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HYBRID TESTING OF A MULTI-SPAN BRIDGE

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ABSTRACT

This paper presents a collaborative research project aimed at developing a robust standardized procedure for hybrid testing through Internet. Modules for control and instrumentation are developed based on the use of standardized software interfaces. A pseudo-dynamic test of a four-pier bridge system is planned using the developed protocols. The design of the hybrid test set-up and procedures, and the test specimens are described in the paper. Numerical results from computer simulation of the test are also presented. The hybrid experiment of testing sub-components of the prototype bridge system will be carried out at three remote sites over long distance. Two of the remotes sites will be in Taiwan while the third remote site will be in Canada, making the test the first cross-continent collaborative networked hybrid test of large scale specimens. This is a collaborative research project between the National Center for Research on Earthquake Engineering (NCREE) in Taiwan, the National Taiwan University (NTU), and Carleton University in Canada.

INTRODUCTION

Experimental research is often carried out using scaled-model test specimen due to the high cost of full-scale testing, the limitations of test equipments, and physical restrictions imposed by the space and facilities of laboratories. In order to be able to conduct experiments of large size specimens to give better insights and understanding of the realistic behaviour of structures under extreme loading conditions, which might not be possible otherwise to be conducted at any one individual laboratory, the concept of Internet-based multiple site virtual laboratory testing is developed. In a multi-site test, the prototype test structure is divided into substructures or sub-components, each of which can be tested at a different test site. The testing of all the sub-components are carried out concurrently in real-time to form a single experiment of the prototype system. The concept of Internet-based multiple site virtual laboratory testing facilitates more efficient utilization of test facilities at different laboratories by giving researchers around the world the flexibility and means to conduct large scale experimental research through sharing of equipment and experimental data on a real-time basis. Similar concepts of Internet-based virtual laboratory testing at multiple sites are currently being developed and implemented by researchers in many countries, such as the NEES Project (Rietherman, 2004) in US, ED-Net (Ohtani et al., 2002) in Japan, KOCED (Kim, 2004) in Korea, and ISEE (Yang et al., 2003; Wang et al., 2003) in Taiwan, which all aim to revolutionize earthquake engineering research by providing researchers at different laboratories anywhere around the world the means to collaborate and to conduct networked collaborative hybrid experiments, which include components of physical testing, computer modeling, and simulation of substructure components at multiple sites. The aim of the current study is to develop a robust standardized procedure for laboratories at different locations to pool and network together their testing facilities to perform collaborative experiments based on the ISEE platform developed by the National Center for Research on Earthquake Engineering (NCREE) (Yang et al. 2003; Wang et al., 2003).

A four-pier bridge system is chosen as the prototype structure for the hybrid collaborative test. Three of the piers will be tested, one at Carleton University, Canada, one at NCREE in Taiwan, and another one at the National Taiwan University (NTU). The loading and responses of the fourth pier will be simulated by computer models. The test specimens will be loaded pseudo-dynamically using input ground motions from the 1999 Chi-Chi earthquake and the simulated Cascadia earthquake in Vancouver, Canada, scaled to the representative seismic hazard levels of 50%, 10%, and 2% probability of exceedance in 50 years.

DESIGN OF TEST SET-UP AND PROCEDURES

For this research, a four-pier bridge system is designed for a high seismic location either in Taiwan or in

Vancouver, Canada. The seismic design provisions of the Taiwan Highway Bridge Design Code (Ministry of Transportation and Communication 1995) and the Canadian Highway Bridge Design Code (CHBDC, 2000) are followed for the design of the prototype bridge structure.

Prototype Bridge System

The prototype bridge system, as shown in Figure 1, consists of 5 spans. Each span is 40 meters long. The deck-to-pier connection is a hinge connection in both lateral and transverse directions at all four piers. The width of the deck is 10.5m for a 2 lane highway bridge. The superstructure is assumed to be pre-stressed concrete girders with a depth of 2.1m. The bridge piers are double-skinned concrete filled tubular (DSCFT) columns, which consist of two concentric circular thin steel tubes with concrete filled in between. The DSCFT member is an innovative system developed in Taiwan (Lin, 2002; Tsai et al., 2002; Tsai and Lin, 2002; Tsai and Wei, 2002) for construction of tall bridge piers in seismic regions. The design shop drawing of the DSCFT pier is shown in Figure 2.

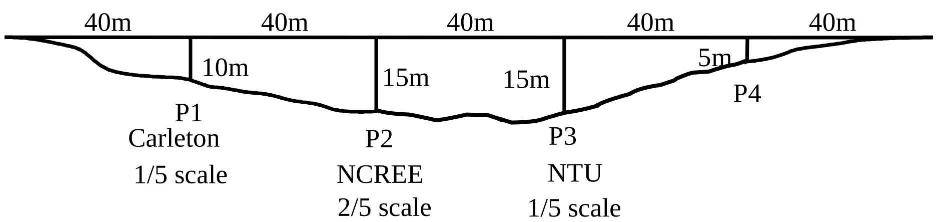

Figure 1. Elevation view of the prototype bridge system

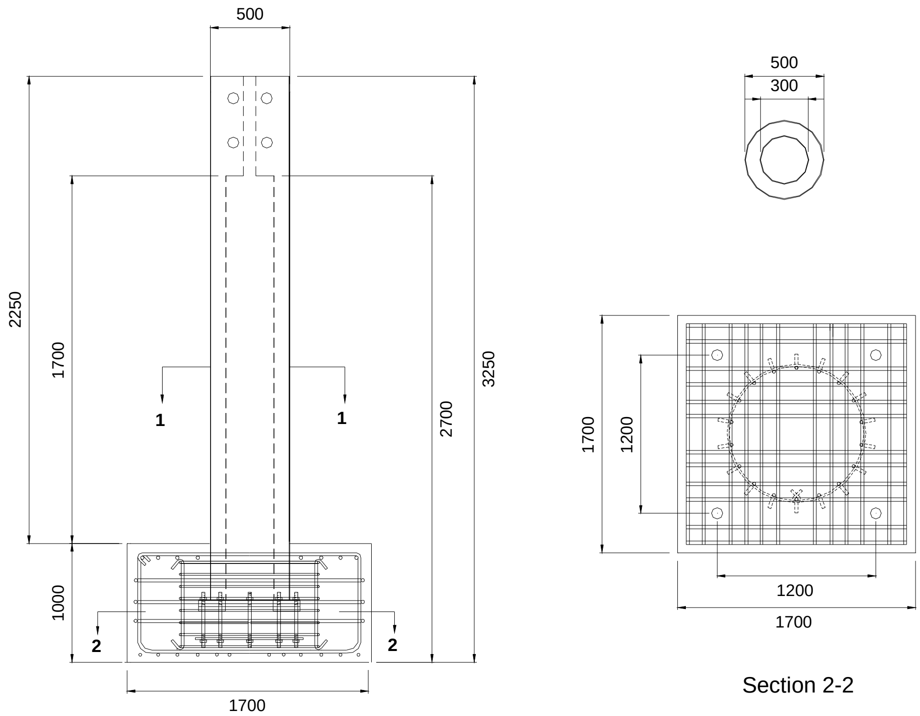

Figure 2. Elevation view of the DSCFT column at Carleton University

Scaled Test Specimen

The test specimens are designed to comply with the similitude requirements following the Buckingham's π theorem (Harris and Sabnis, 1999) for a direct reduce-scale model of the prototype bridge shown in Figure 1. Different scaling factors are used in the design of the sub-component test specimens at the multiple test sites based on the available testing equipment and physical size of each participating laboratory sites in this international pseudo-dynamic experiment. For this research, the scale factors for displacement are chosen to be 1/5 for Carleton University and the NTU Laboratories and 2/5 for the NCREE Laboratory. The scale factor for the Poisson's ratio is unity. Table 1 gives a summary of the scale factors adopted and dimensions of the test specimens to be tested at the participating laboratories. Figure 3 shows the test specimens constructed at the NCREE and NTU laboratories.

Table 1Dimensions of test specimens

	Pier 1	Pier 2	Pier 3	Pier 4
Location	Carleton	NCREE	NTU	Simulated
Scale Factor	20%	40%	20%	100%
Height of the Prototype Structure	10 m	15 m	15 m	5 m
Original outer tube diameter	2.5 m	3.0 m	3.0 m	2.0 m
Original inner tube diameter	1.5 m	1.8 m	1.8 m	1.2 m
Scaled Specimen Height	2 m	6m	3 m	5 m
Scaled outer tube diameter	0.5 m	1.2 m	0.6 m	-
Scaled inner tube diameter	0.3 m	0.72 m	0.36 m	-
Scaled outer tube thickness	4 mm	10 mm	5 mm	-
Scaled inner tube thickness	3 mm	8 mm	4 mm	-
Stress scale	100%	100%	100%	100%
Force scale	4%	16%	4%	100%
Moment Scale	0.8%	6.4 %	0.8 %	100%

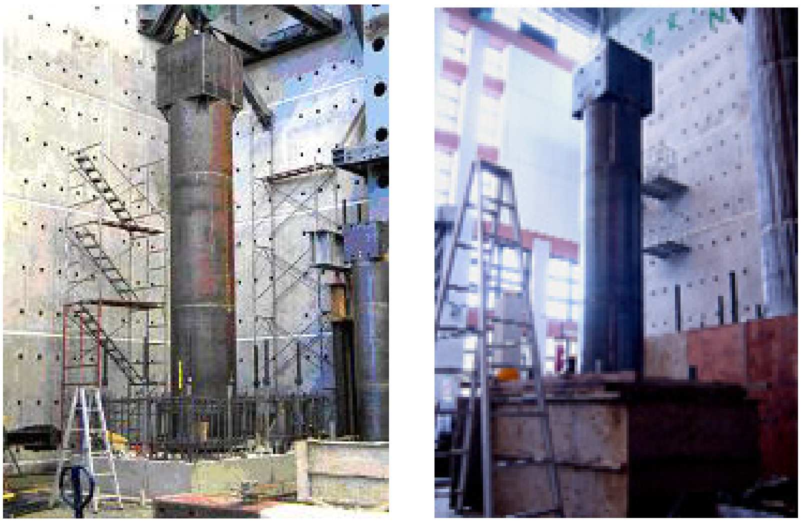

Figure 3. Test specimens at NCREE (on the left) and NTU (on the right) laboratories

Selection of Earthquake Excitation

In the selection of the ground accelerations, records from the 1999 Chi-Chi earthquake in Taiwan and other North America earthquakes have been considered as possible input ground motions for the test. The final selected input ground motions for the test are the 1999 Chi-Chi earthquake motions recorded at Station TCU076 and an artificial earthquake record compatible with the uniform hazard spectrum specified for Vancouver, Canada. The earthquake records are scaled to match the spectral acceleration at the first vibration period of the bridge to specified earthquake hazard levels. The test specimens are tested by subjecting to increasingly higher seismic demands which represent incipient damage level earthquakes (50% probability of exceedance in 50 years), design earthquake (10% probability of exceedance in 50 years), the maximum considered level earthquake (2% probability of exceedance in 50 years) and then another earthquake record of 10% probability of exceedance in 50 years to represent an aftershock earthquake. The response spectra of the selected Chi-Chi earthquake ground acceleration and the spectrum-compatible time history record for western Canadian earthquake are shown in Figure 4.

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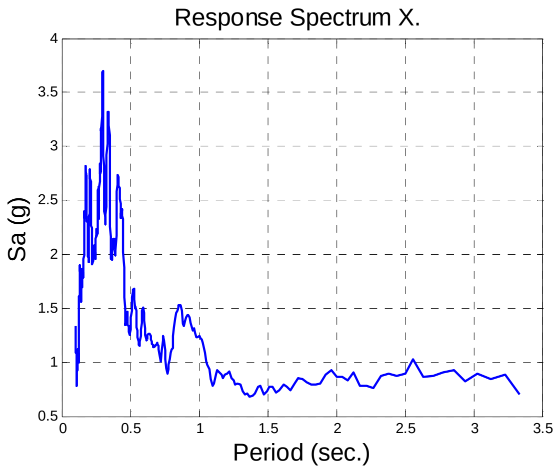
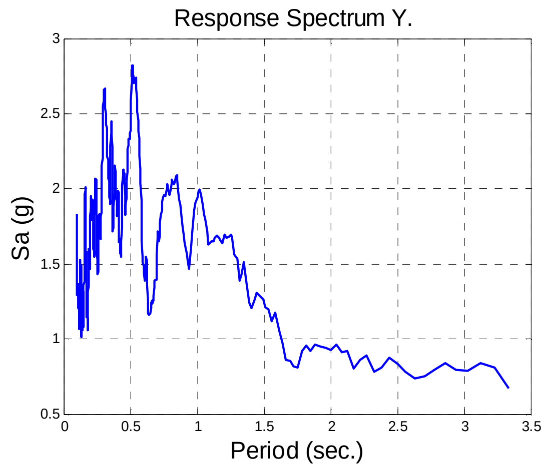
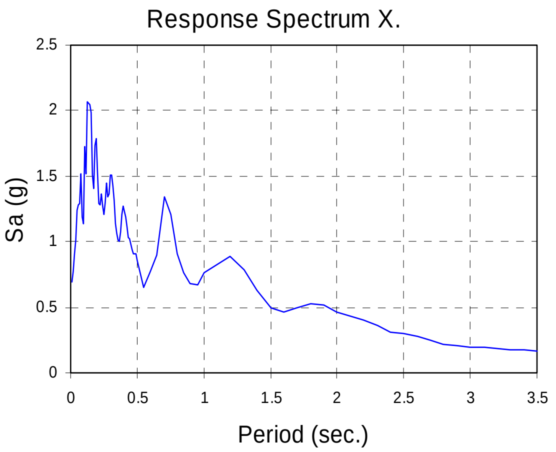


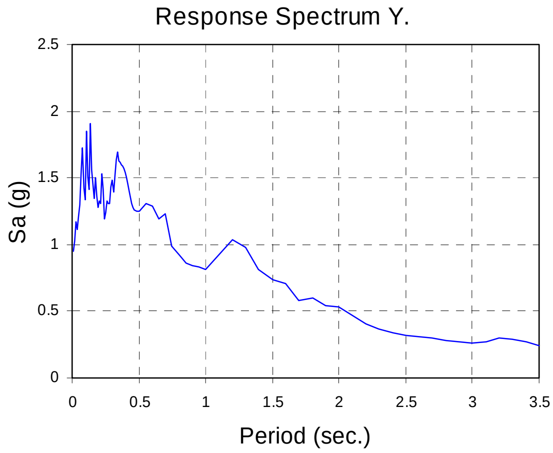
Response spectrum (Ax) of Chi-Chi Earthquake



Response spectrum (Ay) of Chi-Chi Earthquake



Response spectrum (Ax) of the selected western Canadian earthquake



Response spectrum (Ay) of the selected western Canadian earthquake

Figure 4. Acceleration response spectra

EXPERIMENTAL METHOD

A computer platform, Internet-based Simulation for Earthquake Engineering (ISEE), has been developed by researchers at NCREE. This computer platform consists of software and hardware components specially developed for cooperative experimental structural testing and research linked through the Internet environment. The schematic of the ISEE framework configured for the pseudo-dynamic testing of the prototype DSCFT bridge structure in this study is shown in Figure 5. The ISEE framework consists of three major components: the Data Center, the Analysis Engine, and Facility Controllers. The Data Center is a database server which also serves as a data exchange hub between the Analysis Engine and the Facility Controllers. The Analysis Engine simulates and computes the interactions expected between the sub-components tested at participating laboratories according to the information received from the remote sites. The Facility Controller is the software bridging the Data Center and the experimental facilities in each participating laboratory.

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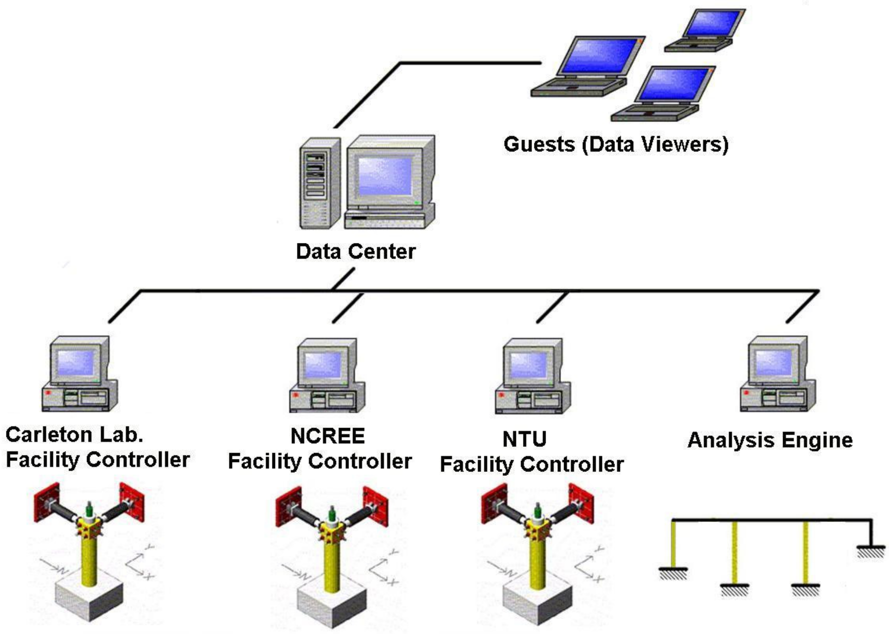


Figure 5. ISEE configuration

The test set-up at NCREE and NTU laboratories is shown in Figure 6. At the Carleton site, reaction frames are used instead of reaction walls for application of the imposed load to the test specimen.

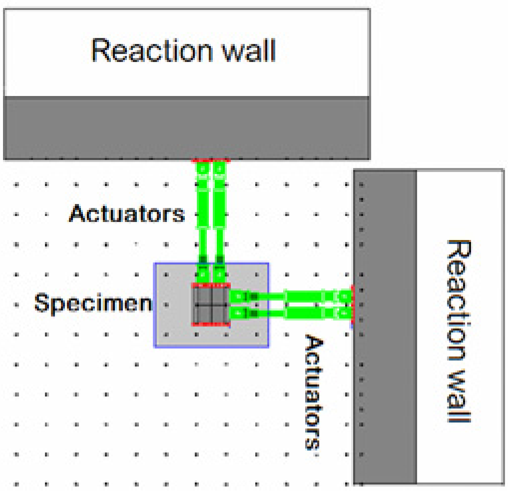


Figure 6. Actuators and specimen installation at NCREE (a top view)

Analysis Engine

In the implementation of hybrid structural testing here, a full scale numerical model of the prototype structure is implemented in the Analysis Engine to calculate the dynamic responses of the entire system using Newmark explicit scheme with a time step of 0.02 second for this 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.

DSCFT is an innovative structural system particularly suitable for construction of tall bridge piers in seismic regions. Since the DSCFT is a complex composite structural system, it is difficult to analyze using general analysis methods. A simplified method developed at Carleton University for prediction of the nonlinear hysteretic responses of composite structural members is applied here to analyze the behaviour of the DSCFT (Chang et al., 2004). In the simplified method, a composite structural member is modeled by an equivalent member of homogeneous nonlinear material with a derived stress-strain relationship, which satisfies the requirement that the equivalent member has the same moment-curvature behaviour as the original member. Selected states in the behavior of the composite structural members are analyzed explicitly to establish directly points on the specified stress-strain relationship of the nonlinear homogeneous material model of the equivalent member by strain energy and strain compatibility in the derivation of the specified stress-strain relationship of the nonlinear equivalent member material. Typical states of the composite structural member section considered in the formulation are cracking of concrete, yielding of reinforcing steel, peak stress in concret, reinforcing steel hardening, residual stress in confined concrete, and ultimate fracture of reforcing steel.

Facility Controller

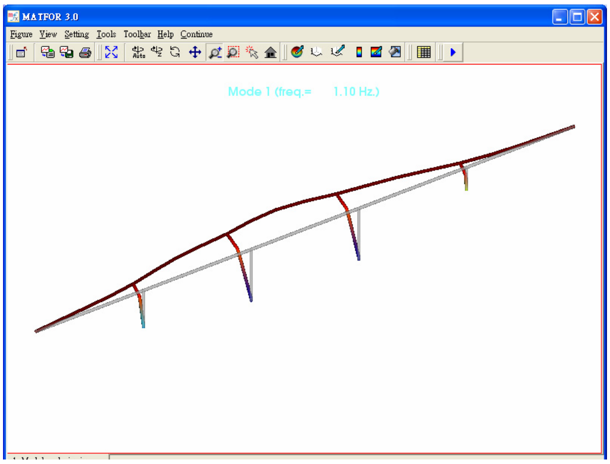
Accurate remote controlling of the load applying actuators at multiple sites is one of the challenges for conducting a networked collaborative pseudo-dynamic experiment. The three participating laboratories use different models of servo-controllers. The controllers at Carleton, NCREE, and NTU are MTS 458, MTS FlexTestIIm, and MTS 407, respectively, and hence, a compatible and standardized control software platform is highly desired for control commands between the various facility controllers at different participating sites in a collaborative test. Presently, different commercial software solutions are available for interface control and instrumentations of tests. Two commonly used software packages are the National Instrumentation LabVIEW and the Hewlett-Packard VEE environment. In this research, LabVIEW is 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 through a computer network. 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 considered 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 test and later for test data interpretation and research, data harmonization and the adoption of a standardized data exchange format will enhance the portability 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 built for instant communication between participating researchers at different laboratories when unforeseen circumstances arise during the test.

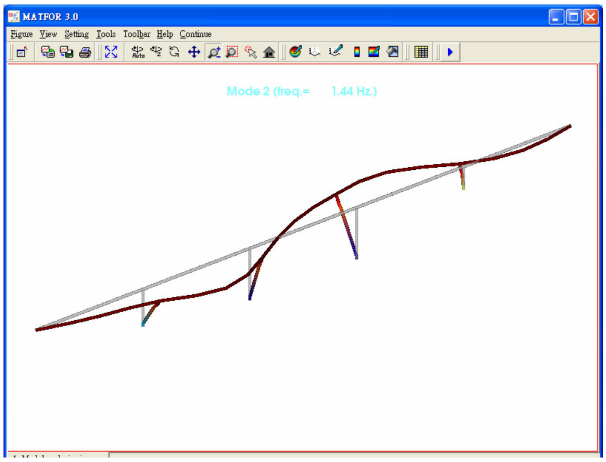
ANALYTICAL MODEL AND SIMULATION RESULTS

Nonlinear static and dynamic analyses are performed using OpenSees, an object-oriented simulation framework developed by researchers at the Pacific Earthquake Engineering Research (PEER) Center for simulating the seismic responses of structural and geotechnical system subjected to earthquakes (Mazzoni et al., 2000; http://opensees.berkeley.edu), 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 exceed. 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.

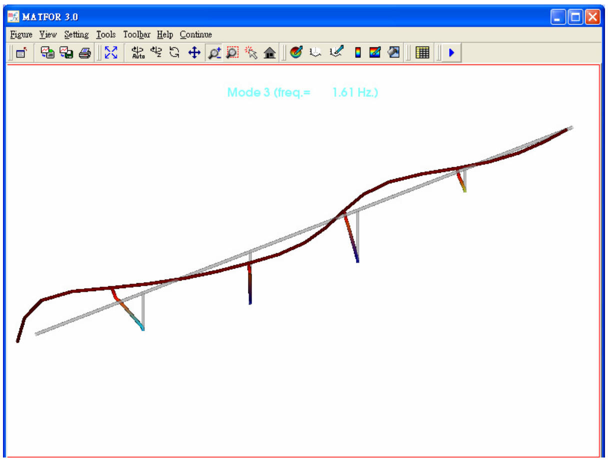
The deck and the piers are modeled in OpenSees by displacement-based beam column elements with five integration points. Each integration point represents a nonlinear section moment-curvature status. The concrete and steel are modeled using the FEDEAS steel and concrete material models (Filippou 1996) implemented in OpenSees. Figure 7 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 displacements, drift ratios, and shear forces of the three piers under the input ground motions are presented in Table 2.



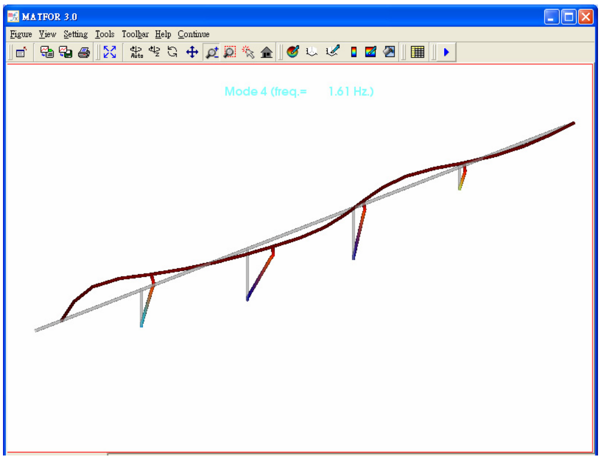
Mode 1 (Freq.= 1.10 Hz; T=0.91 sec.)



Mode 2 (Freq.= 1.44 Hz; T=0.70 sec.)



Mode 3 (Freq.= 1.61 Hz; T=0.62 sec.)



Mode 4 (Freq.= 1.61 Hz; T=0.62 sec.)

Figure 7. Modal analysis results

Table 2 Maximum responses of test specimens from numerical analysis

	Carleton Laboratory	NCREE Laboratory	NTU Laboratory
Maximum displacement	N-S: 23 mm	N-S: 86 mm	N-S: 40 mm
	E-W: 16 mm	E-W: 30 mm	E-W: 15 mm
Maximum drift ratio	N-S: 1.2 %	N-S: 2.2 %	N-S: 2.0 %
	E-W: 0.8 %	E-W: 0.8 %	E-W: 0.7 %
Maximum shear force	N-S: 228 kN	N-S: 1234 kN	N-S: 289 kN
	E-W: 213 kN	E-W: 589 kN	E-W: 136 kN

SUMMARY AND CONCLUSIONS

Because of the complexity and differences in operating characteristics of different testing equipment and facilities, there is the need of a standardized platform for test equipment control and easy set-up of network based collaborative multi-site hybrid tests, and standardized protocol procedure for efficient data exchange. Efficient coordination and management of the instrumentation and data acquisition processes operating under different computing environments are important requirements in the design of collaborative multi-site hybrid tests. The collaborative research project between NCREE, National Taiwan University, Taiwan and Carleton University, Canada is aimed to develop a standardized procedure for laboratories to join in Internet-based hybrid experimental research. A four-pier bridge system is chosen as the prototype structure for a collaborative experiment to evaluate the performance of the developed procedure implemented in the Internet-based simulation for earthquake engineering (ISEE) environment for cross-continent multi-site collaborative structural tests. Three of the scaled test specimens are to be loaded pseudo-dynamically at the participating laboratories over long distance, and the fourth pier is simulated by computer model. Modules for control and instrumentation are developed using the National Instrument LabVIEW. The analyses results from the OpenSees model and PISA3D model correlates well for predicting the possible peak responses of the piers during the test.

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