Submitted to the Eighth National Conference on Earthquake Engineering,
San Francisco, CA, USA, April 17-21, 2006

NETWORK SYSTEM FOR A TRANSNATIONAL COLLABORATIVE PSEUDO-DYNAMIC EXPERIMENT ON A DSCFT-PIER BRIDGE SYSTEM

Y. S. Yang[1] , S. J. Wang[2], K. J. Wang[3], M. L. Lin[1], Y. T. Weng[1], W. C. Cheng[3], Y. Y. Chang[4], K. C. Tsai[5], D. T. Lau[6], S. H. Hsieh[7], F. P. Lin[8] and S. Y. Lin[9]

ABSTRACT

This paper introduces the latest updates of a platform named ISEE (Internet-based Simulation for Earthquake Engineering) and its application on a Taiwan-Canada transnational collaborative pseudo-dynamic experiment of a multiple-span bridge system. Three reduce-scale Double-Skinned Concrete-Filled Tube (DSCFT) pier specimens are located at laboratories at the National Center for Research on Earthquake Engineering (NCREE), National Taiwan University (NTU), and Carleton University (CU), respectively. A Command Generation Module (CGM), based on an extended OpenSees platform is employed for simulation of different ground motion events in the experiment. Laboratory dependent Facility Controlling Modules (FCMs) are developed and installed at all laboratories, transferring controlling commands generated by a CGM to the hydraulic actuator controllers. The ISEE Data Center gathers and shares experimental data with CGM and FCMs. Video Modules transfer real-time video streams from laboratories to Internet. Remotely controlled Camera Modules take high resolution specimen photos, automatically after FCMs complete displacement controlling commands of each time step. Visualization Modules generates 2D plots of experimental data and comparisons of experimental and numerical analysis data, and presents these generated figures on the web page in real-time. The above ISEE components communicate through Internet. Researchers and guests may witness or observe the experiment progress through widely used Web browsers, such as Internet Explorer 6, Netscape 6 or FireFox, without need to install additional programs for viewers' convenience. The numerical model in the CGM and the preliminary numerical simulation of the bridge responses are also introduced in this paper. The networked

[1] Associate Research Fellow, National Center for Research on Earthquake Engineering, Taipei 106, Taiwan
[2] Assistant Technologist, National Center for Research on Earthquake Engineering, Taipei 106, Taiwan
[3] Associate Technologist, National Center for Research on Earthquake Engineering, Taipei 106, Taiwan
[4] Ph.D. Student, Carleton University, Ottawa, Canada
[5] Director, National Center for Research on Earthquake Engineering, Taipei 106, Taiwan
[6] Professor, Carleton University, Ottawa, Canada
[7] Professor, Department of Civil Engineering, National Taiwan University, Taipei 106, Taiwan
[8] Division Head, National Center for High-performance Computing, Hsinchu 300, Taiwan
[9] Assistant Research Scientist, National Center for High-performance Computing, Hsinchu 300, Taiwan

experiment is scheduled in November and December, 2005.

Background of Networked Collaborative Experiments

In view of the continuous advances in earthquake engineering and the increasing awareness of cost in today's society, existing large sized structural laboratories are beginning to experience limitations in their facilities to meet the demands of more complex experiments to address the pressing concerns of latest earthquake engineering problems, such as experiments of multi-span bridges or real-time dynamic hybrid testing using both shake table and reaction walls. Besides endlessly increasing the capacity of each laboratory, it would be more cost effective for laboratories to collabore by pooling their resources to conduct experiments of common interests. In addition, it would be more productive and can make more out of the experimental resources and results if experts at different laboratories can more readily work or participate as a team. Considering the benefits of international cooperation, the concept should be applied to transnational collaborative experiment capability. Some research efforts (Watanabe et al., 2001; Ohtani et al 2003; Kim 2004; NEES Inc., 2005) have been focused on developing the technology of collaborative experiments on earthquake engineering, which allows laboratories to jointly conduct an experiment at multiple testing sites. National Center for Research on Earthquake Engineering (NCREE) has developed a platform called ISEE (Internet-based Simulation for Earthquake Engineering) for collaborative pseudo-dynamic experiments among laboratories through Internet. This platform has been applied on single-site or multi-site experiments (Tsai et al 2003; Chen et al. 2004; Wang et al. 2004; Yang et al. 2004; Tsai et al. 2004; Tsai et al. 2006).

Brief of the Taiwan-Canada Collaborative Experiment

A joint collaboration among NCREE, National Taiwan University (NTU) and Carleton University (CU) has been established to perform a transnational collaborative pseudo-dynamic experiment to simulate the response of a multi-span bridge system (see Fig. 1) subjecting to a series of bi-lateral ground motions. The specimens of P1, P2 and P3 are located at CU, NCREE, and NTU, respectively. Each pier is controlled along two lateral directions with a pre-tensioned axial rod to simulate the bi-lateral responses and the gravity load. The fourth pier and the bridge decks are numerical simulated by a 3D finite element model. The ISEE platform is employed not only for the data repository and communication among laboratories, but also data sharing on Internet, video broadcasting, 2D plots and 3D visualization of bridge deformation. The ISEE software components employed in the experiment are introduced in this paper. More detail about the bridge structural design and ground motion selections can be found in Chang et al. 2005.

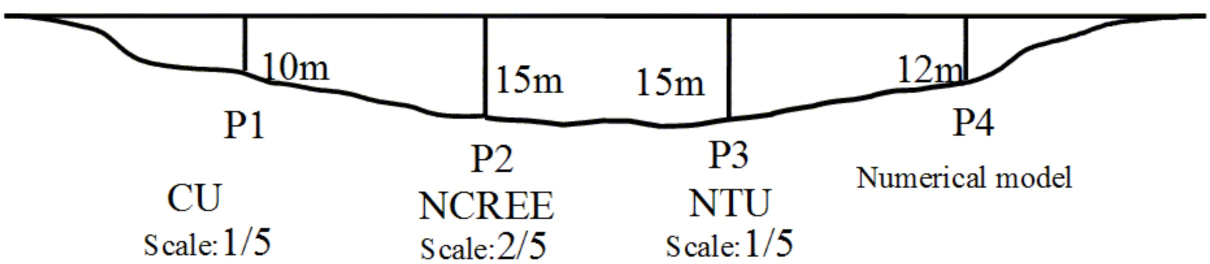


Fig. 1 Elevation of the multi-span bridge system in the experiment

Network Configuration of the Pseudo-Dynamic Experiment

Figure 2 shows the network configuration connecting the hardware and software components for the pseudo-dynamic experiment. Three DSCFT piers, P1, P2, and P3, will be controlled by the Facility Controlling Modules (FCMs) at the laboratories where they are set up and will be tested. The FCMs take actions to comply with the commands (i.e., bi-lateral target displacements at pier top) received from the Data Center, and send back the responses (i.e., bi-lateral resisting forces at pier top). The Command Generation Module (CGM; or so-called Analysis Engine), after receiving and interpreting the specimens' responses, generates the commands of next time increment by performing numerical dynamic analysis. The FCMs and CGM may send some of the Data Acquisition data (e.g., strains, displacements, rotations, load-cell forces) or numerical analysis data to the Data Center. A Visualization Module accesses the experimental or numerical analysis data in the Data Center, generates 2D plots or 3D structure deformation figures, and sends the plots and figures to the Web Server. The Web Server then shares the data, plots and figures on the web page. The Video Modules capture video records of the experiment progress and transmit them as video streams through the Internet. During the experiment, the data, plots, figures, and videos are updated continuously. Participating researchers at remote sites or others with Internet connection can observe the progress of the experiment or access the information. The Camera Modules take photos of the specimens after the FCMs complete their commands at each time step. In the experiment, the camera images are stored off-line and are not shared in real time.

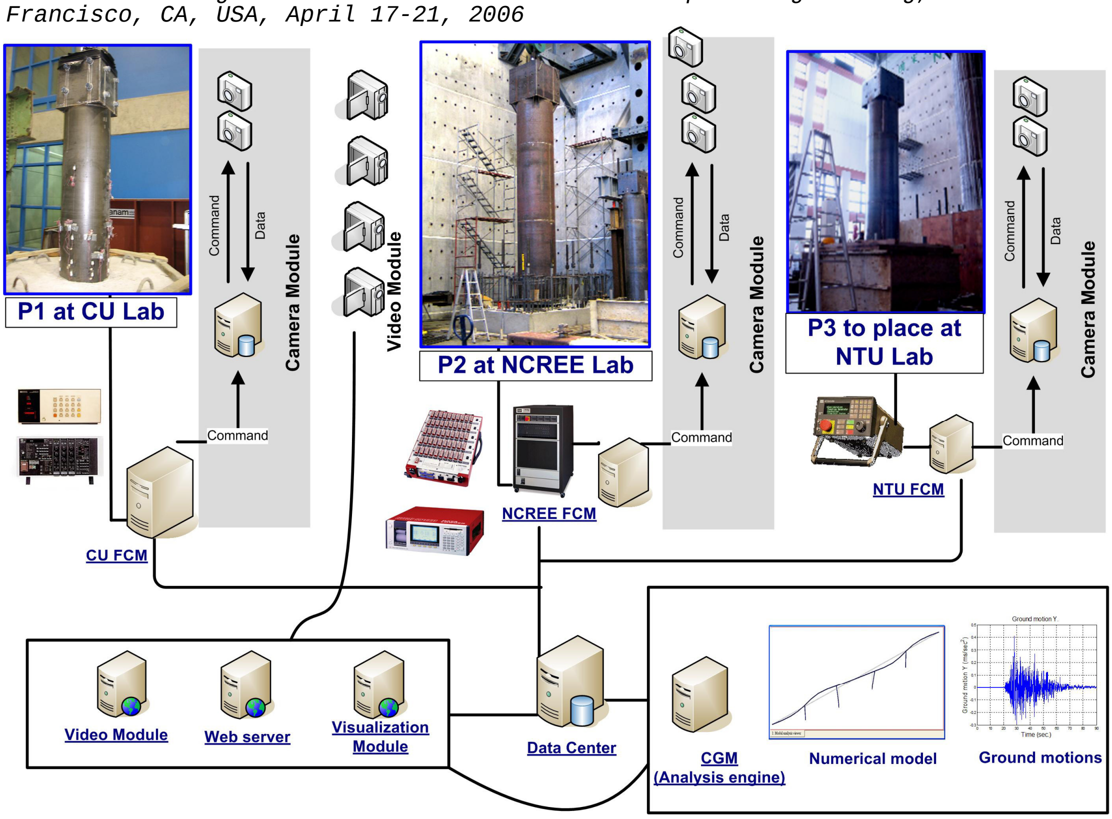


Fig. 2 Network configuration of the pseudo-dynamic experiment

ISEE Components

This section briefly introduces the CGM, FCMs, Visualization Module, Video Modules and Camera Modules employed in the experiment.

Command Generation Module

In the implementation of the pseudo-dynamic experiment, a full scale numerical model of the prototype structure is implemented in the CGM module (or Analysis Engine) to calculate the dynamic responses of the entire system. The Operator-Split (OS) method of Newmark integration family will be employed with a time step of 0.02 second for this experiment. Unbalance-force check and iteration will not be performed to avoid load reversal in the pseudo-dynamic experiment. When each Facility Controller receives instructions for the target displacements for loading the sub-component test specimens from the Data Center, the Facility Controller will calculate the corresponding required displacements to be imposed on each of the sub-component test specimen. Once the target displacements are imposed, the force responses of the test specimens are measured by load cells in the test. The force responses are converted to the corresponding full scale model response values before sending back to the Data Center. The related information is then sent from the Data Center to the Analysis Engine for computation of the target displacements of the next time step.

The OpenSees structural analysis program (McKenna and Fenves 2000; OpenSees 2005) is extended (Yang et al. 2004) and employed for the experiment. The details of extending OpenSees for pseudo-dynamic experiment can be found at Yang et al. 2004. The pseudo-dynamic functionality in this version of OpenSees is implemented to be compatible with ISEE Data Center only. The pseudo-dynamic functionality may be extended in the future official OpenSees program (Fenves et al. 2004). In addition to the extended OpenSees developed for here, PISA3D (Tsai and Lin 2003) can be another option for the pseudo-dynamic CGM if some modifications are incorporated in the communication with the ISEE Data Center.

Facility Controlling Modules

One of the challenges for conducting a networked collaborative pseudo-dynamic experiment is the accurate remote controlling of load applying actuators at multiple sites. To achieve this goal, a compatible and standardized control software platform is extremely desirable for control commands between the various facility controllers at different participating sites in a collaborative test. Presently, different commonly commercial software solutions are available for interface control and instrumentations of tests, such as Labview, MATLAB, C++, etc. In this research, C++ and LabVIEW are selected as the controlling software platform to integrate testing equipment at various participating sites into a unified test platform for the cooperative structural test. In addition, this software platform also provides remote control of the data acquisition instrumentations via Internet or Intranet. In this cooperative program, three participating laboratories, Carleton, NCREE, and NTU, use different models of servo-controllers, which are MTS 458, MTS FlexTestIIm, and MTS 407, respectively. The key design considerations of the controlling software platform for long distance multiple site collaborative hybrid testing are listed as follows

1) Module for equipment control: The primary function of this module is to generate the commands for accurate and robust control of actuators and data acquisition across different manufactures' equipment and standardized software for equipment control operating under different computer operating systems, such as Windows, Linux, UNIX, and Open Source.
2) Module for real time display: Because of the requirement of the software platform to be reliable and robust for long distance multiple site hybrid tests, accurate timing and synchronization of commands and data communication are critically important. Time delay due to heavy network communication and the impact on time sensitive test are critical considerations which must be taken into account in the design of the module.
3) Module for data storage and management: Test data at different sites may be stored locally using different data formats. In order to facilitate the exchange of information during a test and later for test data interpretation and research, data harmonization and the adoption of a standardized data exchange format will enhance the portability of the software design.
4) Module for network and security issues: The primary function of this module is to network participating laboratories together for the purpose to conduct collaborative hybrid test at multiple sites. To prevent unauthorized interruption of the collaborative multiple site hybrid test, access to the collaborative hybrid test network is authorized to researchers at the participating laboratories. Other issues such as network failure or temporally suspension of the collaborative hybrid test due to unexpected damage of test specimen

need to be considered in the design of the module.

5) Module for instant messaging: A module for instant communication or notification between participating researchers at different laboratories should be considered in case of unforeseen circumstances during a test. For example, the status of a collaborative experiment may be suspended, resumed, or even stopped prematurely for various reasons such as safety concern or the necessity of minor specimen adjustment.

Visualization Module

The task of Visualization Module is mainly to transfer experimental or analysis data into images at the end of each time step during experiments. As shown in Fig. 3, the experimental data (e.g., specimen resisting forces or displacements) may be taken from the Data Center, while the structure deformation data (e.g., force or displacements of other numerical components) can be obtained from the CGM. In the current ISEE platform, the Visualization Module includes a 2D Plotter and a 3D Renderer. The 2D Plotter generates time history plots or hysteretic loops of the data, while the 3D Renderer generates the structure deformed shape in 3D computer graphics manner. The generated images are stored in common standardized image formats, such as GIF or JPG formats, so that the web server can access the images and share them directly on the web page in real-time during experiments. At the time this paper was written, the 3D Renderer in the ISEE platform has been applied only to a bi-directional pseudo-dynamic experiment of a 2-story buckling-restrained-brace frame using ISEE Application Protocol Approach (Wang et al. 2004; also shown in 3D Visualization in Fig. 3). It still needs more modifications before it is applied to the DSCFT pseudo-dynamic experiment using ISEE Database Approach (Yang et al. 2004).

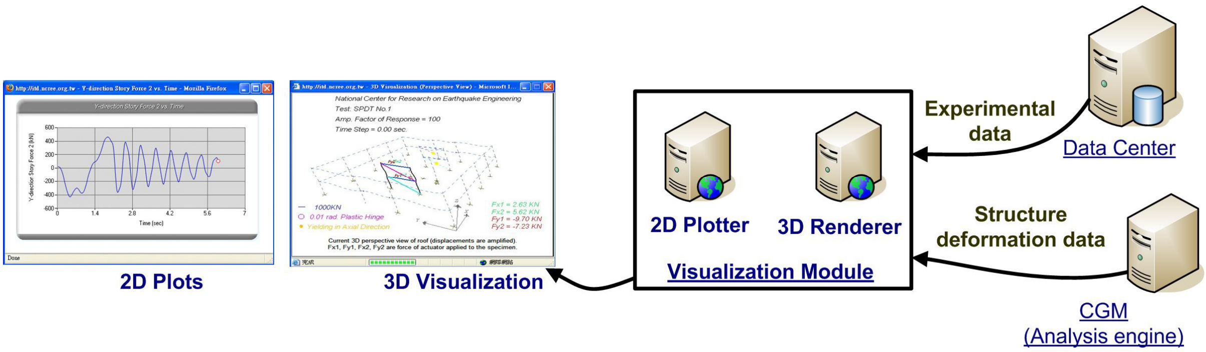


Fig. 3 Visualization Module in the ISEE platform

Video Modules

The functionality of the Video Module is mainly to transfer the video streams from video camcorders to Internet during experiments. As shown in Fig. 4, the video sources are taken from common digital video cameras or pan-tilt-zoom cameras. The viewing range of pan-tilt-zoom cameras can be controlled by the operator. A video switch is used for a video operator to select which video streams are to be recorded and/or broadcasted. A video recorder records the videos to a hard disk. The media encoder is a personal computer with video capture cards, which encodes the original video streams into encoded digital stream data and transfers the stream data to a media server. The media server than broadcasts the video stream on the Internet. The media server can send video streams directly to Internet viewers' web browser during the experiment.

Most hardware and software components of the Video Module are readily available from various manufacturers or suppliers. The currently used camcorders include mini digital video cameras and a few fixed pan-tilt-zoom cameras. The capture card installed in a personal computer is ViewCast Osprey 220 (http://www.viewcast.com/). Microsoft Windows Media Encoder 9 and Windows Media Services 9 Series are used as the media encoder and media server, respectively. Currently, the resolution of the video streams can be up to 720 by 480 pixels with 30 frames per seconds, but they are usually set to lower resolution, such as 320 by 200 due to limited network bandwidth.

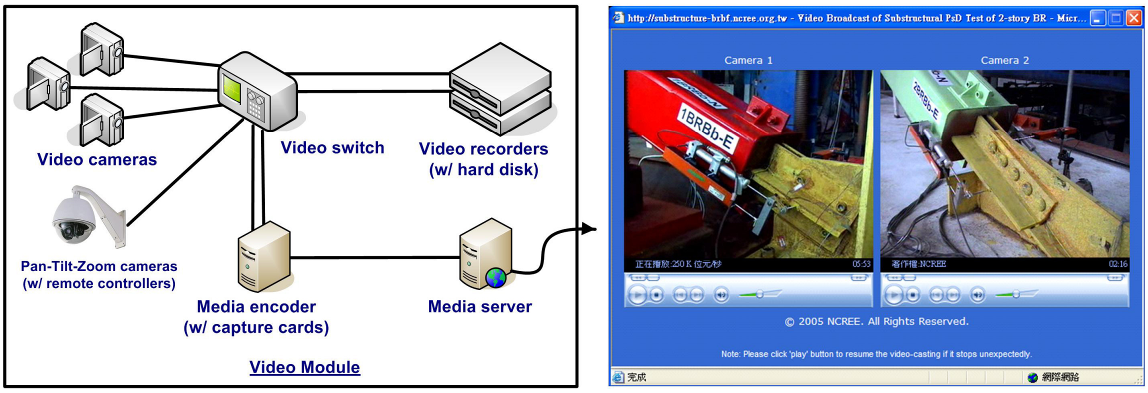


Fig. 4 Visualization Module in the ISEE platform

Camera Module

Pseudo-dynamic experiment is typically performed in a slow manner. For example, a test simulating dynamic responses of a 30-second ground motion may take one hour or more. The slow speed allows researchers the opportunities to take high-resolution still images at proper positions and time points to observe and record specimen cracks, deformations or failure modes. In addition, a video showing the dynamic response of the specimen (or a part of the specimen) can be made by editing a series of still images taken from a fixed viewpoint. Without editing the still images to videos, the dynamic response of the specimen can not be seen due to the slow progress of the tests.

Comparing to the Video Module, the Camera Module captures higher resolution but only in still images. Each camera captures a single image after the facilities complete their commands of each time step. Instead being controlled manually, the camera shutters are controlled by computers because there are typical thousands of time steps in a test and the time intervals are not constant among each time step. Therefore, the shutters of cameras must be remotely controllable by software. The software should be able to detect the completion of facility commands, so that it triggers the camera shutters at proper time points.

The development of the Camera Module in ISEE is on-going and its capabilities are being continuously enhanced. An attempt has been made by using a software package named gPhoto2

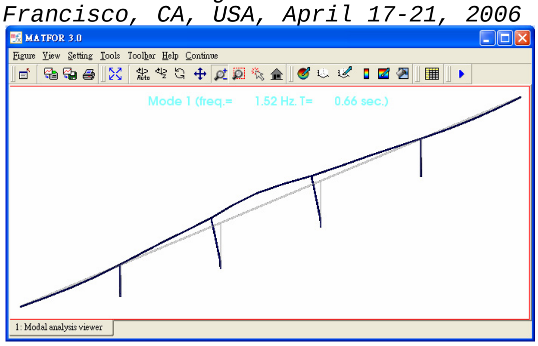
(Waugh et al. 2005). The gPhoto2 follows Picture Transfer Protocol (PTP), a standardized protocol mainly developed by Kodak, as a standard way to access digital cameras. A gPhoto2-based program is developed in this work and can send a signal to a Nikon Coolpix 5700 camera to trigger the shutter (see Fig. 5). This Camera Module takes about 8 seconds to get an image, which is too long to take an image at every time step. This means a photograph image can only be captured at the rate of every several time steps. A fully developed Camera Module needs to take thousands of still images nonstop at the rate of one image per second if researchers need a photograph record of at each time step.

Fig. 5 A laptop being able to trigger a Nikon camera's shutter

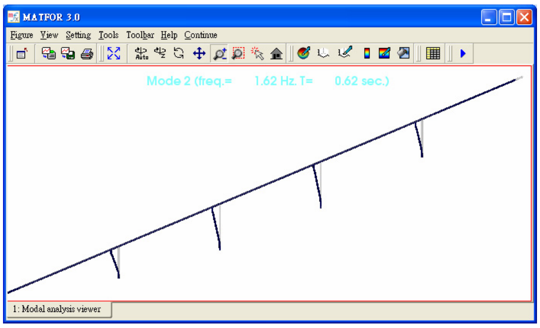
Analytical Model for the Pseudo-Dynamic Expeirment

Nonlinear static and dynamic analyses are performed using OpenSees (McKenna and Fenves 2000; OpenSees 2005) for simulating the seismic responses and PISA3D (Tsai and Lin, 2003) prior to the test to calculate the natural frequencies and periods of the bridge, to predict the possible peak responses of the piers during the test, and to verify the force and stroke limitations of the actuators are not exceeded. The material parameters are based on tension coupon tests of steel tubes and concrete compressive tests of the specimen material at NCREE. The analyses described herein are carried out using OpenSees.

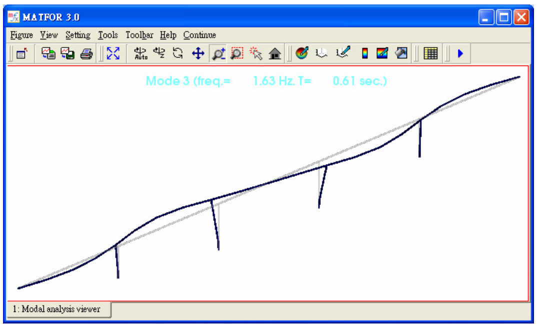
The deck and the piers are modeled in OpenSees by displacement-based beam column elements with five integration points. Each integration point represents a nonlinear section moment-curvature status. The concrete and steel are modeled using the FEDEAS steel and concrete material models (Filippou 1996) implemented in OpenSees. Figure 6 shows the first four modes of the numerical model. The first three modes are vibrations in the transverse direction and the fourth mode shows vibration in the roadway direction. The estimated maximal drift ratios and shear forces of the three piers under the input ground motions are presented in Tables 1 and 2, respectively.



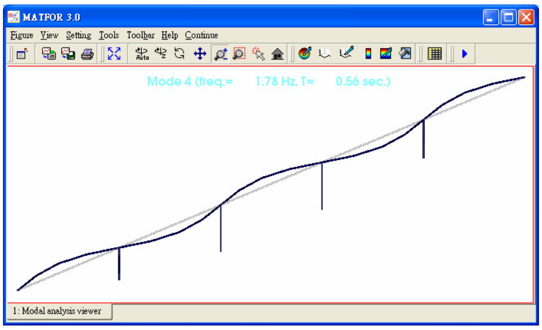
Mode 1 (Freq.= 1.52 Hz; T=0.66 sec.)



Mode 2 (Freq.= 1.62 Hz; T=0.62 sec.)



Mode 3 (Freq.= 1.63 Hz; T=0.61 sec.)



Mode 4 (Freq.= 1.78 Hz; T=0.56 sec.)

Figure 6 First four modes of the bridge system

Table 1 Estimated maximal drift ratios of the four piers under the input ground motions

Piers	Max. Drift Ratio			
	Longitudinal direction (X or N-S)		Transversal direction (Y or W-E)	
P1 at CU	0.46%	-0.52%	0.25%	-0.27%
P2 at NCREE	0.29%	-0.34%	0.26%	-0.25%
P3 at NTU	0.26%	-0.32%	0.25%	-0.22%
P4	0.29%	-0.37%	0.17%	-0.17%

Table 2 Estimated maximal base shear forces of the three piers under the input ground motions

Piers	Max. Shear Forces in Lab.			
	Longitudinal direction (X or N-S)		Transversal direction (Y or W-E)	
P1 at CU	252.4 kN	-229.2 kN	150.1 kN	-139.9 kN
P2 at NCREE	768.5 kN	-631.2 kN	556.6 kN	-540.6 kN
P3 at NTU	188.3 kN	-144.8 kN	117.6 kN	-130.3 kN

Conclusions

The collaborative experiment among NCREE, NTU, and CU is aimed not only to study and validate the seismic performance of DSCFT piers for bridges, but also to develop a standardized procedure for laboratories to join in Internet-based collaborative pseudo-dynamic experimental research. A four-DSCFT-pier bridge system is chosen as the prototype structure for a collaborative experiment to evaluate the performance of the developed procedure implemented in the ISEE (Internet-based Simulation for Earthquake Engineering) platform for cross-continent multi-site collaborative structural tests. Three of the scaled specimens are to be loaded pseudo-dynamically at the participating laboratories separated over long distance, and the fourth pier is simulated by computer model. Command Generation Module based on OpenSees, Facility Controlling Modules based on MTS and LabVIEW, Visualization Module for 2D plots and 3D visualization, and Video Modules for web broadcasting are ready and will work together for the collaborative experiment scheduled in November and December, 2005.

Acknowledgments

The research supports provided by the Natural Sciences and Engineering Research Council Canada and the National Science Council Taiwan are gratefully acknowledged. The authors would also like to acknowledge the technical information and assistance provided by Professor H. A. Khoo of Carleton University, and C. H. Chen of NCREE.

References

Chang, Y. Y., Yang, Y. S., Wang, S. J., Lin, M. L., Weng, Y. T., Wang, K. J., Deng, H. Z., Lau, D. T., and Tsai, K. C., 2005, Hybrid testing of a multi-span bridge, *Proceedings of the First International Conference on Advances in Experimental Structural*, Nagoya, Japan, 307-314.

Chen, C. H., Lai, W. C., Cordova, P., Deierlein, G., and Tsai, K. C., 2004, Pseudo-dynamic testing of a full scale RCS frame: Part 1 – design, construction and testing", Paper No. 2178, P*roceedings*, *13World Conference on Earthquake Engineering*, Vancouver, Canada.

Fenves, G. L., McKenna, F., Scott, M. H., and Takahashi, Y., 2004, An object-oriented software environment for collaborative network simulation, Paper No. 1492, *Proceedings*, *13World Conference on Earthquake Engineering*, Vancouver, Canada.

Filippou, F. C., 1996, FEDEAS: Nonlinear static dynamic analysis from research to practice, *Proceedings of ASCE Structures Congress*, Chicago, USA.

Kim, J. K., 2004, KOCED collaboratory program, *Proceedings of the 2004 ANCER Annual Meeting: Networking of Young Earthquake Engineering Researchers and Professionals*, Hawaii, USA.

McKenna, F. and Fenves, G. L., 2000, an object-oriented software design for parallel structural analysis, *Proceedings of Advanced Technology in Structural Engineering*, Structures Congress 2000, ASCE, May 2000.

NEES Inc., 2005, Network for Earthquake Engineering Simulation Web Page, available at http://www.ness.org/.

OpenSees Web Page, 2005, Available at http://opensees.berkeley.edu/

Ohtani, K., Ogawa, N., Katayama, T., and Shibata, H., 2003, 3-D full-scale earthquake testing facility and earthquake engineering network, *Proceedings of the Third World Conference on Structural Control*, Italy, 1019-1024.

Tsai, K. C. and Lin, B. Z., 2003, User manual for the platform and visualization of inelastic structural analysis of 3D systems PISA3D and VISA3D, Technical report CEER/R92-04, Center for Earthquake Engineering Research, National Taiwan University, Taipei, Taiwan.

Tsai, K.C., Hsiao, B.C., Lai, J.W., Chen, C.H., Lin, M.L. and Weng, Y.T., 2003, Pseudo-dynamic experimental responses of a full scale CFT/BRB composite frame, *Proceedings of Joint NCREE/JRC Workshop on "International Collaboration on Earthquake Disaster Mitigation Research (Methodologies, Facilities, Projects and Networking)*, Taipei, Taiwan, October 2003.

Tsai, K. C., Hsiao, P. C., Lai, J. W., Weng, Y. T., Lin, M. L., Chen, C. H., 2004, International collaboration on pseudo-dynamic tests of a full scale BRB composite frame, *Proceedings of ANCER Annual Meeting*, Honolulu, USA, July 2004

Tsai, K. C., Lin, M. L., Tsai, C. Y., Hsiao, P. C., and Chen, C. H., 2006, Bi-directional sub-structural pseudo-dynamic testing of a full-scale 2-story BRBF Part 3: compressive behavior of gusset plates, *Proceedings of the 8th National Conference on Earthquake Engineering*, San Francisco, USA.

Watanabe, E., Yun, C. B., Sugiura, K. Park, D. U., and Nagata, K., 2001, On-line interactive testing between KAIST and Kyoto University, *Proceedings of the Fourteenth KKNN Symposium on Civil Engineering*, Kyoto, Japan, 369-374.

Wang, S. J., Wang, K. J., Yang, Y. S., Cheng, W. C., Yeh, C. C., and Tsai, K. C., 2004, Networked Pseudo-dynamic Testing Part II: Application Protocol Approach, Paper No. 1548, *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver, Canada. (DVD-ROM).

Waugh, T., Neidermann, H. U., and Rensing, M. J., 2005, The gPhoto manual. Available at web page: http://www.gphoto.org/

Yang, Y. S., Wang, K. J., Wang, S. J., Hsu, C. W., Tsai, K. C., and Hsieh, S. H. 2004, Networked Pseudo-dynamic Testing Part I: Database Approach, Paper No. 1910, *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver, Canada. (DVD-ROM).