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Development of Online Hybrid Testing via Internet and Applications for Simulation of Earthquake Responses of Structures Using Laboratory Networks

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Synopsis

Presented herein is a substructure online hybrid test system that is extensible for geographically distributed tests. In this system, a set of devices conventionally used for cyclic tests is adopted to load the tested substructures to the target displacement or the target force. Multiple tested substructures and numerical substructures using various structural program codes can be accommodated within the single framework, simply interfaced with the boundary displacements and forces. A coordinator program is developed to keep the boundaries among all substructures compatible and equilibrated. An Internet-based data exchange scheme is also devised to transfer data among computers equipped with different software environments. A series of online hybrid tests are introduced, and the portability, flexibility, and extensibility of the proposed online hybrid test system are demonstrated.

Keywords: earthquake engineering, dynamic response, online hybrid test, remote testing

1. Introduction

More than thirty years have passed since the online hybrid test (also referred to as the pseudo-dynamic test) was developed (Takanashi et al., 1978; Mahin and Shing, 1985; Nakashima et al., 1995; Shing et al., 1996; Herrera et al., 2008; Tsai et al., 2008). The test treats the dynamics of a structure numerically, while using restoring forces obtained from an associated quasi-static experiment. The test specimen used in the online hybrid test does not necessarily need physical masses that produce inertia, and can be loaded quasi-statically by means of conventional loading devices that are available in many structural laboratories. Thanks to these advantages over the shaking table test, the online hybrid test has become one of the standard experimental methods for the assessment of the seismic performance of structural components, assemblies, and systems.

Since the incipience of the online hybrid test, the concept of substructuring has been proposed, developed and applied (Dermitzakis and Mahin, 1985; Nakashima et al., 1990; Elkhoraibi and Mosalam, 2007). The online hybrid test associated with the substructure technique, also called the substructure online hybrid test, significantly increases the size of the tested structures. By exchanging data over the Internet, multiple structural laboratories located at remote sites are able to collaborate, each taking one part of the entire structure, increasing the scale at which the structure can be tested. Several notable systems were developed and demonstrated by physical applications (Pinto et al., 2004; Pan et al., 2005 a; Takahashi and Fenves, 2006; Stojadinovic et al., 2006; Yang et al., 2007; Wang et al., 2007; Mosqueda et al., 2008). However, it is not necessarily easy to extend these systems for more versatile applications because of the following limitations. One is the use of costly servo-controlled hydraulic actuators that require large capacity pumps and accumulators. They are not easily transported to other locations, either. The other is the rigid software framework that requires the source-code modification to implement the interaction between numerical and test substructures. A general approach thus far is to incorporate a user-defined experimental element into the numerical substructure models (Pan et al., 2005 a; Takahashi and Fenves, 2006).

To fully achieve the appealing features of the substructure online hybrid tests, a set of portable and flexible loading devices and an extensible software framework are devised. Chapter 2 of this paper describes the developed loading devices, which are characterized by large stroke and force capacities, accurate and flexible displacement and force control, compactness and portability, robustness, and economic efficiency, thus being available in many structural laboratories. Chapter 3 presents the extensible software framework, which is equipped with a coordinator program that makes the system more versatile, a generalized interface to encapsulate both the numerical and tested substructures, and an Internet-based data exchange scheme to realize fast and stable communication between the substructures and coordinator program. In Chapter 4, the effectiveness of the developed system is demonstrated by a series of physical applications, i.e., a physical testing of a three-story frame installed with steel plate walls, an application to an eight-story base-isolated building, a seismic simulation of a steel reinforced concrete (SRC) building with a steel tower on the top, and the distributed testing to explore the collapse behavior of four-story steel moment frames.

2. Conventional Testing Devices

An online hybrid test system that makes the maximum use of conventional test devices available in many structural laboratories consists of a hydraulic pump, a hydraulic jack, a controller, a set of measuring devices for the jack displacement and forces, and a set of computers for control and calculation, as shown in Fig. 1 This test system was first developed at Kyoto University, and has been used extensively for the past fifteen years in a nearly maintenance-free mode (Nakashima et al., 1995). The system is characterized by the strength, flexibility, portability, controllability and robustness, and key components to achieve them are the quasi-static jack, the hydraulic unit, and the digital controller, whose details are described below.

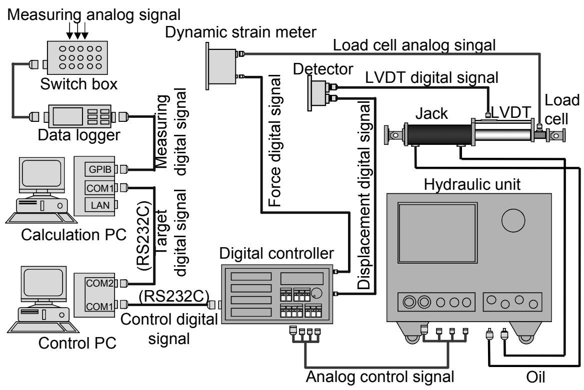

Fig.1 Typical online hybrid test system using conventional loading facilities (External loop)

2.1 Robust quasi-static jack

Compared with the dynamic actuator that is commonly equipped with a complex servo-valve, configuration of the quasi-static jack is much simpler. It consists of a jacket, a piston, and two chambers, as shown in Fig. 2. Each chamber outfits an orifice through which the chamber is able to accept/release oil from/to the hydraulic unit. When loading, the oil pressure in one of the chambers equals the supply pressure in the hydraulic unit, while the pressure in the other chamber is zero. The force imposed on the specimen equals the pressure difference between the two chambers multiplying the area of the piston. The mechanism is simple, but it is very robust and needs nearly no maintenance. Without the need of a sophisticated servo-valve, the quasi-static jack is far less expensive than the dynamic actuator.

The slow loading, ranging normally from 0.1 to 2 mm/s, is not necessarily a disadvantage. It provides a chance for close observation, and a favorable fault tolerance that can help prevent an expensive specimen seriously suffering from wrong loading. A larger supply pressure (about 70 MPa) adopted for quasi-static jacks compared to that normally assigned for dynamic actuators (about 21

MPa) is another asset; for the same cylinder size, the quasi-static jack can possess a force capacity about three times larger than that of the dynamic actuator. A larger pressure also means that the quasi-static jack is stiffer than the dynamic actuator, allowing relatively better precision in displacement control.

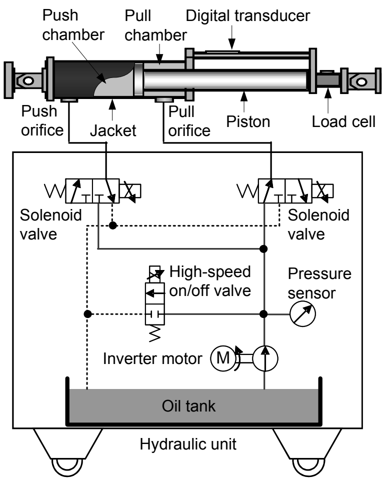

Fig. 2 Hydraulic pump system with inverter motor (At the pulling state)

2.2 Portable hydraulic unit

The hydraulic unit is designed to provide oil to the quasi-static jack and control the jack for loading and unloading according to the input signals from the digital controller. Its function is fulfilled by activating the pump with an inverter motor, two solenoid valves, and a high-speed on/off valve, as shown in Fig. 2. Once it receives the loading signal (a voltage) from the digital controller, the inverter motor starts to pump oil to one of the chambers ("push" or "pull") of the quasi-static jack. The loading speed is controlled by the frequency of the inverter motor, which is proportional to the signal voltage. The flow of the pump commonly ranges from 0.08 to 0.48 l/min, which corresponds to the frequency from 6 to 60 Hz. The "push" or "pull" direction is selected by changing the on/off mode of the two solenoid valves. The unloading action is achieved by releasing oil from the jack to the oil tank through the high-speed on/off valve. The high-speed on/off valve adopts a pulse-width modulation (PWM) control at a frequency of 20 Hz. The flow through this valve ranges from 0.15 to 1.5 l/min by modulating the width of the pulse (also called the duty cycle). In Fig. 2, the solid lines inside the hydraulic unit represent the supplying oil whose pressure is always monitored by a pressure sensor, while the dotted lines show the return oil whose pressure is always zero.

The mechanism of this hydraulic unit is naturally much simpler and most likely more robust than the servo-controlled system that requires an accumulator to collect the pressurized oil. Due to its simplicity and robustness, this hydraulic unit is almost maintenance free. In fact, the system developed fifteen years ago is still fully functional with only minimal maintenance. Because of the slow loading rate, the power needed for the pump is small. The power of the inverter pump is about 0.75 kW, while a pump used for servo-controlled actuators commonly requires a power more than 100 kW. The inverter motor, solenoid valves, high-speed on/off valve, pressure sensor and a 25 liter oil tank, are installed in a portable box, and the total weight is about 170 kg. This hydraulic unit is apparently much lighter, more compact and portable. Such characteristics enhance the possibilities of remote, distributed testing in that quite a few structural laboratories are equipped with space but not with an automatic loading system conforming to the online hybrid test.

2.3 Accurate digital displacement control

To achieve the accurate displacement control required for the accurate reproduction of earthquake responses in the online hybrid test, the proposed system employs a digital displacement transducer and a digital controller. The digital displacement transducer is attached to the quasi-static jack and feeds back the measured value to the digital controller. The digital signal can be applied directly for the displacement control without any digital/analog (D/A) or analog/digital (A/D) conversion. The digital displacement transducer has a large stroke capacity, up to ±500 mm. One of its appealing features is that the accuracy, i.e., the measuring resolution, remains constant at 0.01 mm regardless of the displacement stroke. This is different from commonly used analog displacement transducers whose accuracy is dependent on the full-stroke.

A digital controller is adopted to control the hydraulic unit using the digital displacement signal fed back from the digital displacement transducer (also called the feedback control), as shown in Fig. 3. The feedback control is defined as the internal loop, in contrast to the external loop associated with the solution of the equations of motion (Mercan and Ricles, 2007). The digital controller adopts a 32-bit micro-processor, and has a serial communication port through which it can talk with a computer, i.e., accepting the target values and loading/unloading time, and sending back the measured force and displacement. It is equipped with three input ports to collect signals from the digital displacement transducer, the load cell, and the pressure sensor of the hydraulic unit, and three output ports to send the control signals to the inverter motor, the solenoid valves, and the high-speed on/off valve, respectively.

Fig. 3 shows an example feedback control of the controller, where unloading is conducted first, followed by loading. In each step of loading or unloading, the digital controller accepts the target value (x_{n+1}) and the time (Δt) to reach the target from the control computer, and starts the feedback control to achieve the target physically. The controller first computes the subcommand signals at every 10 ms for the period of Δt, as shown by the thin solid line in Fig. 3, named "SV". By comparing the target with the current state of the jack, the controller sends the subcommand signals to the high-speed on/off valve as a pulse. After every 10 ms, the controller receives the feedback signal from the digital displacement transducer or the load cell attached to the jack, and the supply pressure signal (defined as PVP) from the hydraulic unit. The controller computes the difference between the subcommand value assigned at 10 ms later and the measured value (the thick solid line), converts the difference to the control signal, and sends it again to the pump unit. This loop continues until PVP becomes smaller than a predefined tolerance, PSF, when the controller stops the unloading action and switches to the loading action. It sends signals to drive the two solenoid valves to select the loading direction. After the solenoid valves are repositioned, the loading action starts. The controller repeats the same procedure for unloading, but this time sends frequency signals to the inverter motor for loading. This operation continues until the measured value reaches the target value within a pre-specified band of tolerance.

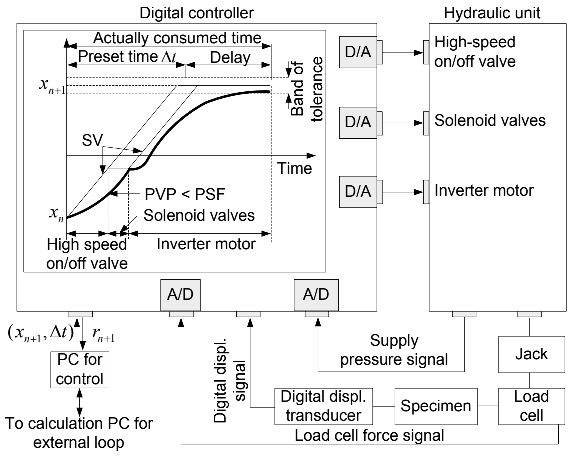

Fig. 3 Feedback control using digital controller (Internal loop)

2.4 Flexible displacement and force mixed control

Two types of control modes are available: the displacement control using the signal feedback from the digital displacement transducer, and the force control using the signal feedback from the load cell. Both controls adopt the scheme described in Section 2.3, except that an A/D module is inserted between the load cell and the digital controller. The control modes can flexibly be switched even during one test. This is made feasible by the external loop of control and the slow loading rate. This characteristic is specifically effective for tests with specimens having large disparities in the magnitude of stiffness in various loading stages. Here, the force control is used when the structure is very stiff; the displacement control is adopted once the structure becomes softer.

Two types of mixed control, namely the "displacement-force combined control" and the "displacement-force switching control", were proposed and validated (Pan et al., 2005 b). In the displacement-force combined control, one jack is operated by the displacement control, and another is operated by the force control, while in the displacement-force switching control, the jack is operated by the displacement control when the test specimen is soft but switches to the force control once the specimen becomes stiff.

3. Extensive Framework for Substructure Online Hybrid Test

The substructure online hybrid test needs an extensible framework to accommodate multiple tested substructures and numerical substructures. Considering different hardware and software environments adopted in different laboratories, the framework should be equipped with: (1) a coordinator program to seek the compatibility and equilibrium at the boundaries among all substructures; (2) a generalized interface to encapsulate each tested or numerical substructure; and (3) an Internet-based data exchange scheme capable of transferring data among computers having a variety of software environments.

3.1 Coordinator program to host multi-substructures

The basic function of the coordinator is to realize the equilibrium and compatibility at the boundaries among substructures. It sends target displacements to all substructures, and accepts reaction forces from them. The compatibility is automatically satisfied by assigning the same displacement vector to all substructures having the common boundaries. The equilibrium is sought by the coordinator program dynamically or statically, depending on where the equations of motion are to be solved. In this online hybrid test framework, the equations of motion can either be solved globally by the coordinator program or treated separately within each substructure. Correspondingly, two types of coordinators are developed, one that solves the dynamics and one that does not, called the dynamic and the static coordinators, respectively.

(1) Dynamic coordinator

The basic idea of the dynamic coordinator is to solve the dynamics of the structure separately from its static tests and analyses, i.e., to formulate and solve the equations of motion of the entire structure using the restoring forces obtained from the static substructures (Wang et al., 2006). Figure 2.4 illustrates the test scheme using an eight-story base-isolated structure as an example. It is reasonable that the dynamics of the structure are simplified into the equations of motion of a nine degree-of-freedom (DOF) system, each DOF corresponding to one story level.

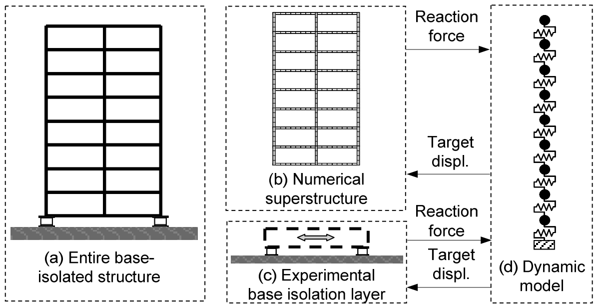

Fig. 4 Concept of dynamic coordinator

The static behavior, i.e., the restoring forces of respective DOFs, is obtained from two substructures: the superstructure simulated numerically by a finite element program, and the base-isolation layer tested physically. The dynamic coordinator uses the information from previous steps to predict the displacement vector for the current step, and sends the next displacements to both substructures for physical loading and static analysis. The restoring forces corresponding to these displacements are then collected and sent back to the coordinator. The global restoring force vector is formed, each component of which is associated with one dynamic degree of freedom. Finally, the coordinator updates the state variables for the next step simulation. With the dynamic coordinator, the boundaries between substructures are always associated with dynamic degrees of freedom, and the equilibrium at the boundary is satisfied explicitly by solving the equations of motion.

(2) Static coordinator

For a structure with more complicated dynamics, it is sometimes efficient to separate the massive dynamic model that represents the entire structure into multiple small dynamic models and treat them independently. Furthermore, the DOFs of substructure interfaces may not be associated with the dynamic DOFs, thus making it difficult to apply the dynamic coordinator introduced above. To solve these difficulties, a static coordinator was proposed (Pan et al., 2006), where the dynamics are always solved within each substructure, and the coordinator is used to statically search the equilibrium and compatibility amongst substructures.

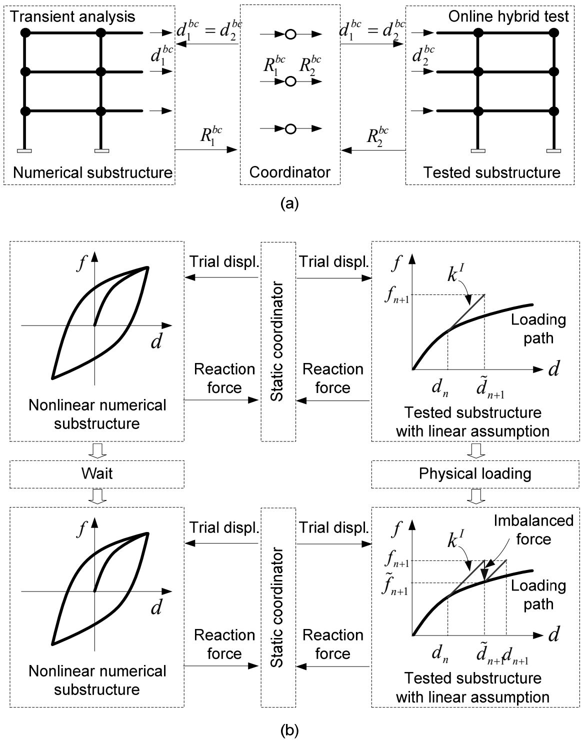

Fig. 5 Static coordinator: (a) Concept; (b) Two-round quasi-Newton test scheme

A generic structure, as shown in Fig. 5 (a), is taken as an example which is decomposed into two substructures, with the degrees of freedom of each substructure grouped into the internal set and the boundary set. The equations of motion are formulated for each substructure, and the boundary compatibility and equilibrium between the two substructures are sought by the static coordinator. The static coordinator first determines a set of trial boundary displacements and sends them to all substructures. In this process, compatibility is achieved automatically. Each substructure then runs a dynamic analysis or conducts an independent online hybrid test with the constraint of the boundary displacements. The reaction forces obtained from each substructure are sent back to the coordinator to check the equilibrium. If the equilibrium is achieved, then the simulation goes on to the next step. Otherwise, the coordinator determines another set of trial boundary displacements and repeats the above procedures until the equilibrium is satisfied. It is essentially a trial-and-error procedure. Its realization is not straightforward, however, and two issues still remain to be resolved: (1) how to systematically find the boundary displacements to achieve the equilibrium; and (2) how to avoid iteration for the tested substructures?

To find the equilibrium systematically, one of the quasi-Newton methods, called the BFGS method (Broyden, 1965), was employed. It uses only the boundary displacement vector and the corresponding reaction force vector to gradually build up the secant stiffness matrix at the boundary, and thus is able to find the equilibrium even for a nonlinear structure.

To avoid multiple iterations for the tested substructure, a test scheme featuring a two-round trial-and-error procedure was devised. The procedure, shown in Fig. 5 (b), is in essence a predicting and correcting scheme, each corresponding to one round of the quasi-Newton procedure. The first round is called the prediction, where the tested substructure is assumed to behave linearly and the reaction force is calculated from the displacement increment and the initial stiffness matrix or the secant stiffness matrix updated from the previous loading. After finding the equilibrium at the boundary, the predicted displacement vector is then applied to the tested substructure for physical loading. Due to the nonlinearity in the tested substructure, the boundary becomes imbalanced again. Finally, the second round of the quasi-Newton procedure is applied to compensate for the imbalanced force, also assuming the tested substructure behaved linearly.

3.2 Generalized interface to substructures

In the extensible online hybrid test system, the coordinator is able to accommodate multiple tested and numerical substructures by virtue of the standard input and output interface, which takes care of the boundary displacements and corresponding reaction forces. The coordinator program provides each substructure with the target displacements and accepts the reaction forces from them. Because of the simplicity of this exchange, laboratories employing different facilities and numerical substructures using various programming languages can readily be incorporated into the framework. Each boundary degree of freedom of the tested substructure shall be controlled physically by loading devices. The interface to the tested substructure directly communicates with the channels that control these devices, which enables the coordinator to send the target displacements to the loading devices and accept the reaction force from them. The interface to the numerical substructure is realized through the standard input/output files of each specific programming language. The interface first generates the input file that contains the boundary displacements of the current step as the external constraint, then calls the program application to run the input file, and finally extracts the reaction forces from the result files created by the program application. The restart option is the key element that allows external intervention from the coordinator, but without revising the source code of the program (Wang et al., 2006).

3.3 Internet-based data exchange scheme

To achieve high-speed data exchange among laboratories, an Internet-based data exchange scheme was developed (Pan et al., 2006). This scheme adopts the socket mechanism based on the TCP/IP protocol. It works as a server-client framework. The server first creates the listening socket and waits for connections from clients. The client then creates a client socket and attempts to connect to the server in reference to the TCP/IP address and the port number. Once the connection is accepted by the server, a channel is built up, and the data can be transferred through it. Two types of data exchange are considered: direct data exchange, and data exchange through proxy. In the direct data exchange, the coordinator and the substructure are set as the server and the client, respectively. The data exchange through proxy enables communication over the Internet with strict firewalls, in which both the coordinator and substructure are clients, and the proxy is the server. Here the proxy is a program developed for forwarding the data between the server and clients. To facilitate the application, the raw socket application programming interfaces (APIs) are encapsulated into a dynamic link library which can be easily implemented by most commonly used programming languages, such as Visual Basic, Fortran, and Visual C++. It is also possible for the data exchange scheme to transfer data among computers with different operating systems, such as Windows, Linux, and Macintosh.

4. Demonstration Tests

The proposed substructure online hybrid test system has been applied for seismic simulation of several structures. In what follows, four of them are introduced, in which the appealing features of the proposed hardware and software framework were demonstrated. They are a three-story steel moment frame equipped with steel plate walls, an eight-story base-isolated building, an SRC building with a steel tower on the top, and a four-story steel moment frame.

4.1 Online test using flexibly reconfigured loading devices

In this application, the seismic response of a three-story steel moment frame was examined, as shown in Fig. 6 (a). One bay of the frame equipped with steel plates was treated as the tested substructure, while the rest of the frame was implemented numerically using a general purpose structural analysis code: Open System for Earthquake Engineering Simulation (OpenSEES, Mazzoni et al., 2006). The dynamics of the structure were simplified as a mass-spring model with three degrees of freedom, and solved by a dynamic coordinator. The tested substructure was significantly stiffer and stronger than the surrounding numerical substructure, so that the contribution of the boundary beams in the numerical substructure to the tested substructure was neglected, and the boundary was treated as if it were pin-supported.

Three sets of conventional loading facilities were reconfigured in parallel as shown in Fig. 6 (b). The controllers and functional computers were integrated as in Fig. 6 (c). Two controllers were connected to one control computer via a RS485 cable and a RS interchanger, while the last controller was connected to one control computer through a RS232C cable. Although RS232C can be used for each individual loading unit, this configuration is maintained to minimize the modification of existing facilities. The calculation computer was used to communicate with each control computer, to exchange data with the coordinator program, and to collect data from GPIB devices. All computers were set within a local network so that a direct data exchange scheme was employed.

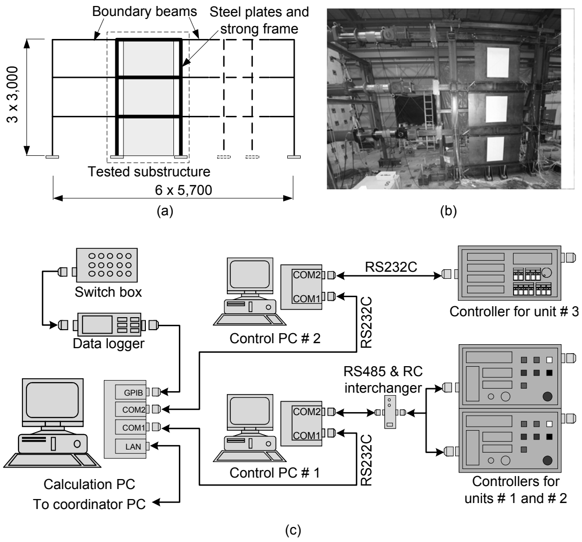

Fig. 6 Three-story steel moment frame equipped with slit walls: (a) Prototype; (b) Installation of loading devices; (c) Integration of loading system

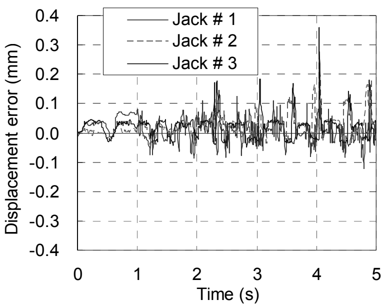

Fig. 7 Displacement errors in three jacks

To examine the loading accuracy of the reconfigured loading facilities, the structure was tested using a small ground motion to keep all substructures elastic. The target and measured displacements are compared as shown in Fig. 7 It is observed that all units achieved the respective target displacements accurately, with differences in most steps not greater than 0.05 mm, and the maximum difference not exceeding 0.4 mm. This demonstrates the feasibility of the proposed online hybrid system in that: (1) the reconfigured conventional loading facility ensures its loading accuracy; (2) the generalized interface encapsulates the numerical substructure well by means of the restart option; (3) the data exchange within the local network runs smoothly and takes almost no time; and (4) the dynamic coordinator reproduces the seismic response reasonably.

4.2 Application of displacement and force mixed control

An online hybrid test for a base-isolated structure to validate the displacement and force mixed control was proposed. The structure was an eight-story and two-span steel moment frame isolated by high damping rubber bearings (HDRB), as shown in Fig. 8 (a). To examine the seismic performance of the structure when subjected to horizontal and vertical ground motions simultaneously, an online hybrid test was conducted in which the isolation layer was tested physically as in Fig. 8 (b), while the superstructure was simplified into a mass spring model and treated numerically. Details were introduced by Pan et al. (2005 b).

One of the displacement-force mixed controls, the displacement-force combined control, was applied in the tests. The HDRBs were assumed to be in a compressive state all the time, and behaved linearly in the vertical direction. Because the vertical force has a significant influence on the horizontal behavior of the isolators, it is necessary to reproduce the variation of the vertical forces. In the test, the horizontal response was obtained using a conventional displacement-controlled online hybrid test, but the vertical response was obtained using a force-controlled scheme. The target displacement in the vertical direction was transformed into the target force in reference to the initial stiffness obtained from the preliminary test, and applied to the specimen. The force-displacement relationships and the displacement histories obtained from the test are shown in Fig. 8 (c) and (d), respectively (Pan et al., 2005 b). The advantage of this control was such that the dependency of the horizontal hysteretic behavior of base-isolators on the magnitude of the vertical force was taken into account explicitly.

If the base-isolated structure is subjected to large vertical ground motion and/or large overturning, the isolators will sustain tension. To deal with such a situation, a force-displacement switching control was developed using the same test setup. This time, only the vertical response was considered, and the force control was adopted when the isolators sustained compression, while the displacement control was adopted when they sustained tension. During the force-control segment, a force equal to the product of the predicted displacement and the vertical initial stiffness was applied to the tested structure, and the predicted displacement was used directly during the displacement-control. The control mode was switched when the force changed from compression to tension or from tension to compression. The test proceeded successfully, and the displacement and force histories are shown in Fig. 8 (e) and (f) for the displacement control and the force control, respectively.

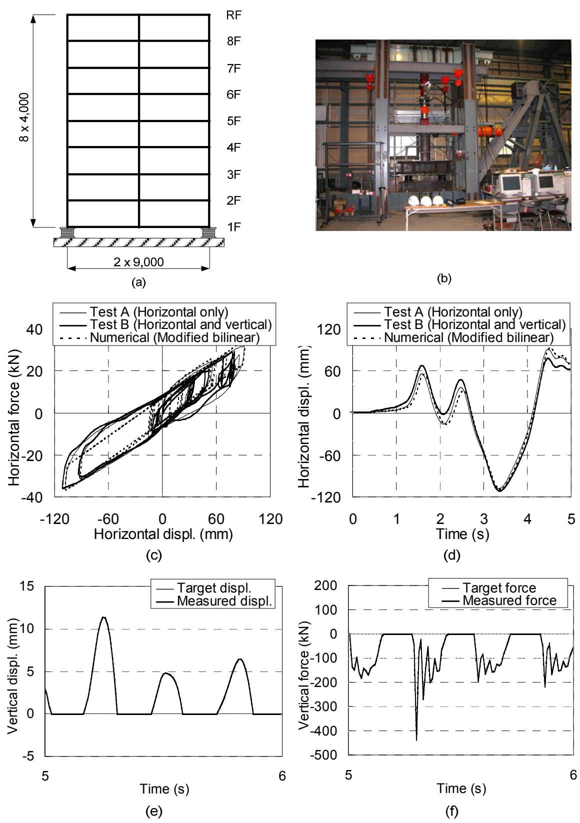

Fig. 8 Displacement and force mixed control: (a) Eight-story base-isolated structure; (b) Specimen installation; (c) and (d) Hysteretic and displacement response curves obtained from displacement-force combined control; (e) and (f) Displacement and force control accuracy in displacement-force switching control

These tests demonstrate that (1) the displacement-force combined control is valid for specimens having distinctly different force-displacement relationships according to the direction of loading; (2) the displacement-force switching control is effective for structures that display large disparity in the magnitude of stiffness during the response; and (3) the control of employed loading devices is accurate.

4.3 Implementation of multiple numerical substructures

The framework employing the static coordinator was applied to investigate the seismic response of a steel reinforced concrete (SRC) structure with a steel braced tower built on the top, as shown in Fig. 9 (a) (Wang et al., 2008 a). The entire structure was divided into three substructures, namely, the SRC frame, the first story of the tower, and the super part of the tower. The static coordinator was employed to handle the horizontal displacements among the three substructures. The first story of the tower was tested physically using a scaled model that maintained the similitude, while the other two substructures were treated numerically. OpenSEES was used to simulate the SRC frame as the program code is equipped with an excellent fiber-formulated element that is particularly suitable for composite members. A general-purpose finite element program, ABAQUS (SIMULA, 2008), was used to simulate the upper part of the tower because of its strength in implementing strong geometric nonlinearity. Each model contained a few hundreds of degrees of freedom. The setup for the tested substructure is shown in Fig. 9 (b). The vertical jack adopted the force control to provide a constant gravity of the tower, while the horizontal jack was used in the displacement control to realize the target boundary displacement sent from the coordinator. All substructures were encapsulated by means of the generalized interface, with boundary displacements and reaction forces exchanged by the input and output files. The restart option of each finite element program was employed, which enabled the simulation to advance step by step.

All three substructures exhibited large inelastic behavior, and in particular the tested substructure sustained the largest deformation and the braces buckled seriously. In order to validate the interface implementation, the seismic responses obtained from the online hybrid test were compared with those of the overall numerical simulation (Wang et al., 2008 a). The displacements at the substructure interfaces are compared in Fig. 9 (c) and (d) for the top of the SRC frame and the specimen, respectively. For both interfaces, the displacements are very close to each other. Some discrepancy is observed in Fig. 9 (d) due to the difference in hysteretic behavior between the numerical model (assumed behavior) and the physical test (actual behavior). The discrepancy has a significant influence on the tower behavior, but had little effect on the SRC frame because the SRC frame was much heavier than the tower.

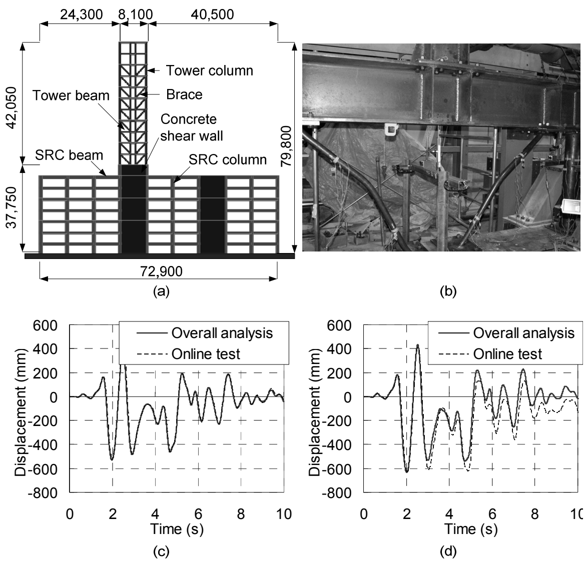

Fig. 9 Online hybrid test hosting multiple numerical substructures: (a) Prototype structure; (b) Photo for specimen; (c) Response of roof of SRC frame; (d) Response of first story of tower

This application validates that (1) the generalized interface is able to encapsulate multiple numerical substructures using different program codes; (2) the static coordinator employing the two-round quasi-Newton procedure is capable of reproducing the seismic response of complex structures; and (3) the data exchange scheme transfers the data quickly and reliably across the Internet with strict firewalls.

4.4 Geographically distributed tests

The seismic behavior of a four-story one-bay steel moment frame, shown in Fig. 10 (a), was simulated. The entire structure was divided into three substructures. The two column bases were treated experimentally, and their complex behavior under varying axial loading was considered. The rest of the structure was simulated numerically by ABAQUS using rigid plastic hinge models (Wang et al., 2008 b). Each column base was loaded simultaneously for the varying axial force due to overturning and for the column base rotation delivered by the horizontal jack. Due to space limitations of the laboratory, the right column base was tested in the writers' laboratory with facilities configured as shown in Fig. 2.10 (b), while the left one, together with two sets of conventional loading facilities, was transported to another laboratory fifteen kilometers away, where the two loading sets were reconfigured to achieve the bi-directional loading. The data were transferred over the Internet. However, the two laboratories were protected by strict firewalls and could not exchange the data directly. To overcome this difficulty, a proxy program was set outside both firewalls and could be accessed by both laboratories. The proxy program worked as a message passenger that accepted the data from one laboratory and passed them to the other.

The test results given by Wang et al. (2008 b) indicated the success of the online hybrid test. Significant failure was observed in both column bases, and the structure underwent very large deformations to collapse (Fig. 10(d)). The force error in the vertical jack was not greater than 3 kN (about 1% of the maximum target force) for most loading steps, and the largest error was about 9.6 kN. The largest displacement error in the horizontal jack was about 0.24 mm, while most of its errors did not exceed 0.04 mm. Note that the maximum target displacement was about 228 mm, which means that the displacement control was accurate enough to reproduce the seismic response. The test lasted for 16.6 hours, during which the data were exchanged continuously and the delay over the Internet could be neglected.

This application demonstrates that (1) the conventional loading devices are portable and flexible enough to be readily transported and reconfigured; and (2) the extensible framework is able to take care of multiple tested substructures having significant nonlinearities.

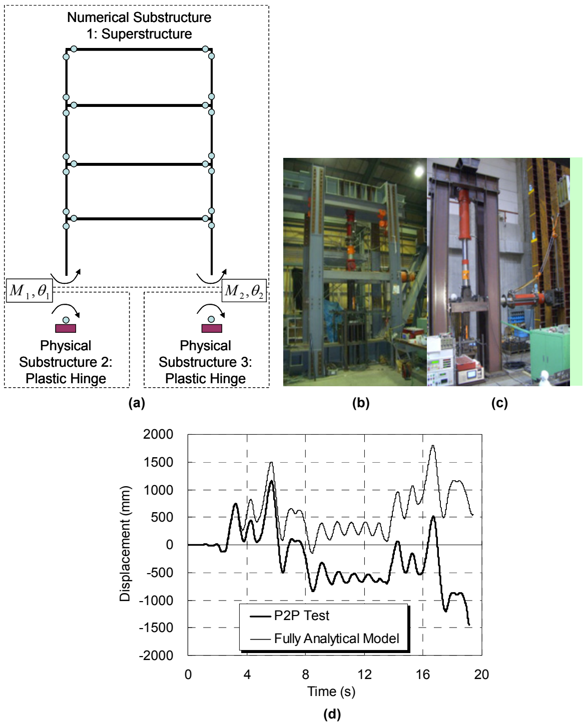

Fig. 10 Four-story steel moment frame: (a) Prototype; (b) and (c) Physical setups in two laboratories; (d) Displacement time histories obtained from test and associated numerical analysis

Using the system developed for geographically distributed tests, another four-story steel moment frame, this time with two bays instead of one, was also simulated. In the distributed online hybrid test, the boundary implementation is always a key issue to determine before the test. To achieve the highest precision, both equilibrium and compatibility should be satisfied at all of the boundary degrees of freedom. The reality, however, is that it is difficult to control stiff degrees of freedom, and the loading facilities and test space are sometimes limited to control all degrees of freedom. The flexible boundary implementation adopted in the test is shown in Fig. 11 (a), and more detail is found in Wang et al. (2011). In the test, one portion of the tested substructure was tested in Kyoto University (KU), and the other part by the State University of New York at Buffalo (BU) (Fig. 11 (b) and Fig. 12). Note that the experimental environment of the two testing sites (laboratories) were very different; in one site servo-controlled hydraulic actuators were used, while in the other site quasi-static jack system was adopted; and the control software was distinctively different. Nonetheless, the test was run successfully without any malfunction.

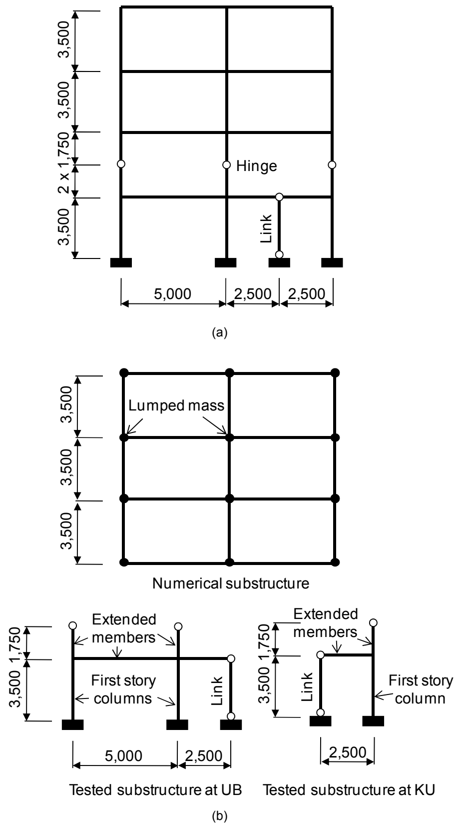

Fig. 11 Substructures for numerical hybrid simulation: (a) Numerical model with hinges; (b) Numerical substructures

From this challenging geographically distributed test, various problems (necessary to resolve or overcome for future applications) were surfaced out. To save time and shipping expense, the tested substructures were manufactured by local fabrications, one in Kyoto, Japan, and the other in Buffalo, the United States. The material properties of the test specimens were not identical, having caused a non-negligible difference in the yield strength, and this caused some errors in the obtained response relative to the prototype response. Time difference was another concern as there is a twelve hour difference between Japan and the Eastern U.S. Since one test may take a few hours, it became necessary for one lab to work through the night. The operators may make some mistakes because they are working in an unusual period. These difficulties shall be of significant concerns to the project administrator.

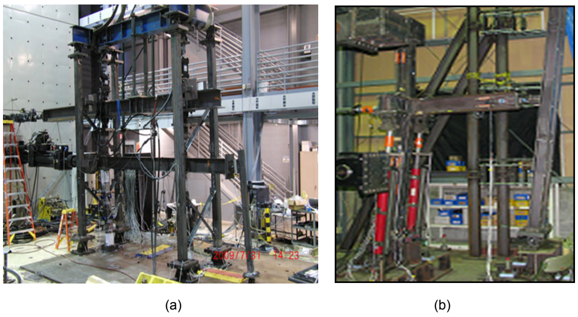

Fig. 12 Test setups at two laboratories: (a) Test setup at UB; (b) Test setup at KU

5. Conclusions

An extensible framework for the substructure online hybrid test is proposed. In this framework, conventional loading facilities are adapted and reconfigured to realize the physical loading of specimens. The extensible framework, equipped with a versatile coordinator program, a flexible test scheme, a generalized I/O interface, and an Internet-based data exchange scheme, can satisfy the demands of many applications, and is particularly suitable for geographically distributed online hybrid tests. This framework has been tested with several applications. The major findings of this study are as follows.

(1) The conventional loading devices are robust and portable and can be reconfigured flexibly to satisfy the demands of various structural tests. The loading performance can be adjusted by tuning the parameters of digital controllers, and the control modes can be flexibly selected prior to or during the test.

(2) Thanks to the outstanding performance of the digital displacement transducer, accurate displacement control can be ensured to conduct the online hybrid test.

(3) The online hybrid test framework is extensible to host multiple tested and numerical substructures. The versatile coordinator program can be applied to structures with simple dynamics as well as those with complex dynamics. The generalized interface can encapsulate substructures completely only by accessing the boundary displacements and forces. The Internet-based data exchange scheme is also demonstrated to be fast and stable.

(4) To demonstrate the strength of the proposed test system, a series of physical applications are presented, including a physical testing of a three-story frame installed with steel plate walls, an application to an eight-story base-isolated building, a seismic simulation of a steel reinforced concrete (SRC) building with a steel tower on the top, and the distributed testing to explore the collapse behavior of four-story steel moment frames. In the last applications, the idea of "geographically distributed online hybrid testing" is realized, and its effectiveness as well as problems to resolve or overcome is discussed.

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インターネットを介した並列実験の実現とネットワーク型耐震構造実験の試行

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要　旨

複数の異なった実験場で同時に実験を実行し，それぞれの実験から得られるデータを，インターネットを介して逐次参照しあうことから，大型構造物の地震応答を再現する実験手法とシステムを開発した。このシステムは，準静的ジャッキの利用を始めとして，多くの構造実験で用いられている実験・計測装置を有機的に組み合わせることから，汎用性を確保している。本実験システムを用いた幾つかの実験を紹介することから，この実験手法がもつ有効性を検証するとともに，これがネットワーク型耐震構造実験として，海を超えた連携を可能にすることを実証した。

キーワード：耐震工学，地震応答，オンラインハイブリッド実験，並列実験