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NETWORKED PSEUDO-DYNAMIC TESTING PART I: DATABASE APPROACH

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SUMMARY

This paper briefly presents the framework and testing result of an Internet-based platform named ISEE (Internet-based Simulation for Earthquake Engineering) for networked pseudo-dynamic simulation tests at multiple sites. This platform allows the integration of geographic-distributed structural laboratories with different facilities to become an integral part of a virtual laboratory system. It simplifies the complexity of multiple remote laboratories participating in Internet-based virtual laboratory testing and allows real-time data sharing through World-Wide Web (WWW). This paper focuses on one of the approaches in ISEE entitled Database Approach. The other approach, the Application Protocol Approach is introduced in Paper no. 1548 of the proceedings (Wang et al. [1]). The framework of the Database Approach mainly is composed of a Data Center, an Analysis Engine, and Facility Controllers. A series of networked pseudo-dynamic experiments are conducted and shows that the Database Approach is feasible for low-speed pseudo-dynamic simulation tests. The network and data processing time cost per step is about 0.2 seconds for networked domestic experiments and is about 2 seconds for transnational experiments. A 1000-time-step transnational experiment between Taiwan and US can be completed in one hour.

INTRODUCTION

As the complexity and scale of structural experiment increases and the increasing awareness of cost in today's society, the existing large-size earthquake engineering laboratories gradually become incapable of satisfying the demand of various types of experiments. Besides endlessly increasing the capacity of each laboratory, it would be more cost effective for geographic-distributed earthquake engineering laboratories to collaboratively conduct one experiment through network. The concept of a networked laboratory environment is initiated to meet this demand. In the concept of networked laboratory, sub-components of a test structure can be tested at different laboratories through network.

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Previous research efforts have been made on developing the technology of collaborative structural experiments that allows multiple laboratories jointly conduct a test of a prototype structure. In Japan, a network technique was applied to a pseudo-dynamic simulation test of a viaduct that consists of different types of piers. The experiment was performed at Kyoto University using two experiment stations for exchanging experimental data and visualization data through a shared file system (Sugiura et al. [2]). In Korea, a networked pseudo-dynamic simulation test of a base-isolated bridge was carried out collaboratively at three laboratories that are hundreds of kilometers apart (Yun et al. [3]). Also, a transnational pseudo-dynamic simulation test is conducted between Kyoto University (in Japan) and Korea Advanced Institute of Science and Technology (in Korea), which demonstrates the capability and feasibility of future international collaborative experiments (Watanabe et al. [4]). A 3-D full-scale earthquake testing facility named E-Defense with a network named ED-Net is also being constructed, which will provide tele-observation and tele-discussion capabilities (Ohtani et al. [5]). In the US, a project named NEES (Network for Earthquake Engineering Simulation) is initiated with aim to explore the benefits of sharing and integrating laboratory resources including equipment, experiment data, and simulation software through network (NEES [6]; Mahin [7]). Not only various types of experiment facilities will be updated or constructed, but also a network system called NEESgrid (Kesselman et al. [8]) will be completed. The NEESgrid will provides remote operation and observation of experiment equipment, real-time or time-independent data sharing and visualization, data linking among facilities, data repository and numerical simulation programs, and robust security management.

This research is mainly to develop the technology of performing collaborative pseudo-dynamic simulation experiments at multiple sites. In this research, a computer platform entitled ISEE (Internet-based Simulation for Earthquake Engineering) has been prototyped for integrating experimental testing facilities at multiple sites, which include components of actuator control, computing engine, and data acquisition by using the Internet. Within the framework of the ISEE, data exchange and test equipment control can be facilitated by using either the Database Approach or the Application Protocol Approach [1]. This paper presents the overview of the Database Approach. The application of ISEE currently focuses on slow pseudo-dynamic simulation tests for the possible network time lag among the participating laboratories is acceptable.

BRIEF INTRODUCTION TO DATABASE APPROACH

The Database Approach is mainly composed of a Data Center, an Analysis Engine, and Facility Controllers as shown in Fig. 1. The Data Viewers and the Cameras are the accessory parts of the ISEE framework. The functions of each component are described in the following sections.

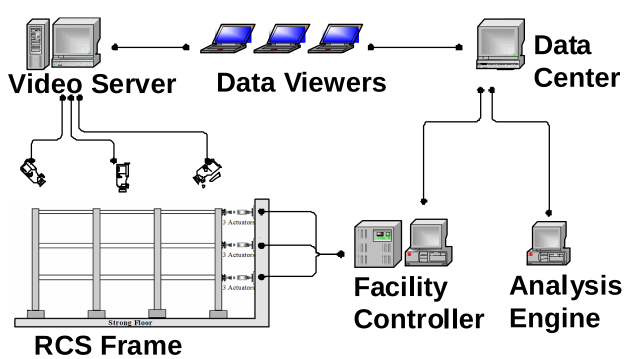

Figure 1 Database Approach in ISEE

The Data Center

The Data Center employs a database server and serves as a data exchange hub and it is also used for data repository. During an experiment, the test data and analysis data are collected and sent to the Data Center at each time step. The Data Center provides a WWW interface for researchers to setup required experimental parameters for a collaboratively networked experiment before the experiment starts, as well as accesses to public viewers, referred to as Data Viewers in Fig. 1, so that they can browse test data online on a real-time basis. Figure 2 shows a typical user interface for viewing test results online. In this work, the Data Center employs the Microsoft SQL Database Server and the IIS Web Server. In order for the Analysis Engine and the Facility Controllers to easily communicate with the Data Center, a C++ class named SQLAccess is developed (Hsu et al. [9]) for incorporation into the C++ programs used in the Analysis Engine and Facility Controllers.

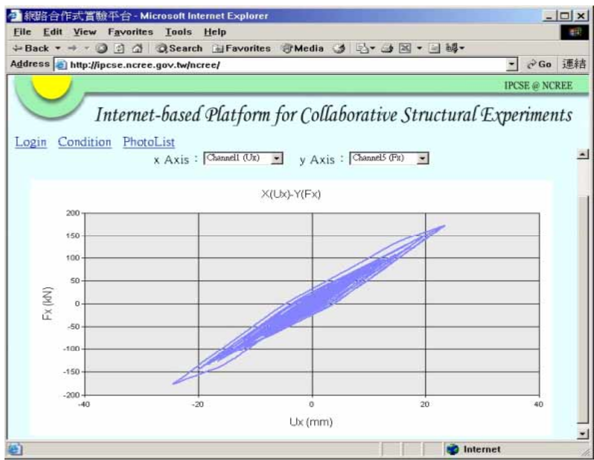

Figure 2 A Real-time Force-displacement Hysteresis Plot Shown by Data Center

The Analysis Engine

The Analysis Engine is to simulate and compute the dynamic responses of a structure by considering both the finite element analytical responses and the experimental responses measured from the specimens. During a collaborative pseudo-dynamic simulation test, the Analysis Engine receives the measured resisting forces from the Data Center, simulates the dynamic analysis, and then sends the computed displacements back to the Data Center. In this work, a finite element software framework OpenSees [10] is extended and adopted for performing finite element analysis in the Analysis Engine. This work developed new element types and added them into the OpenSees framework to represent the actual specimen in the finite element model.

The Facility Controller

Facility Controller is a software layer which is used to drive the corresponding experimental facility in the laboratory. In a networked pseudo-dynamic test, the Facility Controllers receive the displacement data from the Data Center and then send the displacements to the equipment facilities. Once each Facility Controller receives the restoring forces of each specimen from the corresponding equipment facility, the information is then sent back to the Data Center. Facility Controllers may be facility dependent. In this work, the Facility Controllers are developed and used at National Center for Research on Earthquake Engineering (NCREE, Taiwan) laboratory and the National Taiwan University (NTU, Taiwan) laboratory, which employ the MTS FlexTest IIm and MTS 407 controllers, respectively.

Network Fault Tolerance Function

Network stability is a key factor in a networked collaborative experiment. Any network disconnection during an experiment, even for a short period of time, may cut off the experimental procedures. In case of a network disconnection during a collaborative pseudo-dynamic simulation test, the Analysis Engine and Facility Controllers may not get the data they required. As a result, the experiment gets suspended even after the network is re-connected. It is not suitable to re-do a suspended experiment from the beginning if the specimen has been in the nonlinear range in which the behavior of the specimen may not be restored to the initial conditions. Therefore, a fault tolerance function is developed to overcome the possible failures of network connection due to any unforeseen circumstances. The quality of the Internet connection provided by various servers is not in the current scopes of work.

The fault tolerance function in the Database Approach allows resuming of a suspended experiment. By setting the initial conditions such as displacements, velocities, accelerations, and material stress-strain histories to the restart experiment, a suspended experiment can be followed by a restart experiment. The initial conditions of the restart experiment are taken from the final conditions of the suspended experiment. After the restart experiment finishes, a complete set of experiment result is obtained by combining the experiment results of the suspended experiment and the restart experiment. During a networked pseudo-dynamic test, the displacements and resisting forces of the test specimens are exported to a restart output file step-by-step. Once the resisting forces are measured and the information is sent back to the Analysis Engine, the displacements and forces of the test specimens are appended to the restart output file. In case of a network disconnection, the experiment gets suspended (see Fig. 3), say, at the i-th step, the restart output file will contain the data of displacements and resisting forces at least the previous (i-1) time steps. At that time, the specimens are in the status of either the (i-1)-th or the i-th step depending on the instance of the network disconnection. To resume the suspended experiment, a new restart experiment has to be constructed in the Data Center. In the restart experiment, the Analysis Engine imports resisting forces from the first step to the (i-1)-th step from the restart output file of the suspended experiment (see Fig. 4). The analysis results for the first (i-1) steps of the restart experiment are expected to be exactly the same as those of the suspended experiment because the resisting forces fed into the Analysis Engine should be exactly the same if the same Analysis Engine is employed. After the i-th step, the Analysis Engine begins to send and receive data from the Data Center until experiment completes. If the network disconnection happens again in the restart experiment, the fault tolerance function can be applied again until the entire experiment completes.

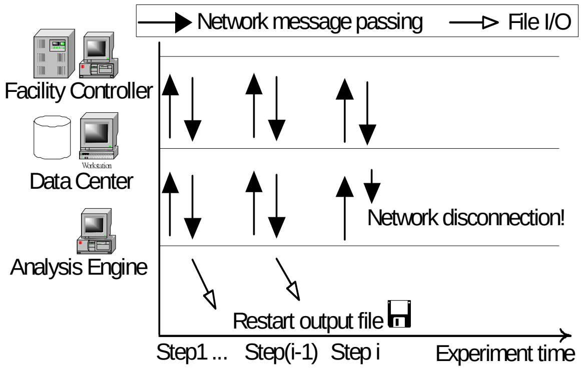

Figure 3 An experiment encountering an accident network disconnection

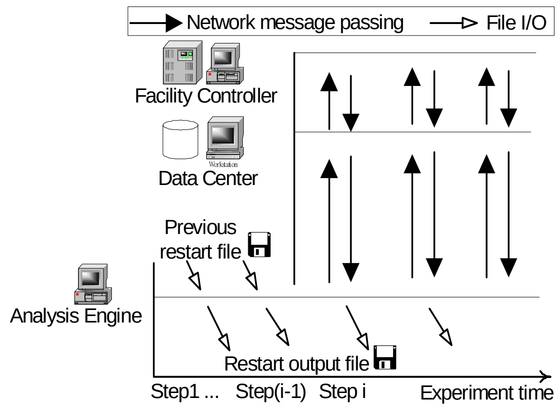

Figure 4 A restarted experiment completing a previously disconnected experiment

Other Accessory Parts

Anyone on the Internet can access the experimental data from the Data Center using a Data Viewer, a WWW browser such as Microsoft Internet Explorer or Netscape Navigator, without installing any additional software. The viewers can browse the experimental results, such as time history curves of or resisting forces and hysteresis loops of resisting forces and displacements of any specimens, of any completed or in-progress experiments. With proper authorization, users can also get tabular or XML-formatted (Simon [11]) numerical data from the WWW page of the Data Center. With proper setup of cameras and the Video Server, public viewers can also watch the real-time video images of the experiment. The Video Server also provides a WWW interface to the Data Viewers.

NETWORKED PSEUDO-DYNAMIC TESTS

Several collaboratively networked pseudo-dynamic simulation tests have been conducted and some of them are presented in this paper. This section introduces two representative networked experiments showing the feasibility and efficiency of the Database Approach.

Double-Skinned Concrete Filled Tubular Columns

A series of pseudo-dynamic simulation tests on Double-Skinned Concrete Filled Tubular (DSCFT) columns using the Database Approach were conducted to investigate the behavior of the DSCFT columns and the efficiency of the proposed platform. A four-pier bridge system subjected to a series of earthquake input excitations is simulated using the Database Approach. The numerical model of the bridge system is shown in Fig. 5. The numbers in circles denote the indices of the nodes. Nodes adjacent to the decks are in pairs with roller constraints or hinge constraints. The three rigid decks and the two side piers (marked B1, B2, B3, C1 and C4 in Fig. 5) are modeled using linear beam-column elements in OpenSees. The flexural stiffness of the decks (B1, B2 and B3) and the side piers (C1 and C4) are set as 2200 MN-m2 and 41.2 MN-m2, respectively. The two middle piers (marked C2 and C3 in Fig. 5) are simulated by two DSCFT piers (Tsai and Yeh [12]), which are located at the NTU Lab. and the NCREE Lab., respectively (see Fig. 6). In the longitudinal (NS or X) direction, node 1 and 10 of the bridge superstructure are roller-connected to node 2 and 11 of piers, while node 4 and 7 hinge-connected to node 5 and 8. In the transverse (EW or Y) direction, all four piers are hinge-connected to the decks. Node 2 and 11 are lumped with a 25.36-tonne mass in Y direction; node 5 and 8 are lumped with a 126.8-tonne mass in X direction and 101.44-tonne mass in Y direction. Vertical applied load on pier C1 and C4 is 249kN and that of pier C2 and C3 is 883kN. In this experiment, C2 and C3 are DSCFT columns are simulated by using a new element type mentioned above, developed by the authors and added in OpenSees. The external and internal tube diameters are 0.5m and 0.3m, respectively. The thickness is 5mm for the external steel tube and is 3mm for the internal steel tube. The network configuration of the DSCFT experiments is shown in Fig. 7. The details of the experiments can be found in Tsai et al. [13].

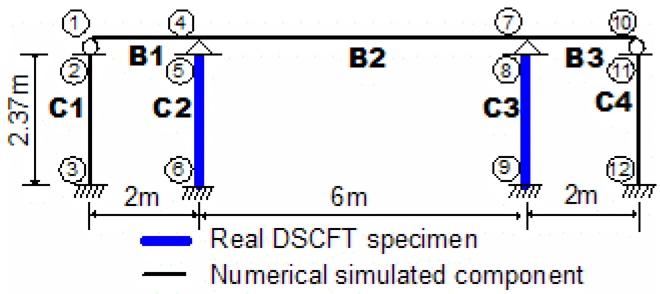

Figure 5 Geometric configuration of the 4-pier bridge


Figure 6 Installation of DSCFT piers in NTU (left) and NCREE (right)

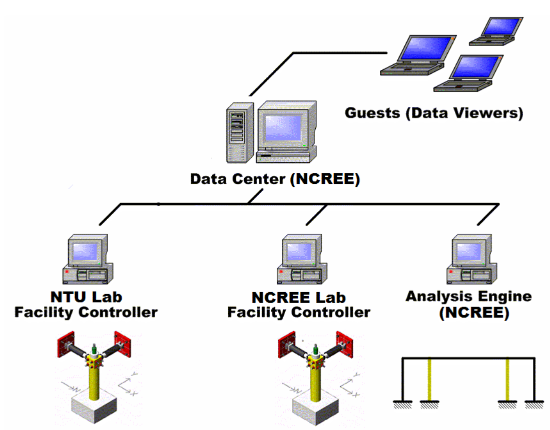

Figure 7 Network configuration of the DSCFT tests

The recordings of the 1999 Chi-Chi earthquake at station TCU082 are used as input excitations. Each input excitation consists of motions in both X (North-South) and Y (East-West) directions; therefore, each specimen is installed at the corner of the reaction walls with two actuators as shown in Fig. 6. The test specimen then can be controlled (by displacements) and measured (resisting forces) in both X and Y directions. The ground accelerations recorded during the 1999 Chi-Chi earthquake at TCU082 station in the NS direction were applied in the X direction and the accelerations recorded in the EW direction were applied in the Y direction. The time duration is 50 seconds and the time step is 0.02 seconds. The records are scaled to represent different hazard levels. The first level is 20% of the second level, which is 50% of exceeding probability in 50 years. The second level is 50% of exceeding probability in 50 years, which results in the peak ground accelerations (PGAs) of 0.0567g and 0.0696g in X and Y directions, respectively. The third level is 10% of exceeding probability in 50 years, which results in the PGAs of 0.173g and 0.209g in X and Y directions, respectively. The fourth level is 2% of exceeding probability in 50 years, which results in the PGAs of 0.216g and 0.262g in X and Y directions, respectively.

Table 1 lists several DSCFT experiments using the Database Approach. These experiments employ different PGAs of earthquake ground motions and place Analysis Engine at different location. The input excitations for the first two tests (Exp. #144 and #153) can be treated as small perturbations, which the specimens are expected to behave linear-elastically. For the last four tests, greater input excitations are applied to observe the nonlinear behaviors of the DSCFT piers.

Table 1 Experiment list of the DSCFT Database Approach tests

Exp. ID	Earthquake PGAs	Place of Analysis Engine
144	NS:0.0113g EW:0.0137g	NCREE
153	NS:0.0113g EW:0.0137g	Stanford University
155	NS: 0.0567g EW: 0.0696g	NCREE
156	NS: 0.1730g EW: 0.2090g	NCREE
157/158*	NS: 0.2160g EW: 0.2620g	NCREE
159	NS: 0.1730g EW: 0.2090g	NCREE

* Exp. 157 encountered an accident network disconnection and restarted by Exp. 158

Table 2 lists the breakdown of total networked experiment time. In the Exp. #153, the Analysis Engine was placed at Stanford University. As expected, the network communication time becomes the major time cost in these transnational experiments. Comparing to the Exp. #144, the Exp. #153 requires 1740 seconds more (1944 sec.-204 sec.=1740 sec.; i.e., 1.74 seconds per time step in average) for network communication time because of the limited transnational network performance. Roughly speaking, by using the pseudoGen2 elements (Exp. #144 and Exp. 153), the network and data processing time per time step is about 0.2 seconds (204 sec. / 1000 time steps) for domestic experiments and less than 2 seconds (1944 sec. / 1000 time steps) for transnational experiments, which are less than 20% and 70% of the total elapsed time, respectively.

Table 2 Timing statistics of the experiments DSCFT experiments (1000 time stepped)

Exp. Id	Network and database processing	Pseudo-dynamic analysis	Facility controlling
144	204 sec.	13 sec.	907 sec. * (NTU: 715 sec.; NCREE: 907 sec.)
153	1944 sec.	10 sec.	905 sec. * (NTU: 556 sec.; NCREE: 905 sec.)

* The facility control time of experiments depends on the maximal control time at NTU and NCREE

The fault tolerance function is implemented for these experiments. The earthquake input excitation in Exp. #155 is small so the specimen is expected to behave linear-elastically and hence the specimen can restore to its initial condition after the experiment. For Exp. #156 to #159, the input excitations represent higher hazard levels and the behavior of the structure cannot be restore to the initial elastic conditions; therefore, it is assumed that the structure suffers a 150-second earthquake, which is composed of three 50-second TCU082 acceleration records at different amplitudes (see Table 1). Exp. #156 is performed from 0.02 seconds to 50.0 seconds; Exp. #157 is performed from 50.02 to 62.16 seconds; Exp. #158 is performed from 62.18 to 100.0; and Exp. #159 is performed from 100.2 to 150.0 seconds. During Exp. #157, an unexpected network disconnection occurred at time step of 62.16-second and the experiment got suspended. Exp. #158 is the restart experiment of Exp. #157. Figure 15 shows the displacement time history of experiments #156 to #159 in the X direction. The nonlinear behavior of the DSCFT columns is described in details in Tsai and Yeh [13] and is not repeated here.

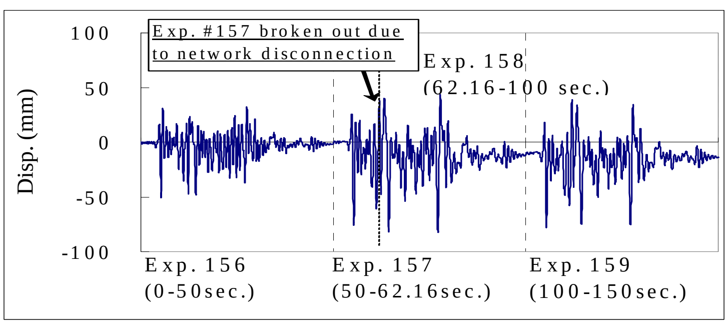

Figure 8 Time history of the displacement along X of Exps. #156 to #159

RCS Frame

The ISEE Database Approach is applied on a one-site full-scale 3-bay 3-story RCS (Reinforce Concrete and Steel) experiment at NCREE. Researchers from NCREE and Stanford University collaboratively performed a pseudo-dynamic simulation test on the RCS moment frame. The RCS test was conducted primarily to investigate strong-column weak-beam criterion, composite action of concrete slab and steel beams, integrity of the pre-cast column and composite beam-column connections. The ISEE Database Approach is applied in the one-site test mainly for real-time (or nearly real-time) data sharing. Researchers in Taiwan and United States, even though some of them were not at NCREE during the experiment, can get the most updated experimental data and video images through the Internet. The success of the ISEE Database Approach provides impetus to explore international collaboration and data archiving envisioned for the NEES initiative.

Measuring 12 meters tall and 21 meters long, this RCS frame is among the largest frame tests of its type ever conducted (see Fig. 9). The three-story prototype structure is designed for a highly seismic location either in California or Taiwan, following the provisions for composite structures in the International Building Code 2000. The frame is loaded pseudo-dynamically using input ground motions from the 1999 Chi-Chi earthquake and 1989 Loma Prieta earthquake. Both earthquakes are scaled to represent 50%, 10%, and 2% in 50-year seismic hazard levels. The details of the experiments can be found in Tsai [13]. Figure 10 shows the network configuration of the RCS test.

Figure 9 RCS frame at NCREE

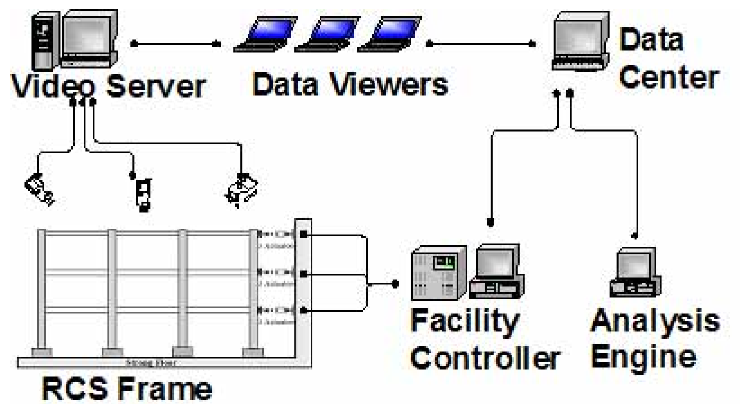

Figure 10 Network configuration of the RCS frame test

In addition to the Data Center, Analysis Engine and Facility Controllers, three cameras are placed around the frame to capture the real-time testing videos for public viewing. The Data Viewers, which can be anyone on the Internet, can browse the experiment data and watch the real-time videos through the web page of the Data Center. The detail of the test and the experiment results can be found on the web page at http://rcs.ncree.gov.tw. This experiment successfully demonstrates that ISEE Database Approach can be applied to achieve collaborative pseudo-dynamic simulation tests through network on a real-time basis.

CONCLUSIONS

This paper introduces the Database Approach in the ISEE framework, which consists of three major parts: Data Center, Analysis Engine, and Facility Controllers. The Data Center consists of a Microsoft SQL Database Server and an IIS Web Server. Taking the advantage of the object-oriented finite element framework of OpenSees, new element types are developed and implemented to allow using the restoring force of a specimen measured in the laboratory as its element restoring force for analytical simulation. The Analysis Engine and the Facility Controllers are connected with the Data Center through a C++ class consisting of SQL database commands. Several pseudo-dynamic experiments were conducted to evaluate the validity and efficiency of the components using the Database Approach in ISEE framework. The three-layer architecture of the Database Approach simplifies the complexity of integrating multiple remote laboratories participating in networked experiments. Test results show that the Database Approach in ISEE can be effectively applied to single- or multi-site pseudo-dynamic tests through network on a real-time basis.

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