interface constraints are continuously verified both in terms of compatibility and in terms of equilibrium. By using substructuring techniques typically applied to conventional dynamic analysis, the complete structure can be partitioned into several subassemblies. As a result, the parts of a structure that experience complex behavior, which may be difficult to model numerically, are tested physically, while those parts of the structure that have a consistent behavior and are well defined are analyzed numerically.

Dermitzakis and Mahin (1985) suggested utilizing substructuring techniques in order to divide a structure into experimental and numerical subassemblies and perform substructure hybrid simulations. A major advantage of the substructuring technique is that it reduces the space required in order to perform hybrid simulation. Thereby, it facilitates large-scale testing and increases the ability to consider specific local component behavior. Recent advances in substructuring techniques include the implementation of overlapping techniques (Wang et al. 2012; Hashemi and Mosqueda 2014; Del Carpio Ramos et al. 2015) and model updating techniques in hybrid simulation (Hashemi et al. 2014; Elanwar and Elnashai 2015; Shao et al. 2015).

2.3 Time-Integration Algorithms in Hybrid Simulation

One of the most important components of hybrid testing that has a crucial role in the stability and accuracy of the simulation is the numerical integration algorithm. Although there have been many advancements in the development of numerical time-stepping algorithms for pure numerical simulations, most of these methods are not well suited for hybrid simulation. Therefore, there have been many efforts to develop stable, efficient and accurate algorithms for time-integration schemes, specifically for hybrid simulation.

During hybrid simulation, similar to pure finite-element analysis, the equation of motion is discretized in space utilizing elements that are connected with the nodes. This process is carried out to make the system suitable for numerical evaluation and implementation on digital computers. The spatially discretized differential equation can further be simplified utilizing element assembly from local to the global structural DOFs containing all the element contributions:

$$[\mathrm{M}]\{\ddot{u}\} + [\mathrm{C}]\{\dot{u}\} + [\mathrm{K}]\{u\} = \{\mathrm{P}\} \tag{2.1}$$

where M, C and K are, respectively, the mass, damping and stiffness matrices assembled from nodal and element properties, $\ddot{u}, \dot{u}$ and u are, respectively, the vectors of nodal accelerations, velocities and displacements for the global DOFs of the structure and P is the vector of system interface and external forces. Note that, while C and K may change during the analysis, M will be regarded as a constant, assuming mass conservation even during failures and collapse.

The equation of motion, which is a second-order ordinary differential equation (ODE), is next discretized in time. This process is performed to advance transient (time-varying) solutions step by step, assuming idealized properties over small time steps. These properties, depending on the scheme considered, are obtained through a set of equations, which can be written in the form of Eqs. 2.2 or 2.3:

$$u_{i+1} = f(u_i, \dot{u}_i, \ddot{u}_i, u_{i-1}, \dot{u}_{i-1}, \ddot{u}_{i-1}, \ldots) \tag{2.2}$$

$$u_{i+1} = f(u_i, \dot{u}_{i+1}, \ddot{u}_{i+1}, u_{i-1}, \dot{u}_i, \ddot{u}_i, \ldots) \tag{2.3}$$

Given that Eq. 2.1 is satisfied with the solution u_i, the task of numerical integration is to advance the solution by finding a displacement increment Δu in such way that Eq. 2.1 is also in equilibrium for $u_{i+1} = u_i + \Delta u$. The various numerical integration schemes can be classified into two types: explicit or implicit.

An explicit scheme, as illustrated in Eq. 2.2, computes the response of the structure at the end of the current time step $(i+1)$, exclusively based on the state of the structure at the beginning of step (i) or earlier. This is an attractive property for hybrid testing, because the actuators are commanded a target displacement without the knowledge of the specimen properties at the target.

An implicit scheme, as illustrated in Eq. 2.3, requires the knowledge of the structural response at the target displacement and is dependent on one or several values from time step $(i+1)$ in order to compute the response. Therefore, an implicit scheme involves a more complex implementation than an explicit one, often including an iterative process or a predictor-corrector algorithm.

Explicit methods are computationally very efficient, easy to implement and fast in their execution. However, the fact that an implicit scheme relies on a future term makes it more stable, regardless of the chosen time step length. In fact, explicit schemes are typically conditionally stable, while implicit schemes can be unconditionally stable (Shing et al. 1996). The implicit schemes, however, require a tangent stiffness matrix, which can be difficult to obtain from physical elements of the hybrid model. In addition, they are often used in combination with an iteration strategy such as the Newton–Raphson algorithm and lead to non-uniform rapidly decreasing displacement increments, which can introduce spurious loading cycles on the physical parts of the hybrid model. In order to address these issues, integration methods have been introduced to apply the implicit iterations only in numerical substructure, while using the initial-elastic stiffness matrix for the experimental substructure to approximate its behavior (Dermitzakis and Mahin 1985; Nakashima et al. 1990; Schellenberg et al. 2009).

2.4 Continuous Hybrid Simulation

In conventional pseudo-dynamic testing methods, the load is applied to the specimen using a ramp-hold procedure. In continuous hybrid simulation testing, the load is applied smoothly, without starts and stops. There are two main reasons for running the simulation continuously. The first problem associated with ramp-hold loading is that during the hold period, reductions in the restoring force can occur due to force relaxation. Force relaxation is caused by stress relaxation, which is the decay in stress over time while the strain is held constant. Another reason is that the modern servo-hydraulic controller systems run at the sampling rate of 1024 Hz and above. As a result, signal generation for actuator commands should be performed at this sampling rate, which is deterministic. On the other hand, in hybrid testing there are inevitable time lags and delays that are generally non-deterministic. Therefore, these two processes should be synchronized to avoid systematic errors and also enable the achievement of a smooth loading for the test structure and a reduction in overall testing time. For this purpose, a predictor-corrector command generation algorithm is placed between computation solver and the controller to generate the command displacement for the actuator controller, while the computation driver solves the equation of motion. Once the target displacement is computed, the algorithm corrects the command displacement path toward the target displacement.

Takanashi and Ohi (1983) first introduced the concept of continuous loading and fast hybrid testing. Mosqueda et al. (2005) presented a system for continuous hybrid simulation with distributed experimental sites connected through the Internet. Since the time required for network communication is random, a solution using an event-driven controller was proposed. The resulting system was an event-driven version of the system proposed by Nakashima and Masaoka (1999), in which the tasks of integration of the equation of motion and signal generation run as two different processes.

2.5 Real-Time Hybrid Simulation

Hybrid simulation does not require dynamic loading, since dynamic effects such as inertia and damping forces are considered in the numerical portion of the equations of motion. However, the development of velocity-dependent structural components and devices to control the response of structures caused researchers to seek to expand the capabilities of hybrid simulation to work in real time.

Real-time hybrid simulation has been proposed to fully capture strain rate, damping and inertial effects by computing each numerical integration time step of the experiment in exactly that amount of time. Studies on real-time hybrid simulation began in the early 1990s and have continued to the present as more velocity-dependent systems are applied to structures. The major difference between real-time hybrid simulation and quasi-static hybrid simulation is that in addition to displacements, velocities are controlled for the experimental portion of the test.

Nakashima (2001) presented an overview of the development of real-time hybrid simulation systems. To conduct real-time testing, it was essential to develop a procedure that allowed for continuous real-time loading without interruption of the displacement signals sent to the digital controller. While the initial tests (Horiuchi et al. 1999; Nakashima and Masaoka 1999) dealt only with SDOF systems, more difficulties arise as a result of controlling the multiple actuators needed for MDOF tested structures. As a result, many of the hybrid simulation studies focused on resolving some of these limitations (Reinhorn et al. 2004; Shing et al. 2004; Bonnet 2006; Shao and Reinhorn 2012). Real-time hybrid simulations have been successfully conducted for the investigation of the dynamic behavior of structures with rate-dependent devices (Wu et al. 2007; Carrion and Spencer 2008; Karavasilis et al. 2011; Chen and Ricles 2012).

2.6 Geographically Distributed Hybrid Simulation

The popularity of hybrid simulation among structural engineering researchers has grown to a great extent. Geographically distributed testing is one recent concept that has been developed from the use of substructuring techniques and benefited from technological advances in data transfer and computing.

The concept of geographically distributed testing is that individual substructures do not need to be within the same facility, but can be linked by either the Internet or another methods of data transfer. By breaking a model into selected subassemblies and distributing them within a network of laboratories and computational sites, a researcher is able to take advantage of different capabilities available at the various facilities.

Campbell and Stojadinovic (1998) first suggested the geographical distribution of structural subassemblies within a network of laboratories, where the individual sites are connected through the Internet. Mosqueda et al. (2005) developed a three-loop architecture that allowed for the first time the execution of continuous, geographically distributed hybrid simulations with multiple subassemblies. Compared to previous geographically distributed hybrid simulations that utilized a hold-and-ramp loading procedure, it was possible to significantly reduce execution times and eliminate force relaxation problems. Kim et al. (2012) presented a framework used to successfully conduct geographically distributed real-time hybrid simulation tests.

2.7 Error Propagation in Hybrid Simulation

While hybrid simulation is an attractive test method, it is prone to both numerical and experimental errors that must be carefully addressed to achieve reliable results (Ahmadizadeh and Mosqueda 2009). For example, in substructure hybrid simulations, a significant portion of a structure is typically modeled numerically, with the simulation result being highly dependent on the performance and stability of the computation. Experimental errors can also be introduced into the simulation mainly through two sources of error: (1) errors generated by the difference in the imposed displacement versus the computed displacement or (2) errors generated by incorrect force measurements from the experimental substructure, which is then used to solve the equation of motion. Since hybrid simulation is a closed-loop system and also a stepwise process, these errors can accumulate, resulting in an overall decrease in the accuracy of the hybrid simulation and sometimes instability of the simulation (Hashemi et al. 2016a, b). Implementation of simplified or approximate substructuring techniques may also contribute in the form of modeling errors. Small errors can accumulate during the experiment and significantly affect the simulation results.

The propagation of random and systematic errors in hybrid simulation has been thoroughly studied. Shing and Mahin (1983), Nakashima et al. (1985), and Thewalt and Mahin (1987) provided significant contributions to identifying and determining the characteristics of experimental errors within hybrid simulation tests. It was found that systematic overshoot error increases the apparent damping of the system, while systematic undershoot results in negative damping and can produce an increase in the response, particularly corresponding to the higher-frequency response modes. Mosqueda et al. (2005), Ahmadizadeh and Mosqueda (2009) and Hashemi et al. (2016a, b), provide detailed explanations and summaries on errors in hybrid simulations, including errors based on modeling, implementation techniques and the experimental setup.

2.8 Collapse Simulation Through Hybrid Testing

Understanding and modeling structural failure under dynamic loadings remain a difficult challenge in structural engineering. Specifically, structural behavior through collapse has become increasingly important for applications in performance-based design. Although experimental simulations of structures have been conducted to investigate the seismic capacity of various structural systems and critical components, few hybrid tests have examined structures up to collapse with significant geometric and material nonlinearities (Schellenberg et al. 2008a, b; Shoraka et al. 2008; Wang et al. 2008, 2012; Del Carpio et al. 2014; Hashemi and Mosqueda 2014; Hashemi et al. 2016a, b, 2017).

Collapse simulation of large-/full-scale structures is not always feasible due to space requirements and high costs. On the other hand, reduced-scale experiments are not always reliable due to the difficulties in reproducing local behavior such as connection details. Wang et al. (2008) simulated the seismic behavior of a one-bay, four-story steel moment frame through collapse. The simulation was geographically distributed with substructuring, considering the column bases as the experimental portion, while the superstructure was analyzed numerically.

In an effort to show the potential of hybrid testing to simulate structural behavior through collapse, Wang et al. (2012) conducted a geographically distributed hybrid test that reproduced the collapse behavior of a four-story, two-bay, steel moment frame, previously tested at the Hyogo Earthquake Engineering Research Center of Japan (E-Defence). The hybrid testing was capable of successfully tracing the response of the structure to collapse.

Hashemi and Mosqueda (2014) proposed a framework for collapse simulation of complex structures through hybrid testing that facilitates the system-level experimental testing of the structures with distributed damage through collapse. This framework uses an advanced substructuring technique that handles the interface between a complex numerical model and the physical subassembly through the use of additional sensing in the feedback loop to obtain internal member forces. This framework was later used in another study to investigate the seismic response of large-scale steel gravity and moment frames through collapse (Del Carpio Ramos et al. 2015).

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