

Internet-based collaborative pseudo-dynamic testing of multi-span bridge structure

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Abstract

In this paper, the first Internet-based collaborative pseudo-dynamic testing of a multi-span bridge system in mainland China is presented in detail, which has been carried out by the collaboration of Hunan University (HNU), Harbin Institute of Technology (HIT) and Tsinghua University (TU) in mainland China, and the University of Southern California (USC) in the USA. The prototype system of Russian River Bridge at Southern California in America is illustrated. Different testing specimens, testing equipments and substructure boundary conditions at HNU and HIT laboratories are described. A network protocol platform for collaborative pseudo-dynamic testing, called NetSLab, and some function modules developed on the use of its standardized interface are introduced. Aiming at the MTS system widely used in structural testing, two approaches are presented to implement the communication interface between NetSLab and testing equipment, respectively, studied by HNU and HIT. The integrated networked testing system and collaborative testing procedures are presented. The testing results manifest that the networked collaborative testing system with powerful capability provides a testing platform with good coordination for complex models or actual structures, and achieves remote sharing of testing equipments. © 2009 National Natural Science Foundation of China and Chinese Academy of Sciences. Published by Elsevier Limited and Science in China Press. All rights reserved.

Keywords: Internet-based collaborative pseudo-dynamic testing; Multi-span bridge structure; Network protocol platform; Communication interface; Remote sharing of testing equipment

1. Introduction

Internet technology enables earthquake engineering researchers to carry out networked collaborative testing by linking structural laboratories distributed remotely and realizing data transmission and remote control. Through the Internet, several single laboratories can be integrated into one powerful networked testing system to complete some large-scale structural testing with complexity models or testing for actual structures, which enhances testing capability and shares resources.

Several attempts have been made to carry out collaborative testing for large-scale structural models with remotely distributed laboratories. In America, supported by the Network for Earthquake Engineering Simulation (NEES) project [1], Multi-Site Online Simulation Test with large-scale model took place on July 30, 2003 [2]. As the selected testing model, a two-bay single-story steel frame with pinned beam-column connection at one side and moment beam-column connection at the other side was divided into three substructures. Physical testing was carried out for the substructures at the University of Colorado at Boulder and at the University of Illinois at Urbana-Champaign, respectively, and these substructures were numerically simulated at the National Center for Supercomputer Application. Three collaborators were coordinated by a simulation coordinator developed on

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NEESgrid Teleoperation Control Protocol (NTCP) [3] that provides a common network protocol for remote testing or simulation. By the collaboration of the University of California at Berkeley, the University of Colorado at Boulder, the University of Illinois at Urbana-Champaign, the University at Buffalo and the University at Lehigh, fast hybrid simulation with geographically distributed substructures about a six-span bridge model was carried out in July 2004, which uses the improved NTCP, quickens the testing velocity and improves the reliability of the testing results [4]. In Taiwan, China, a networked collaboration platform, called ISEE (Internet-based Simulation for Earthquake Engineering), was established by the National Center for Research on Earthquake Engineering (NCREE) for networked collaborative structural experiments among geographically distributed structural laboratories [5]. Two approaches, the Database Approach and the Application Protocol Approach, have been employed to provide different solutions for network communication in ISEE. The Database Approach consists of three major parts: the Data Center as a data exchange hub and repository, the Analysis Engine for analyzing the dynamic responses of a structure, and the Facility Controller used to drive the corresponding experimental facility in the laboratory. The Application Protocol Approach aims at building a platform, “Platform for Networked Structural Experiment” (PNSE), by a proposed application protocol “Network Structural Experiment Protocol” (NSEP) based on TCP/IP [6]. Using the ISEE environment, a collaborative hybrid testing of a multi-span bridge was carried out by NCREE, National Taiwan University and Carleton University in Canada in February 2006 [7].

In mainland China, supported by the National Natural Science Foundation, some research communities, including Hunan University, Harbin Institute of Technology and Tsinghua University, began to devote in setting up the networked collaborative testing system by the full use of the existing testing equipments and computing resources at three structural laboratories in 2004. A network platform for networked collaborative pseudo-dynamic testing, called NetSLab (Networked Structural Laboratories) [8,9], has been developed by Hunan University. Aiming at the MTS system widely used in structural testing, two approaches were studied to implement the communication interface between NetSLab and the MTS system, respectively, by Hunan University and Harbin Institute of Technology, which enables NetSLab to control the testing equipments to carry out physical testing. Using the integrated networked collaborative testing system, the first Internet-based collaborative structural pseudo-dynamic testing in mainland China was carried out successfully in December 2007 by the collaboration of Hunan University, Harbin Institute of Technology and Tsinghua University in mainland China, and the University of Southern California in America. In this paper, the whole testing setup, the collaborative testing system and the testing procedures and results are presented in detail.

2. Multi-span bridge structure and description of testing setup

2.1. Prototype system of Russian River Bridge

The prototype bridge system in this paper, Russian River Bridge, is located in Southern California in America. The bridge system, as shown in Fig. 1, consists of six spans and five piers numbered from P1 to P5. Two side spans are both 38.1 m long while four mid-spans are all 50.292 m long. Five piers P1 to P5 are, respectively, 17.72, 15.17, 13.43, 11.31 and 5.43 m high. The piers P1 and P5 were designed and constructed to be 1/6 scale specimens and physical testing was carried out at the laboratories of Hunan University and Harbin Institute of Technology, while the other three piers P2 to P4 were numerically simulated at the University of Southern California, Tsinghua University and HNU. For piers P1 and P5, the deck-to-pier connections are assumed to be the fixed connections along the longitudinal direction; while for other piers, the deck-to-pier connections are assumed to be the hinged connections.

2.2. Scaled testing specimens

The reduced-scale testing specimens at both HNU and HIT laboratories are designed to comply with the requirements for pseudo-dynamic testing specimen provided by Specifying of Testing Methods for Earthquake Resistant Building (Professional Standard of the People's Republic of China, 1996) [10] in China. The 1/6 scale factor is used in the design of the testing specimens based on the available testing equipments and physical size of laboratory sites at HNU and HIT. The scale factor for Poisson's ratio is unity to all specimens. A summary of the scale factors and dimensions of the testing specimens at remote sites can be seen in Table 1.

2.3. Testing specimens and testing equipments

2.3.1. Testing specimen and testing equipment at HNU laboratory

As shown in Fig. 2(a), the testing specimen at HNU laboratory was designed and constructed as the bending reinforced concrete (RC) pier column. The cross section of the pier column was circular in shape. The longitudinal reinforcement rebar was evenly distributed along the circumferential direction, and fixed by hoops with minor spacing interval along the vertical direction. The top and the footing foundation of the pier column were rigidly reinforced in order not to be destroyed during the testing. The concrete with high strength was used as the filling material. Based on the testing equipment shown in Fig. 2(b), the top of the pier column was designed to be free end. In fact, the testing substructure is the part between the footing foundation and the contra flexure point of the 1/6 scaled pier col-

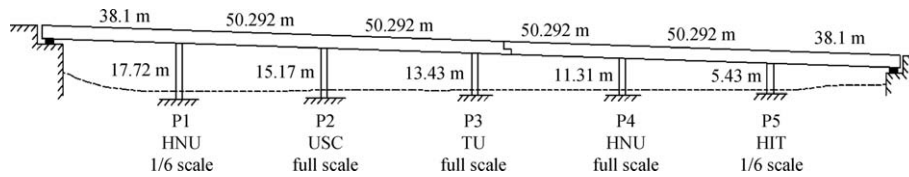


Fig. 1. Elevation view of the prototype bridge system.

Table 1
Scale factors and dimensions of testing specimens.

Serial number of the piers	P1	P2	P3	P4	P5
Testing site	HNU	USC	TU	HNU	HIT
Scale factor	1/6	1	1	1	1/6
Height of the prototype structure (m)	17.72	15.17	13.43	11.31	5.43
Diameter of the prototype structure (m)	2.10	2.10	2.10	1.80	1.80
Scaled specimen height (m)	3.00	15.17	13.43	11.31	0.90
Scaled specimen diameter (m)	0.35	2.10	2.10	1.80	0.30
Stress scale	100%	100%	100%	100%	100%
Force scale	1/36	100%	100%	100%	1/36
Displacement scale	1/6	100%	100%	100%	1/6
Ratio of axial compressive force to axial compressive ultimate capacity of section	0.10	0.10	0.10	0.20	0.15

umn, so that the height of the constructed pier column is 1.5 m but not 3 m as shown in Table 1.

The top horizontal force of the pier column was loaded by the electro-hydraulic servo actuator horizontally placed between the top of the pier column and the strong reaction wall. The top horizontal displacement of the pier column was measured by a high precision sensor built in the actuator. The restoring force was measured by a load cell built in the actuator. The top vertical axis force of the pier column was calculated by the ratio of axial compressive force to the axial compressive ultimate capacity of the section and load by hydraulic jack.

2.3.2. Testing specimen and testing equipment at HIT laboratory

As shown in Fig. 3(a), the testing specimen at HIT laboratory was designed and constructed as the shear RC pier column. The cross section of the pier column was also circular in shape. The longitudinal reinforcement rebar was evenly distributed along the circumferential direction, and fixed by spiral hoops with rather large spacing interval along the vertical direction. Two uniform RC beams with stiff reinforcement details were designed on the top and as the footing foundation of the pier column. The concrete with general strength was used as the filling material. The whole pier column was reinforced along the circumferential direction by the two layers of Carbon Fiber Reinforced Plastic (CFRP). As shown in Fig. 3(b), four-bar testing equipment was used to implement the fixed boundary condition through putting the strong L-Shaped reaction steel beam on the top of the testing specimen. Thus, the testing substructure is the 1/6 scaled pier column. As shown in Fig. 3(c), the construction of four-bar testing equipment is illustrated in detail. The horizontal force of the pier column was loaded by the electro-hydraulic servo actuator

horizontally placed between the L-Shaped reaction steel beam and the strong reaction wall. The horizontal force must be loaded at the middle of the pier column along the vertical direction, where the maximum shear force occurs when the two ends of the pier column are both fixed. The top horizontal displacement of the pier column was measured by a LVDT sensor horizontally connected with the top RC beam. The restoring force was measured by the load cell built in the actuator. The top vertical axis force of the pier column was calculated by the ratio of axial compressive force to axial compressive ultimate capacity of section and load by hydraulic jack, at the same time, the hydraulic jack was kept moving with the pier column through rolling shafts. It is also the first time that the four-bar testing equipment was used to carry out pseudo-dynamic testing at HIT laboratory.

3. Networked collaborative pseudo-dynamic testing system

3.1. Network protocol platform and networked structural laboratories — NetSLab

One of the major technologies of carrying out networked collaborative testing is to develop a network protocol platform like NTCP in MOST that provides a data model and the communication protocols in order to realize the data transmission and remote control on the Internet. Several single laboratories and computers remotely distributed can be integrated into one powerful networked collaborative testing system through the network protocol platform. Thus, some large-scale structural testing with complexity that could not be completed in single laboratory will be possibly implemented in such networked structural laboratories. NetSLab platform was developed on the

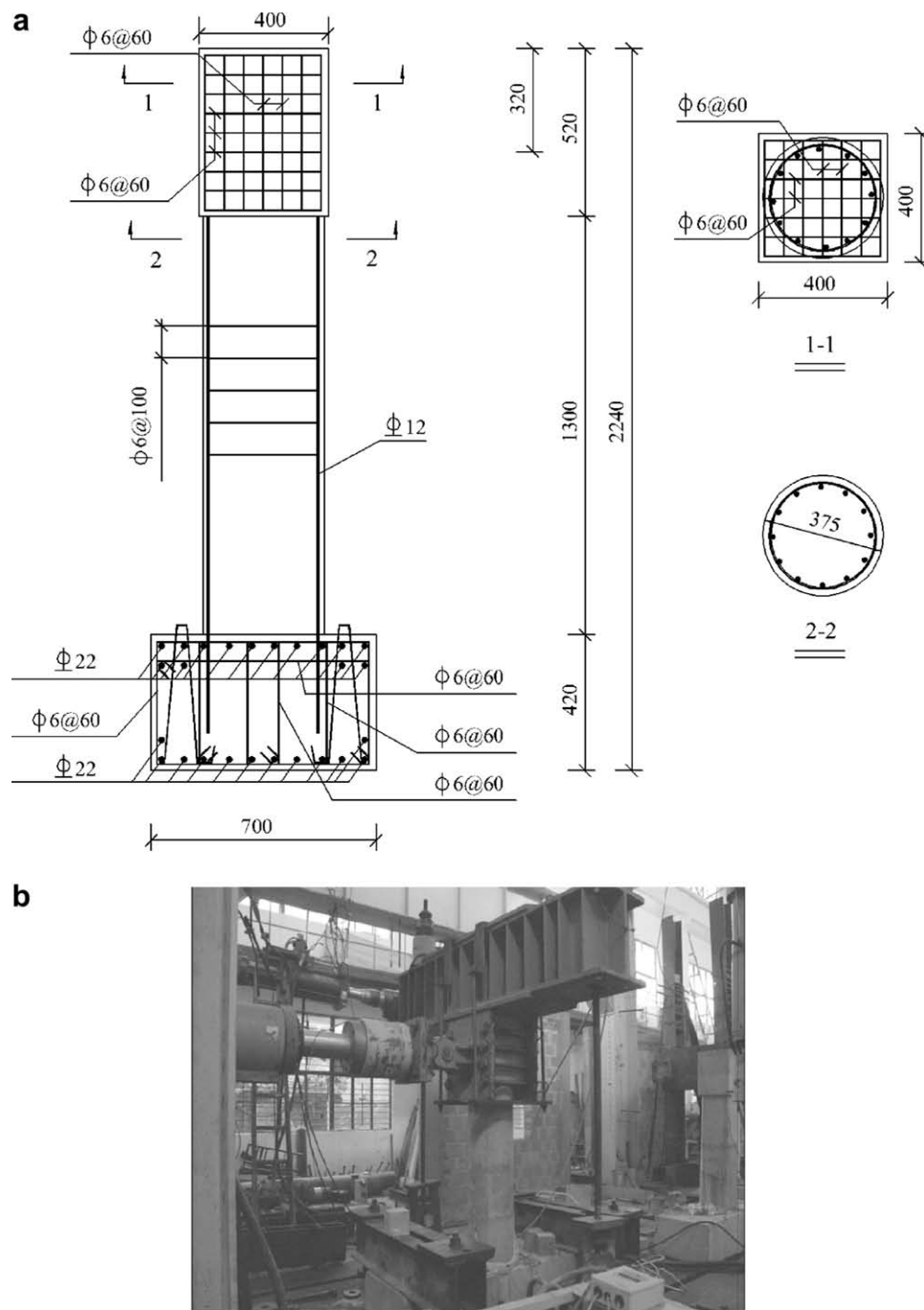


Fig. 2. Testing specimen and testing equipment at HNU laboratory. (a) Reinforcement details of the bending RC pier column (units: mm); (b) Testing equipment.

concept of client/server, and was used to operate networked structural laboratories.

3.1.1. Data model and communication protocols of NetSLab [8,9]

The data communication model of NetSLab consists of testing results, three types of participants, communication protocols and dataflow. The testing results are presented by an array according to the proposed data model. Three types of participants are controller, testers and observers.

In order to maintain the simplicity of the platform for understanding, further development and practical application, two concepts, Dynamic Unified Data Packet (DUDP) and Generalized Data Communication Agency (GDCA), are applied to fulfill these goals. DUDP covers all communication-related components, including current stage data of testing results, controller's request, tester's current status and communication requirements, etc. GDCA is the unique communication components in NetSLab, which can be attached to its master entity, such as controller, tes-

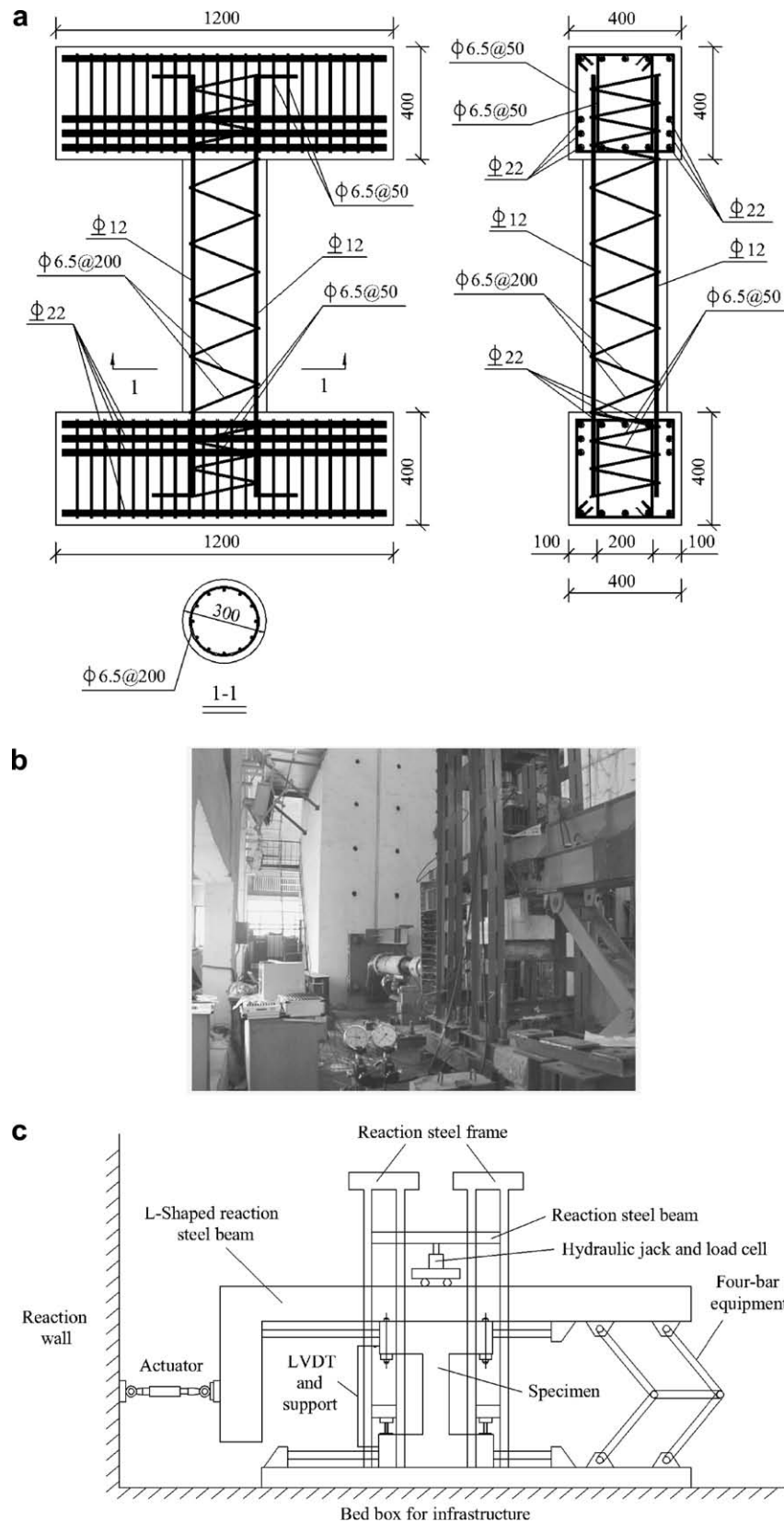


Fig. 3. Testing specimen and testing equipment at HIT laboratory. (a) Reinforcement details of the shear RC pier column (units: mm); (b) Four-bar testing equipment; (c) Constructional drawing of the four-bar testing equipment.

ters or observers. GDCA receives the standard XML formatted DUDP from its master entity, and then sends it

to the specified destination and activates the corresponding entity if necessary. For example, during testing, when the

tester receives one DUDP or command requests sent out from the controller, the tester will receive the data and the target command through analyzing the DUDP parser. New DUDP will be generated and sent out to GDCA after the tester completes some necessary operations (obtaining results from physical testing or numerical simulation), and then new DUDP will be sent back to the controller by GDCA. GDCA will activate the controller to continue testing. Compared with the tester, the controller needs to achieve more functions, such as organizing communication and assigning missions to the testing participants, while the observer achieves less function. GDCA provides the client agent interface and the controller interface, the former allows the tester and the observer to implement the data communication, while the latter allows the controller to integrate the testing system.

3.1.2. NetSLab application

In order to facilitate the application, NetSLab provides a standard ActiveX control (named UPCtrlATX) with powerful function for the user to program, which supports any high-level program language with ActiveX control function, such as VB and VC++. In addition, the development of NetSLab is targeted to flexibility and suitability in various network environments. Four function modules for networked collaborative testing were developed as follows [8,9]:

- (1) *Controller*: who organizes the whole testing procedure, inputs the structural information and the earthquake acceleration, and combines the feedback information of each tester to perform the time history analysis of the structural system, then sends the target displacement to each tester. There should be only one controller in one testing.
- (2) *Actual tester*: who receives the command from the controller, carries out physical structural testing, and obtains restoring force and other testing results, then sends the results back to the controller.
- (3) *Virtual tester*: who does not connect testing equipment to carry out physical testing, but simulates the characteristic of structural restoring force using computer.
- (4) *Observer*: who shares testing results and provides the people to observe the course of testing without any interference of the processing.

3.2. MTS system and actual tester program

Although NetSLab has been tested successfully on the Internet, hurdles still remain in providing smooth communications between NetSLab and a variety of testing equipment, which enables NetSLab to control the testing equipment to carry out physical testing. The communication interface and actual tester program should be implemented according to the characteristics of different

control systems. At present, the MTS system is widely used in structural testing of civil engineering. Therefore, the tester program developed on the MTS system will have versatility and significance. Based on the application interface provided by the MTS, two approaches and programs were developed, respectively, by HNU and HIT.

3.2.1. MTS system

The MTS system mainly consists of the FlexTest GT control system and electro-hydraulic servo actuator. The FlexTest GT control system is the product of MTS Corporation in America, which consists of the computer and GT controller box. The series of software named MTS 793.10 should be installed in the computer to control the actuator and to carry out the testing. MTS 793.10 software is the composition of several software packages with powerful function, including the Function Generator Software, the Basic TestWare Software, the Multi-Purpose Testware (MPT) Software and the Station Manager Software [11,12]. As the main control module, the Station Manager Software will send the target command to the actuator and receive the feedback from the actuator via the input/output (I/O) channel of the GT controller box during testing.

3.2.2. Software control approach of MTS at HNU laboratory

The MTS Corporation provides commercial DLL (Dynamic Link Libraries) that enable users to program conveniently by VC++, VB or other program languages to perform I/O function and control the actuator. This method needs complex program technology of MTS. A standard ActiveX control, named RemoteAct, was developed by HNU and used to send the target command to the actuator and receive feedback from the actuator at specified frequency [13]. The actual tester program was developed through loading this ActiveX control and UPCtrlATX control of NetSLab under the Visual Basic programming environment, and should be operated on the control computer of MTS. The MTS control computer was connected into the Internet to implement the telecommunication.

3.2.3. External command control approach of MTS at the HIT laboratory

The GT controller box provides the hardware interface of the I/O channel that enables users to connect other hardware devices. Therefore, the control to the I/O channel of the GT controller and the actuator can be realized by controlling these hardware devices. Although this method needs an additional computer to program to control these hardware devices, it provides easily operational hardware connection and makes it flexible and convenient for the users to develop the testing system or function by using a familiar program language. Since the control to the actuator is implemented through connecting an external command signal from hardware devices, the process of programming can avoid complex low-layer technology of

MTS software. The method is also suitable for any other testing system.

As shown in Fig. 4, the Analog/Digital (A/D) and Digital/Analog (D/A) acquisition board were, respectively, used to joint with the I/O channel of the GT controller. The control to the actuator is implemented by programming to control the acquisition boards. During the pseudo-dynamic testing, the voltage signal of the feedback displacement is received

from the LVDT sensor connected with the specimen and collected into the A/D acquisition board. The voltage signal of the feedback force is received from the load cell of the actuator and collected into the Analog Input (AI) channel of the GT controller box, and then output via the Analog Output (AO) channel and collected into the A/D acquisition board. The voltage signal of the target displacement is sent out into the AI channel of the GT controller box via the D/A acquisition board, and then output into the actuator via the AO channel to move the actuator.

In this paper, serial acquisition boards of the Advantech Corporation were selected. The Advantech acquisition board can be driven and controlled by the ActiveDAQ method based on ActiveX technology [14]. A good many ActiveX controls provided by Advantech can be loaded in high-level program language for the application. Because the NetSLab program also supports ActiveX, the interface between the external command control program and the NetSLab program can be implemented easily. The actual tester program was developed through inserting ActiveDAQ controls and UPCtrlATX control into one program interface under the Visual Basic programming environment. Both the acquisition boards and the actual tester program should be installed in the industry computer. The industry computer was connected into the Internet, and was used to communicate with the controller. More details about the external command control approach can be consulted in Ref. [15].

3.3. Network environments of the integrated testing system

The integrated networked collaborative testing system consists of one controller and five testers. Among five testers, two actual testers were used to carry out physical testing at HNU and HIT; three virtual testers were used to simulate numerically based on the bilinear model for the restoring force and the displacement at USC, TU and HNU. In order to test the condition of NetSLab under a variety of network environments, the components of the integrated testing system were placed in different network environments. Controller and one actual tester were placed at the testing control room of the HNU laboratory, where lays a specific network line for networked collaborative testing. The virtual tester at USC was placed at the computer room, where the general Internet is used. Virtual testers at TU and HNU were placed at the computer room. Another actual tester was placed at the testing control room of the HIT laboratory. The network environments of these three departments are all China Education and Research Network.

4. Testing procedures, testing results and evaluation

4.1. Testing configuration and procedures

4.1.1. Configuration of the controller program

The controller program sets up the model of the whole bridge system, assigns the network parameters to each test-

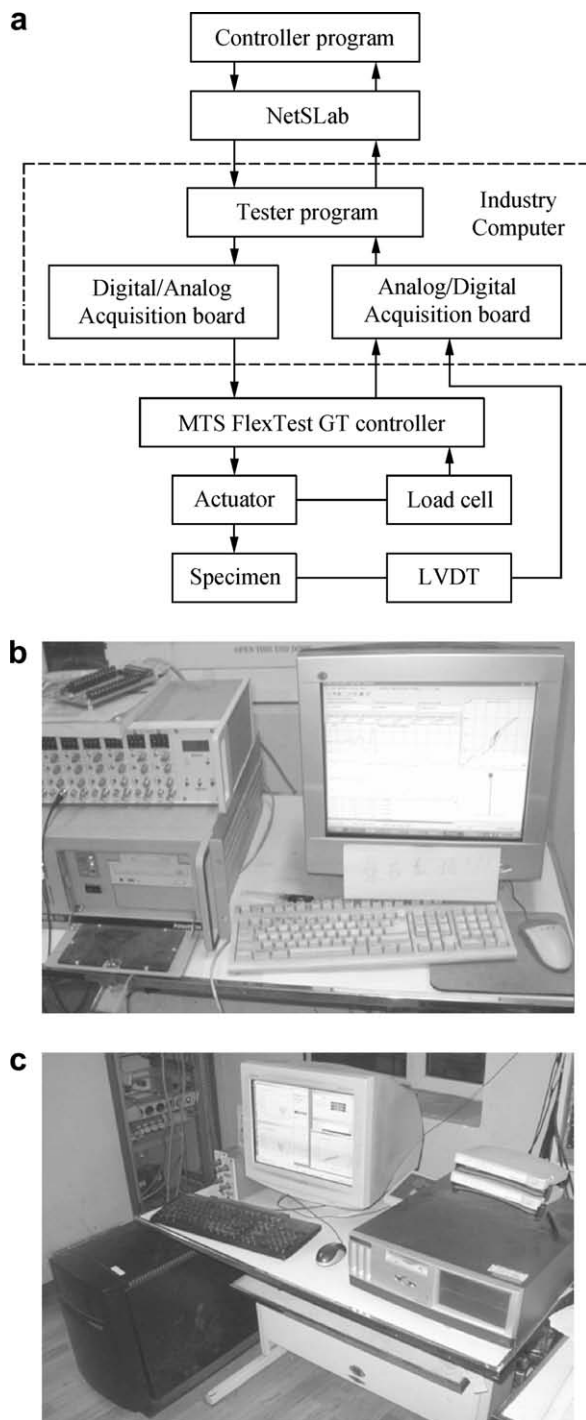


Fig. 4. External command control system at the HIT laboratory. (a) Diagrammatic sketch of the external command control system; (b) Industry computer; (c) the MTS GT controller.

ing participant, inputs the earthquake ground acceleration record, and specifies the algorithm for the numerical integral.

The whole model information consists of the mass of the bridge system, the initial stiffness of the physical pier columns, the initial and two-stage degraded stiffness of the simulated pier columns, and the damping ratio of the material. The frequency of the whole bridge system along the longitudinal direction is about 1.83 Hz.

The network parameters assigned to each testing participant consists of the tester name and the port.

The El Centro earthquake ground acceleration record (NS, 1940) was selected as the input ground motion with the peak acceleration of 341.7 cm/s^2 , the interval of 0.02 s and the duration time of 53.76 s. Based on the peak acceleration requirements for the time history analysis provided by the Code for Seismic Design of Buildings (National Standard of the People's Republic of China, 2003) [16] in China, the first 300 steps for testing were adjusted to be the peak acceleration of 70 and 400 cm/s^2 , respectively, compatible with the work condition under frequently occurring earthquake and seldom occurring earthquake of eight degree earthquake impact. In addition, the peak acceleration of 220 cm/s^2 was used to be an additional work condition.

The explicit Newmark algorithm was selected as the numerical integral method. The numerical integral was based on the prototype bridge system, while the load in physical testing was based on the scaled testing specimen. Thus, some parameters of the prototype bridge system need to be calculated and updated from the scaled specimen by the scale factors at each step. Of course, the shortcoming of this method is that once plastic deformation occurs in the scaled testing specimen, the scale factors between the scaled specimen and the prototype bridge system will not be constant and will be difficult to determine. In this paper, the error influence on the testing results brought by this method was not considered.

The controller program initiates NetSLab firstly and it waits for other testers.

4.1.2. Configuration of actual tester program

The actuator parameters, including the testing error limitation, the range of the displacement and the force of the actuator, were both assigned in actual tester programs at the HNU and HIT laboratories. In order to protect the testing specimens and equipments, and ensure continuity of the testing process, the range of the displacement and the force of the actuator were also limited by the “inter-lock” function in MTS software.

In addition, the external command mode of MTS was set up to assign the actuator, the AI and AO channels the GT controller box at the HIT laboratory, which should be initiated before the actual tester program.

Some parameters, including the network parameters, the calibration coefficients of the sensors, and the load velocity of the actuator, were assigned in the actual tester program

at the HIT laboratory. The network parameters consist of the tester name, the tester port, the IP address of the controller and the port of the controller. The calibration coefficients of the sensors is the corresponding relation between every unit voltage signal input or output by the acquisition boards and some parameters, including the feedback displacement, the feedback force and the target displacement.

After all has been done, the actual tester program initiates NetSLab to connect with the controller program.

4.1.3. Configuration of the virtual tester program

The configuration of the virtual tester program is relatively simple. Except for some network parameters, the initial stiffness, two-stage degraded stiffness, and the inflection point values of the restoring force and the displacement in the bilinear model need to be determined. In this paper, the bilinear model was determined by the results of quasi-static testing carried out by the HNU and HIT laboratories. The virtual tester program also initiates NetSLab to connect with the controller program.

4.1.4. Testing procedures

As shown in Fig. 5, during the testing, when all testers programs were connected with the controller program, the whole testing process was started by the controller program. The controller program performs the time history analysis of the structural system, figures out the displacement of current step, and then sends the target displacement to every tester via NetSLab. Every actual tester receives the target displacement, and then sends the displacement command to the control program of the specific testing equipment. The control program of testing equipment mobilizes the actuator to the target displacement, and sends the measured restoring force back to the controller via NetSLab. Every virtual tester receives the target displacement, and then sends the displacement command to the simulation analysis program, figures out the feedback restoring force and sends it back to the controller via NetSLab. When receives all feedbacks, the controller program continues to calculate the target displacement of the subsequent next step. Such a cycle is repeated till the end of a complete testing. The whole testing procedures and the database of the testing information and results were published in real time on the website <http://netslab.hnu.cn>.

4.2. Testing results and evaluation

After testing under three work conditions, the testing specimen P1 at the HNU laboratory was still in elastic work condition while the testing specimen P5 at the HIT laboratory resulted in obvious plastic deformation because of the characteristic of different testing specimens. As can be seen in Fig. 6, the testing results under seldom occurring earthquake (peak acceleration 400 cm/s^2) showed good operation condition of the testing system. The program interface showed real-time testing information per step, including the time history curve of displacement, the hys-

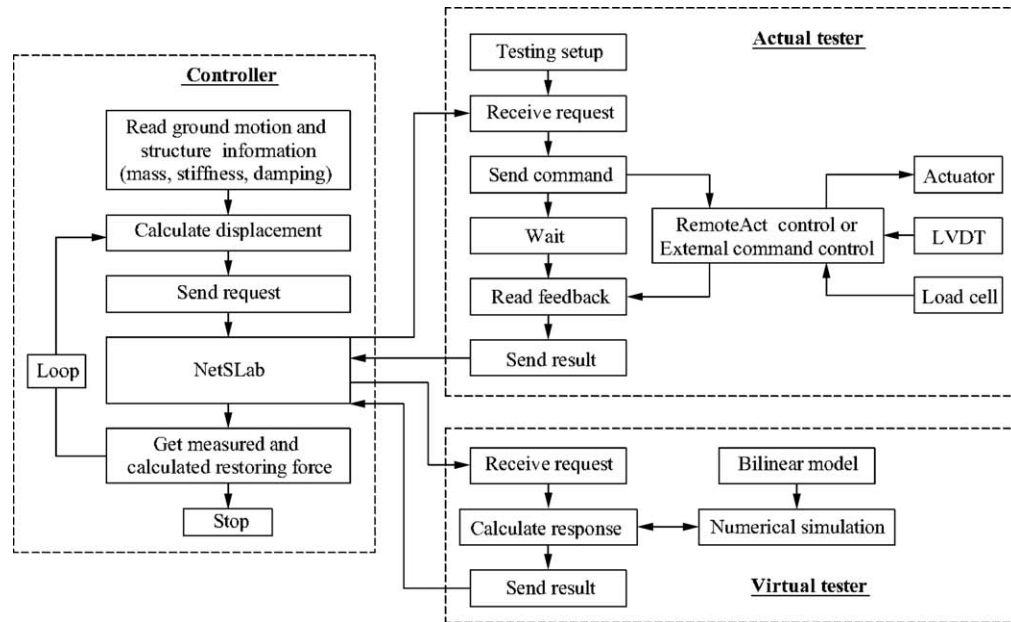


Fig. 5. Flow chart of the main procedure for networked collaborative pseudo-dynamic testing.

teretic curve for restoring force and displacement, the earthquake ground acceleration record and the deformation of the structure. Compared with the results of quasi-static testing, the hysteretic curve for restoring force and displacement in pseudo-dynamic testing is relatively narrow, which manifests that the energy dissipation of the structure in pseudo-dynamic testing is less than that in quasi-static testing, and the evaluation of earthquake impact by quasi-static testing is relatively conservative. Although the bearing capability of the pier column is not obviously improved by reinforcement with CFRP, the aseismic performance of the pier column is still improved because of the violent enhancement of the ductility and the energy dissipation capability.

The testing results of the testing specimen at the HIT laboratory, including maximum displacement on the top and maximum shear force on the footing of the pier column, are listed in Table 2. The maximum responses of positive and negative directions on symmetric sections are greatly different, which demonstrates that the damage of the specimen possibly occurs at one direction, in the meantime, the damage results in the degradation of bearing capability and stiffness in this direction.

The average time of each step was about 24 s under the third work condition, the time duration of which is the longest one among the three work conditions. The time cost of each step consists of the communication time between the computers at the remote site and those at the local site, the load time of the actuator, and the waiting time to ensure the stability of the actuator. Most of the time was spent on the latter two aspects, which are relative to the loading capability of the actuator and to the assignation of testing error limitation. The testing results validate that the networked collaborative testing system achieves its

function and is adequate for the applications across the Internet.

5. Conclusion

An Internet-based platform, called NetSLab, has been presented for the organization and data communication of the networked collaborative pseudo-dynamic testing. The focus of the investigation is on the control of the NetSLab platform to the testing equipment and how a networked collaborative pseudo-dynamic testing system can be set up using NetSLab platform. Based on the characteristic of the MTS actuator system currently widely used in structural testing, two approaches were used to implement the communication interface between NetSLab and MTS developed, respectively, by HNU and HIT. The efficient data transmission and remote control of the integrated testing system was validated by a networked collaborative pseudo-dynamic testing of a multi-span bridge. In the meantime, it has been shown by the testing results that the environment and some modules based on NetSLab are user-friendly and can really achieve the testing function.

Of course, there are still some issues that should be considered carefully. Although the application of NetSLab breaks through the limitation of firewall on the China Education and Research Network and communicates smoothly on a variety of network environments, it also arises a good many issues about the network technology considered, such as the security and the management. Because of the complexity and differences in operating the characteristics of testing equipments at different laboratories, there is the need for a standardized interface for the communication between testing equipments and the network platform sim-

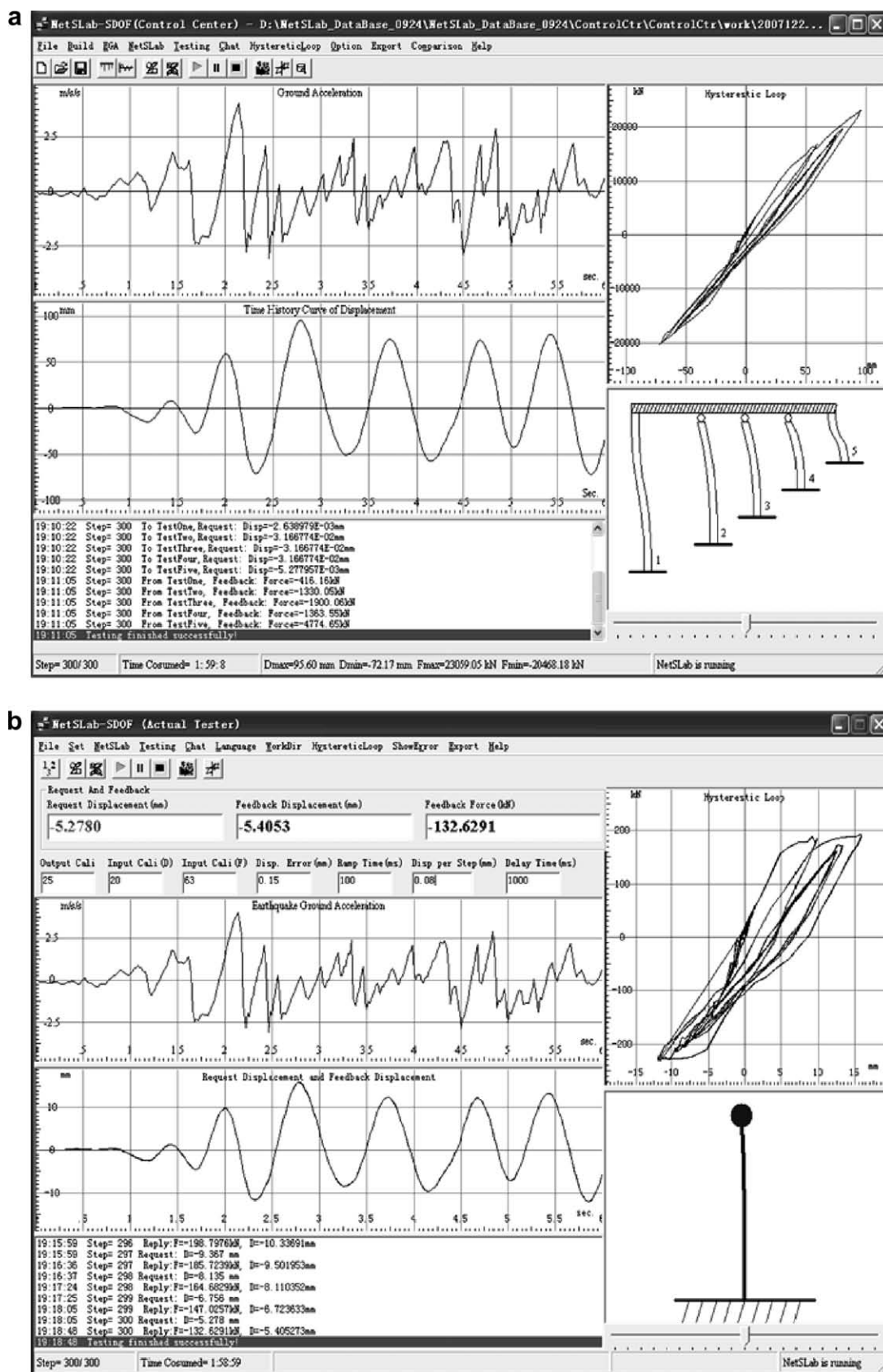


Fig. 6. Program interface at physical testing sites. (a) Controller program interface at the HNU laboratory; (b) Actual tester program interface at the HIT laboratory.

Table 2

Testing results of the P5 specimen under three work conditions.

Testing results	Peak acceleration		
	70 cm/s ² (frequently occurring earthquake)	220 cm/s ²	400 cm/s ² (seldom occurring earthquake)
Maximum displacement on the top of the pier column (mm)	1.90 –1.85	7.73 –6.39	15.93 –12.03
Maximum shear force on the footing of the pier column (kN)	95.47 –128.14	158.08 –221.96	192.54 –231.07

ilar with OpenFresco (Open Framework for Experimental Setup and Control) developed by the University of California at Berkeley in America, which enables more laboratories to participate in the networked collaborative pseudo-dynamic testing. In further research, advanced special analysis software can be applied to simplify and standardize the computing module, such as OpenSees (Open System for Earthquake Engineering Simulation) developed by the University of California at Berkeley in America. In addition, because of the error on the boundary condition brought by the division of testing substructures, the reliability of the testing results needs to be further proved by more complex testing.

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