RECENT RESEARCH ACTIVITIES IN NCREE: DEVELOPMENTS OF THE EARTHQUAKE LOSS ESTIMATE SYSTEM AND INTERNET TESTING TECHNIQUES

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Abstract: This paper describes two team efforts on the research of earthquake loss estimate system and networked internet testing techniques in the National Center for Research on Earthquake Engineering (NCREE). The application software "Taiwan Earthquake Loss Estimation System (TELES)" is developed in NCREE to simulate earthquake scenarios and estimate induced damages and losses. This paper focuses on demonstrating the analysis models, software features and applications of the Early Seismic Loss Estimation (ESLE) module which is contained in TELES. The second part of the paper presents an effort in developing an Internet-based environment, entitled "Internet-based Simulations for Earthquake Engineering", for collaborative networked structural experiments among geographically distributed structural laboratories. Two approaches, the Database Approach and the Application Protocol Approach, are the described to provide different solutions for network communication as well as collaborative framework in networked hybrid testing. Database Approach shows that the network and data processing costs about 0.2 seconds and 2 seconds per time step in domestic and transnational experiments, respectively. Application Protocol Approach testing results show that it took less than 0.2 seconds for two data packets to travel back and forth between NCREE laboratory in Taiwan and Stanford University in USA.

1. INTRODUCTION

The National Science Council of Taiwan started HAZ-Taiwan project in 1998 to promote researches on seismic hazard analysis, structural damage assessment, and socio-economic loss estimation. The associated application software, "Taiwan Earthquake Loss Estimation System (TELES)", integrates various inventory data and analysis modules to fulfill three objectives. Firstly, it helps to obtain reliable estimates of seismic hazards and losses soon after occurrence of large earthquakes. Secondly, it helps to simulate earthquake scenarios and to provide useful estimates for local governments or public services to propose their seismic disaster mitigation plans. Thirdly, it helps to provide catastrophic risk management tools, such as proposing the seismic insurance policy for residential buildings. The first part of this paper focuses on the development and application of analysis modules used in early loss estimation system. These modules include assessments of ground motion intensity, soil liquefaction potential, building damage and casualty. The second part of the paper presents an effort in developing an Internet-based environment, called ISEE (Internet-based Simulations for Earthquake Engineering), for collaborative networked structural experiments among geographically distributed structural laboratories. Two approaches, the Database Approach and the Application Protocol Approach, have been employed to provide different solutions for network communication as well as collaborative framework in ISEE. This paper presents the ISEE environment for collaborative networked structural experiments among geographically distributed structural laboratories. Several networked pseudo dynamic tests have been conducted to investigate the feasibility and efficiency of ISEE. Based on these test results, the feasibility of ISEE for collaborative networked tests is presented. A series of networked pseudo-dynamic test examples using the Database Approach shows that the network and data processing costs about 0.2 seconds and 2 seconds per time step, around 20% and 70% of total elapsed time in domestic and transnational experiments, respectively, which is feasible for most of the low-speed pseudo-dynamic experiments. Application Protocol Approach testing results show that significant laboratory events were promptly reflected and data transmission was satisfactorily efficient since less than 0.2 seconds for two data packets to travel back and forth between NCREE laboratory in Taiwan and Stanford University in USA.

2. EARTHQUAKE LOSS ESTIMATE SYSTEM

Taiwan is located at the circum-pacific earthquake belt and has suffered from devastating earthquakes in almost every decade. In 21 September 1999, Chi-Chi earthquake attacked central Taiwan due to the rupture of Chelongpu fault. Its Richter magnitude was 7.3 with a focal depth of 7 kilometers. This earthquake has resulted in about 2,500 deaths, 11,000 injuries, and caused more than 100 thousand households severely wounded due to various degrees of building damages. The total economic losses were about US$11.5 billions. Since then, the central government of Taiwan has devoted efforts on reconstructing the disastrous regions and implementing the seismic disaster reduction systems against future earthquakes. Several coordinated projects are undertaken in Taiwan to identify the hazard sources, reinforce the civil infrastructures, integrate information and scenario simulation systems, improve communication capabilities, and to educate as well as disseminate these information to the general public.

In general, risk can be defined by occurrence probability of a seismic event, exposure of people and property to the event, and consequences of that exposure. Based on the previous definition of risk, an earthquake loss-estimation methodology, integrated with geographic information system (GIS) and designed to run on personal computers, has been developed in the United States. The methodology and associated application software are contained in HAZUS (RMS, 1997). The National Science Council (NSC) of Taiwan started HAZ-Taiwan project in 1998 to promote researches on seismic hazard analysis, structural damage assessment, and socio-economic loss estimation. After gaining experiences on simulation of earthquake scenarios for several years, the National Center for Research on Earthquake Engineering (NCREE) has completed the prototype of "Taiwan Earthquake Loss Estimation System (TELES)" in 2002 to fulfill the objectives of HAZ-Taiwan Project.

The HAZ-Taiwan project and associated application software TELES follow a similar approach used in HAZUS. However, TELES has made major modifications in analysis models, parameter values and software architecture, not only to accommodate the special environment and engineering practices in Taiwan, but also to reflect the state-of-the-art technology. Furthermore, through modular approach and step-by-step improvement, TELES has added a new feature of early seismic loss estimation to estimate automatically the disaster scale and its distribution soon after the occurrence of large earthquakes. In order to serve as a seismic risk assessment and management tool, TELES plans to integrate probabilistic seismic hazard analysis in the near future. HAZUS does not have the features of early seismic loss estimation and probabilistic seismic risk assessment.

The results of the HAZ-Taiwan project help to plan and stimulate efforts to reduce risk from earthquakes, and to prepare for emergency response and recovery from an earthquake. It also provides a standard risk assessment and loss estimation methodology to evaluate the performance of seismic hazard mitigation efforts and to set the priorities of local, regional or nation-wide public works/services. Expected benefits of a standard methodology also include more economic use of available resources and improved sharing of knowledge.

2.1 Analysis Framework of TELES

The HAZ-Taiwan project is mainly consisted of three parts:

- collection of seismic sources, geologic and inventory database;
- development and modification of analysis modules in hazard analysis, vulnerability assessment and loss estimation;
- improvement of the application software TELES.

To collect complete and useful database is one of the key factors leading to the success of HAZ-Taiwan project. Nonetheless, database collection is often the most time consuming and expensive aspect in performing a comprehensive loss study. The analysis modules contained in TELES can be roughly divided into four groups, namely the potential earth science hazards (PESH), the direct physical damages, the indirect physical damages, and the socio-economic losses, as shown in Figure 1. In general, the civil infra-structures are classified into general building stocks, essential facilities, transportation and utility systems by their usage and functionality. Each general category of inventory data is further divided into several specific categories according to their specific usages. The inventory data are also classified according to their structural types, seismic resistant characteristics, etc. in order to assess damage-state probabilities based on site specific ground motion intensity and ground failure extent. The data classification schemes as well as the associated analysis models should depend on the content of inventory database.

The analysis modules and sub-modules are interdependent. The output from one module may act as input to another. The modular approach allows estimates based on simplified models and limited inventory data. Addition or replacement of existing modules may be done without reworking the entire methodology. The modular approach also facilitates information exchange and technology transfer between the research communities and the end users. Although development of each module may require a comprehensive study, the degree of sophistication and the associated cost often varies greatly by user and application.

Like HAZUS, TELES can simulate earthquake scenario due to single event. The Central Weather Bureau (CWB) of Taiwan is currently in charge of earthquake monitoring networks and has developed "Taiwan Rapid Earthquake Information Release System (TREIRS)", which can obtain earthquake magnitude, epicenter location and focal depth within 90 seconds after occurrence of earthquakes. CWB will automatically send out the earthquake alerts to all clients by mail, fax, etc. Combining functionalities of TREIRS and TELES, an Early Seismic Loss Estimation (ESLE) module has been developed and integrated in TELES. It monitors the mailbox continuously and will be triggered and start analysis automatically when a large earthquake is detected. Applications of ESLE will be further explained in the following sections.

As shown in Figure 1, the probabilistic seismic hazard analysis will be integrated in the analysis framework of TELES. Addition of this feature helps to identify the maximum probable earthquake for each county/city, to evaluate seismic risk of various facilities and lifeline systems in different regions, to propose reasonable risk management policies such as seismic insurance for residential buildings and high-tech industrial plants, to evaluate performance and to set priority of seismic retrofit of public works, etc.

In summary, the analysis framework of TELES provides basis for applications on emergency responses, local disaster mitigation plans and risk management tools. However, this paper focuses on the analysis modules related to ESLE.

2.2 Prediction of Ground Motion Intensity

The PESH module calculates estimates of ground motion intensity and ground failure extent. Based on the source parameters of a scenario earthquake and the local geologic conditions, ground motion demands are in terms of response spectra and peak values (PGA and PGV). The response spectra are simplified and expressed in terms of S_{as} and S_{a1}, which denote the spectral accelerations with structural periods 0.3 and 1.0 seconds, respectively. The occurrence probability of soil liquefaction and the induced permanent ground deformation (PGD) are also estimated. Other related earth science hazards, such as tsunami and inundation, may affect social/economic environment, but are not considered in the current framework of TELES.

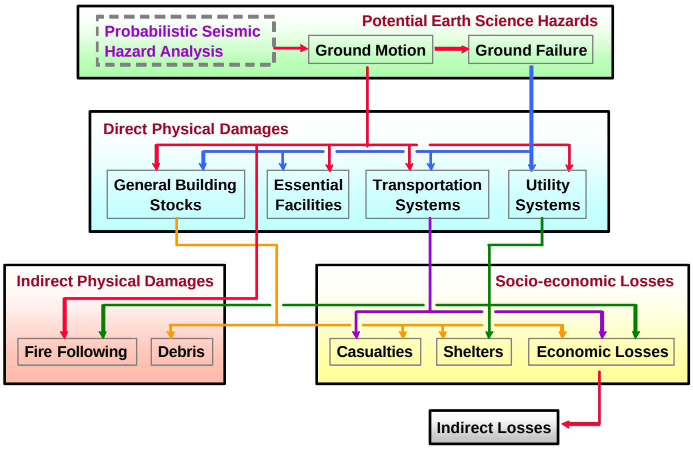

Figure 1. Methodology framework of Taiwan Earthquake Loss Estimation System.

The first step in simulating earthquake scenario is to set source parameters of a seismic event. The basic source parameters include event date, time, magnitude, epicenter location and focal depth. If the earthquake has large magnitude and shallow focal depth, it often accompanies surface fault rupture. The fault mechanism (reverse, normal or strike), the orientation of fault trace, the dip angle, length and width of rupture plane are required to define the source parameters. In case there is no actual fault information, the rupture plane can be assumed as a rectangle with certain orientation, dip angle, and passing through the hypocenter of scenario earthquake. If actual faults are used in defining the seismic source, the surface fault trace may compose of many line segments, though not necessarily continuous, to depict reality. Default rupture length and width are provided by using Wells et al (1994) empirical formula; however, they can be customized to match the actual observation.

Different attenuation laws for ground motion intensity parameters use different definitions for earthquake magnitude and source-to-site distance. Furthermore, different definitions for earthquake magnitude may be used in different analysis modules. Since both moment magnitude (M_w) and Richter local magnitude (M_L) are often used in Taiwan, TELES internally converts them by using the following equation (Wu et al, 2001),

$$M_L = 4.533 \ln M_w - 2.091 . \tag{1}$$

Depending on the attenuation laws chosen by the user, TELES automatically selects corresponding definition for source-to-site distance. For example, Jean (2001) uses Richter local magnitude and shortest distance to rupture plane, while Boore et al (1994) uses moment magnitude and shortest distance to the horizontal projection of rupture plane. If the rupture length reduces to zero, focal distance is automatically used in the attenuation laws. The effect of seismogenic rupture zone is also taken into consideration when evaluating the source-to-site distance.

Estimation of ground motion intensity due to a scenario earthquake may divide into three steps. Referring to Figure 2, the first step uses the attenuation laws to predict the intensity at bedrock level. The second step uses the local site modification factors to obtain the intensity at ground surface. When the monitored data at strong-motion stations are available, for example, in early seismic loss estimation, the local intensity can be updated accordingly.

The local site conditions are classified into six categories in HAZUS by using properties of the soil profile such as shear wave velocity, SPT-N value, etc. The site modification factors depend on the soil type as well as the ground motion intensity. However, topography and geology are very complex in Taiwan, basin effects or topographic conditions may influence the ground motion intensity significantly. To overcome the shortage of rough classification scheme of soil types, micro-zonation of the site modification factor is necessary. Since the strong-motion stations installed by CWB are dense enough, the site modification factors for each region are studied by using historical earthquake records and local geologic conditions at the strong-motion stations (Yeh et al, 2003).

2.3 Estimation of Soil Liquefaction Potential and Settlement

The influence factors in soil liquefaction are the intensity level and the time duration of ground excitation and the ground water depth. The peak ground acceleration (PGA) is commonly used to indicate the excitation intensity, while the earthquake magnitude is used to indicate the duration of excitation. Following the methodology of HAZUS, the soil liquefaction susceptibility is classified into six categories, that is, “very high”, “high”, “moderate”, “low”, “very low” and “none”. Yeh et al (2002a) analyzed more than 11,000 sets of borehole data in Taiwan and proposed a classification scheme to identify the liquefaction susceptibility category of each borehole. Based on the knowledge of liquefaction susceptibility for each borehole and a small-scale geologic map, the liquefaction susceptibility map of Taiwan has been roughly estimated. As an example, Figure 3 shows the soil liquefaction susceptibility map in Taipei city.

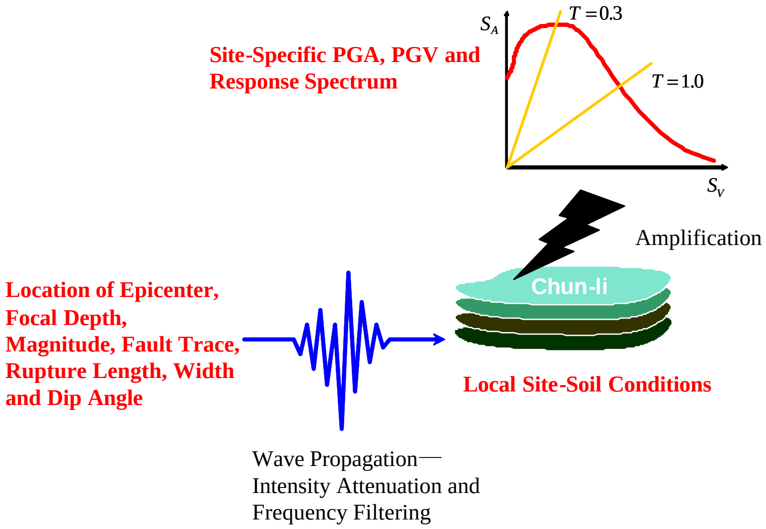

Figure 2. Procedures in estimation of ground motion intensities.

The semi-empirical formulas to estimate the liquefaction probability and the amount of settlement are obtained from nonlinear regression analysis (Yeh et al, 2002b). They are summarized as follows. It is assumed that the liquefaction potential index P_L (Iwasaki et al, 1982) is proportional to liquefaction potential and the liquefaction probability is greater than 0.8 when $P_L \geq 15$. The P_L for susceptibility category *i* can be estimated by

$$(P_L)_i = a_i \cdot f(M) \cdot g(d_w)(\mathrm{PGA}) + b_i \tag{2}$$

$$f(M) = 0.0353M^2 - 0.1855M + 0.4069 \tag{3}$$

$$g(d_w) = 0.0002d_w^{\ 4} - 0.0051d_w^{\ 3} + 0.0535d_w^{\ 2} - 0.2758d_w + 1.3105 \tag{4}$$

where $f(M)$ and $g(d_w)$ are correction functions for earthquake magnitude and ground water depth, respectively; a_i and b_i are constants and listed in Table 1.

Using the approach in Ishihara (1993), it was observed that the relationship of average settlement

S_i for category i and PGA, when the earthquake magnitude and the ground water depth are kept constant, is similar to a lognormal distribution with two parameters m_i and s_i indicating median and coefficient of variation, respectively. When PGA becomes larger and larger, the average settlement S_i approaches a limiting value $\bar{S}_i$, which is not influenced by varying earthquake magnitude and ground water depth. Thus, the average settlement can be expressed as

$$S_i = \bar{S}_i \cdot \int_0^A \frac{1}{\sqrt{2p}\, s_i x} e^{-\frac{[\ln(x/m_i)]^2}{s_i^2}} dx = \bar{S}_i \cdot \Phi\left[\frac{\ln(A/m_i)}{s_i}\right] \qquad (5)$$

$$m_i = m_i \cdot \bar{f}(M) \cdot \bar{g}(d_w) \qquad (6)$$

$$s_i = l_i \cdot \bar{h}(d_w) \qquad (7)$$

$$\bar{f}(M) = 0.1231M^2 - 2.2052M + 10.5954 \qquad (8)$$

$$\bar{g}(d_w) = -0.007188d_w^{\ 2} + 0.145195d_w + 0.7919 \qquad (9)$$

$$\bar{h}(d_w) = 0.003208d_w^{\ 2} - 0.042231d_w + 1.0611 \qquad (10)$$

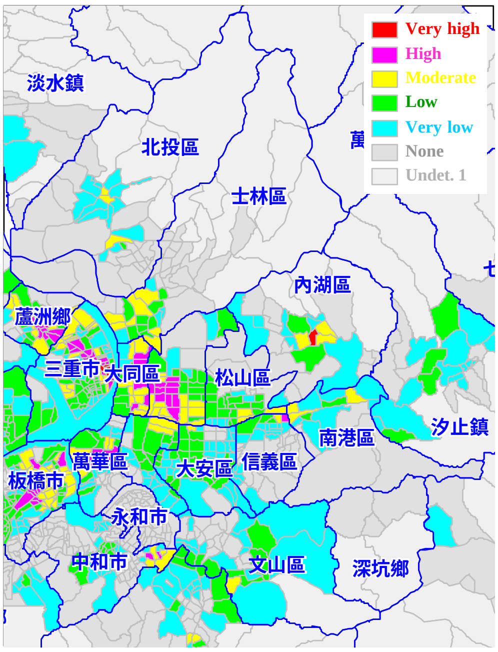

Figure 3. Soil liquefaction susceptibility map of Taipei city.

Table 1 Coefficients in empirical formula for estimating liquefaction potential index.

Category	a_i	b_i
Very High	227.52	-13.63
High	188.30	-18.45
Moderate	157.35	-20.51
Low	103.02	-14.95
Very Low	66.95	-10.64

Table 2 Coefficients in empirical formulas for estimating settlement due to soil liquefaction.

Category	$\bar{S}_i$ (cm)	m_i (g)	l_i
Very High	47.43	0.0872	0.4522
High	50.22	0.1292	0.3657
Moderate	46.21	0.1613	0.3433
Low	35.89	0.1875	0.3430
Very Low	25.66	0.2104	0.3764

where $\bar{f}(M)$, $\bar{g}(d_w)$ and $\bar{h}(d_w)$ are correction functions for earthquake magnitude and ground water depth, respectively; $\bar{S}_i$, m_i and l_i are constants as shown in Table 2.

2.4 Damage Assessment of General Building Stocks

The general building stocks consist of many buildings of different structural types, seismic behavior and usages. These buildings are grouped into several model building types, seismic design levels, and occupancy classes in order to facilitate damage, casualty and loss estimations. The building tax data from ministry of finance and local governments have been used to calculate various kinds of statistics of general building stocks, since it is the only database that provides consistent format and up-to-date information of buildings in Taiwan.

Based on the content of the building tax data, the general building stocks are grouped into several model building types according to their construction material and building height. There are 15 model building types, namely, wood (L), steel (L, M, H), light steel (L), reinforced concrete (L, M, H), pre-cast concrete (L), reinforced masonry (L, M), un-reinforced masonry (L), and steel reinforced concrete (L, M, H) buildings. The letters L, M and H in the parenthesis indicate low-rise, mid-rise and high-rise buildings, respectively. Each model building type is further divided into four seismic design levels according to their construction years, seismic zoning factors, and local site conditions.

Some inventory data, such as bridges and tunnels, may be treated as point objects. Some others, such as highway segments and airport runway, may be treated as line objects. However, for general building stocks, it is neither necessary nor practical to evaluate individual building. In this case, the mapping scheme of specific occupancy to model building type plays an important role in the framework to estimate various social impacts and economic losses. The mapping scheme for each town in Taiwan has been calculated from building tax data.

TELES evaluates the damage state probabilities for each model building type and seismic design level due to ground motion and liquefaction-induced settlement. The procedures in building damage assessment are depicted in Figure 4, where damages in structural system and nonstructural component are evaluated separately. The effects of hysteretic damping and system degradation are considered in calculating the seismic demand. The seismic capacity and fragility curves for each model building type and seismic design level are determined by reference to seismic design codes in various periods, nonlinear push-over analysis, and historical data collected after Chi-Chi earthquake.

2.5 Casualty Estimation

TELES considers only the casualties due to severe damage or collapse of buildings. Although other factors, such as fire following earthquakes, sudden failure of critical dams, unseat of bridges, etc may cause significant casualties, they are not considered in the current methodology. Referring to Figure 5, the first step in casualty assessment is to estimate spatial distribution of population at different times. For simplicity, only three population migration patterns are taken into consideration, that is, daytime, nighttime, and commute time. It is assumed that the population density (number of persons per unit floor area) can be estimated for all specific occupancies at three different times. The population can be obtained by multiplication of the population density and the floor area. Assuming the population is uniformly distributed within the same occupancy class, the mapping schemes are used to calculate the number of people in each model building type.

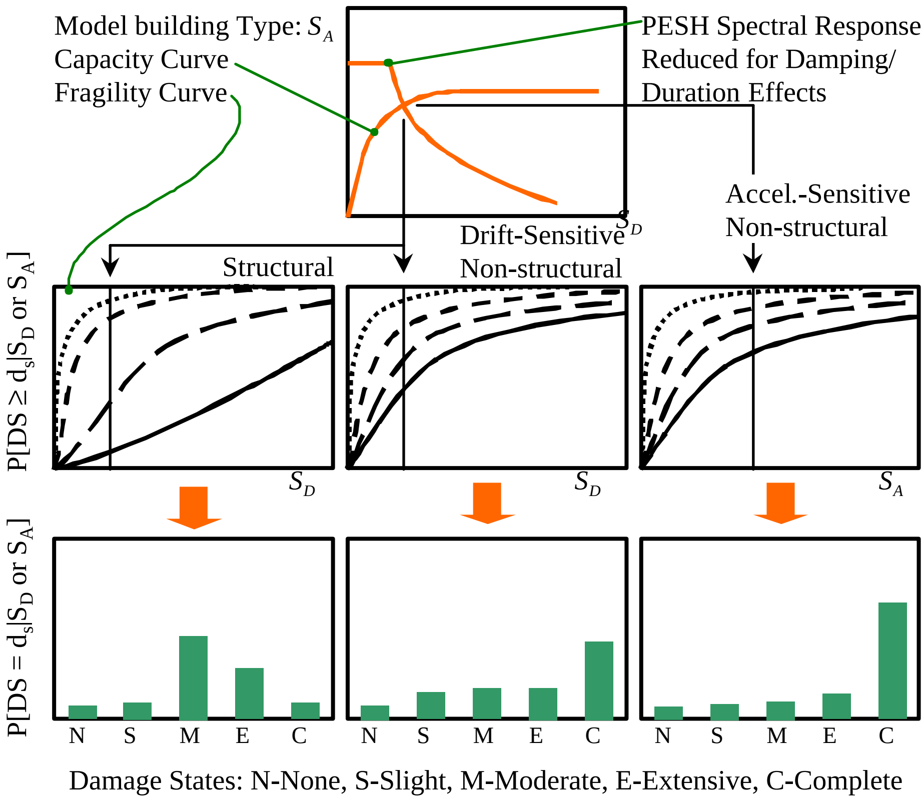

Figure 4. Damage assessment of general building stocks.

The output of casualty module contains estimates breakdown into four injury severity levels, namely, "injuries requiring basic medical aid without hospitalization," "injuries requiring a greater degree of medical care but not expected to threaten life," "injuries requiring adequate and expeditious treatment to avoid loss-of-life," and "instantaneous killed or mortally injured." The casualty rates for different model building types and under various damage states are calibrated considering the effects of structural and nonstructural damages. Complete damage state of buildings is further divided into collapse and without collapse. By combining casualty information with loss-of-function estimates for hospitals, alternate plans may be prepared for treatment of victims outside of the affected area.

2.6 Software Features

The application software, TELES, is written in Visual C++, which is an object-oriented programming (OOP) language, and MapBasic, which is the language used to communicate with MapInfo. Through the object linking and embedding (OLE) technology, the TELES integrates the functionalities and custom usages of MapInfo, which is famous application software of geographical information system (GIS). The main functions of MapInfo in TELES are to view and to edit records and map objects in various kinds of database. All the numerical analysis is written in C++ and FORTRAN. The software architecture of TELES has modular design, so addition and modification of individual module will not affect the other modules. TELES allows users to open multiple documents and multiple map windows at the same time, so the users can compare different thematic maps and obtain in-depth understanding of the relationships between input and output database. TELES also allows users to monitor the earthquake occurrence and run scenario simulation in separate application windows at the same time. HAZUS and the first version of HAZ-Taiwan software do not have these features.

2.7 Application of Early Loss Estimation System

Having the functionality of early loss estimation which can be auto-trigger after occurrence of large earthquakes, TELES can act as a decision making support system in emergency responses. The time delay between earthquake occurrence and analysis start is normally within two minutes. The affected region of the earthquake is determined by ground motion intensity. All the towns with PGA greater than 80 $cm/\sec^2$ are selected in the study region. The ground motion intensity, soil liquefaction potential and induced settlement, damage state probability and quantity of general building stocks and casualty assessment of each town are calculated one by one. Some of the important results are automatically output in raster maps and tables, which can be used in the presentation to chief commander of emergency response center, or in dispatching the rescue forces and medical resources, etc. Since the required work force and equipment are different to rescue people in low-rise or high-rise buildings, the statistics of at-least-severe damage building counts are obtained for low-rise, med-rise and high-rise buildings, separately.

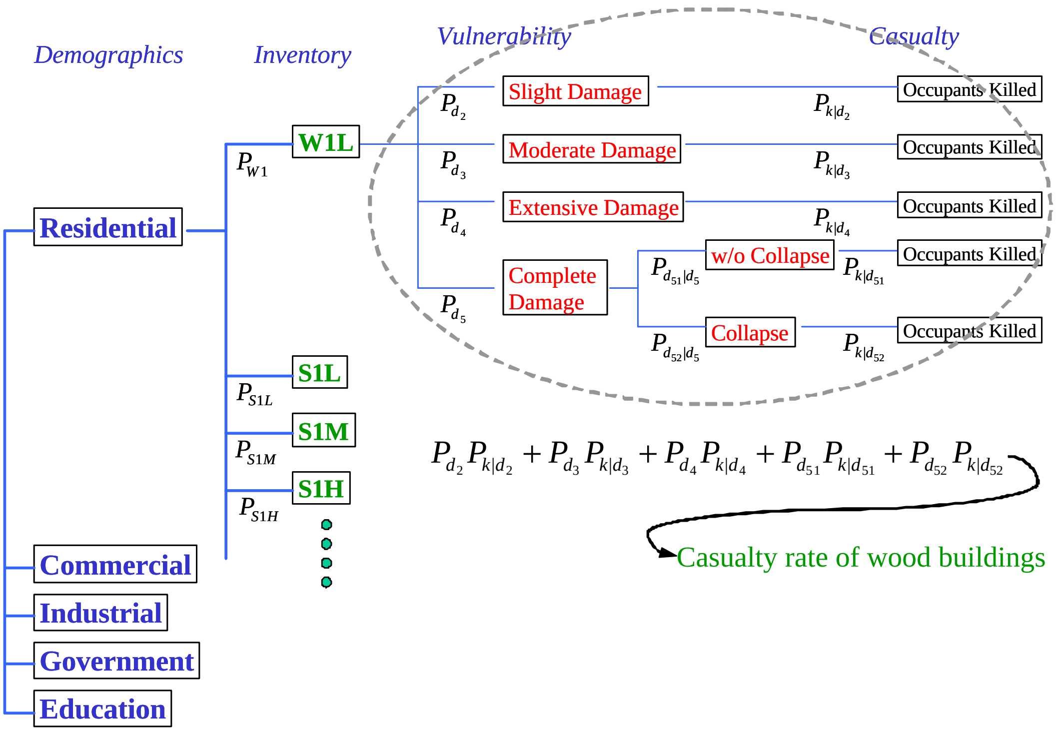

Figure 5. Assessment of casualties caused by building damages.

In practice, application of early loss estimation system divides into three stages. The first stage automatically uses a point-source model to predict the ground motion intensity and associated disasters, when TELES receives email from CWB. Since using a point-source model often under-estimates ground motion intensity and disaster scale, before the actual source mechanism is available, reasonable assumptions can be made about the orientation, dip angle, length and width of the rupture plane. Therefore, the second stage uses several artificial sets of source parameters to calculate probable range of disaster scale and distribution. In the meantime, actual disaster information are gathered and studied to identify the true source mechanism. Once the true source mechanism and rupture fault are identified, early loss estimation enters the third stage and obtains the most reliable results.

As examples, Figures 6, 7 and 8 show the estimations of PGA, building damage count and induced casualty in Chi-Chi Taiwan Earthquake. These figures are only part of the raster maps that are automatically generated by TELES after occurrence of strong earthquakes.

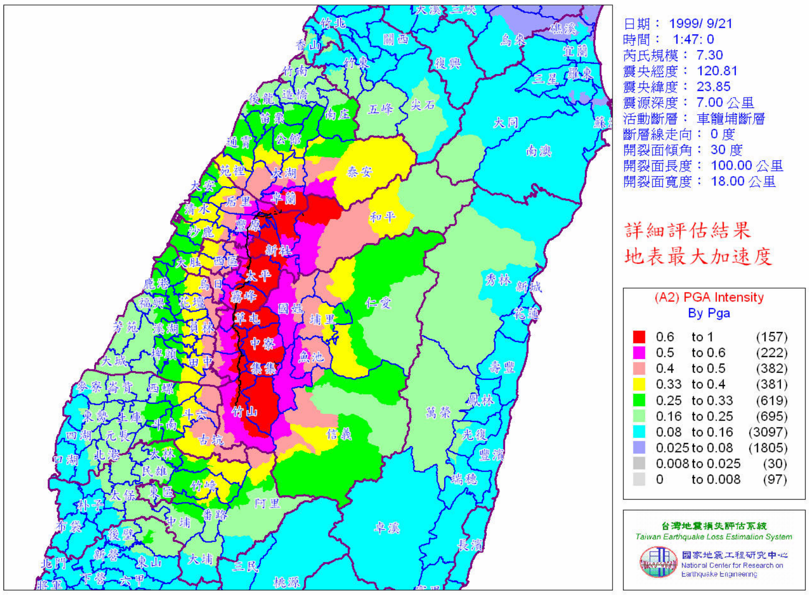

Figure 6. Estimated distribution of peak ground acceleration in Chi-Chi Taiwan earthquake. The black line represents the trace of Chelongpu fault.

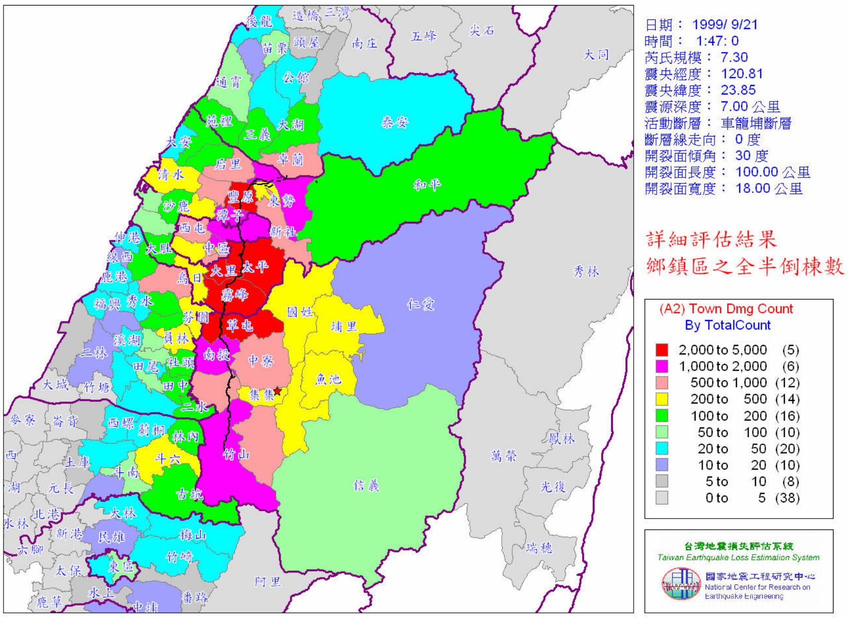

Figure 7. Estimated distribution of building counts in at least severe-damage state in Chi-Chi Taiwan earthquake.

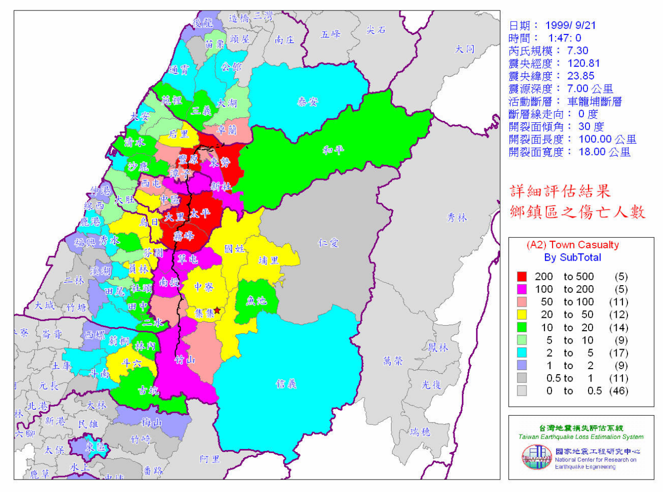

Figure 8. Estimated distribution of casualties in injury levels 3 and 4 in Chi-Chi Taiwan earthquake.

2.8 Summary

Taiwan Earthquake Loss Estimation System (TELES) is part of research accomplishment of HAZ-Taiwan project. It can be applied in proposing local seismic disaster mitigation plans and act as a decision-making support system soon after occurrence of strong earthquakes. In the near future, TELES will also integrate probabilistic seismic hazard analysis and may have applications in proposing maximum probable earthquakes for each county, in proposing adequate seismic insurance policies, etc.

3. INTERNET-BASED SIMULATION ON EARTHQUAKE ENGINEERING

Structural experiment plays an important role in the earthquake engineering research. In view of the continuous changes in structural engineering and the increasing awareness of cost in today's society, the existing large-sized structural laboratories are gradually becoming incapable of satisfying the various types of demand of the experiments. Besides endlessly increasing the capacity of each laboratory, alternatively it would be more cost effective for different laboratories to collaboratively conduct such experiment. In addition, it would be more productive and can make most out of the experiment resources and results if experts around the world can participate in. Such demand can be accommodated by the virtual laboratory. In the concept of virtual laboratory, each laboratory sited around the globe with different facilities becomes part of this virtual laboratory and participate jointly in the experiment. The participating researchers or general viewers could concurrently view the experimental results and launch discussions in a timely manner. Considering the benefits of international cooperation, the concept of virtual laboratory should be applied to transnational collaborative experiment capability.

Some research efforts have been made on developing the technology of collaborative structural experiments, allowing more than one laboratory can jointly conduct a test involving more than one specimen at different test sites. The network technique was applied to a pseudo-dynamic test of a viaduct consisting of different types of piers performed at two experiment stations exchanging experimental data and visualization data through a shared file system in Kyoto University in Japan (Sugiura et al., 1998.) A networked numerical simulation of a pseudo-dynamic test of a base-isolated bridge is then carried out at three laboratories hundreds of kilometers apart in Korea (Yun et al., 2000.) A transnational pseudo-dynamic test is then successfully simulated between Kyoto University (Japan) and Korea Advanced Institute of Science and Technology (KAIST, Korea), which exchanging data through shared disk units, demonstrating the capability and feasibility of future international collaborative experiments between Japan and Korea (Watanabe et al., 2001; Part et al., 2003) In an under-constructing 3-D full-scale earthquake testing facility in Japan, E-Defense, an ED-Net is being constructed, which may provide tele-observation and tele-discussion capability to both domestic and international research institutes, universities, or private sectors in the near future (Ohtani et al., 2002)

A NEES (Network for Earthquake Engineering Simulation) project, which has been launched by the National Science Foundation in USA. About fifteen universities or laboratories will be connected by high-performance network to explore the benefits of sharing and integrating laboratory resources, including expensive equipments, experiment data, and simulation codes, via network. Not only various types of experiment facilities will be updated or constructed, but also a network system, NEESgrid, will be developed to provide 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 (NEES, 2003; Mahin, 2002.)

In this work, an Internet-based environment, named ISEE (Internet-based Simulation for Earthquake Engineering) is being developed for collaborative networked pseudo-dynamic experiments among geographically distributed laboratories. The key task in this research work is to develop the capability to perform distributed pseudo-dynamic experiments, which will be particularly valuable for evaluating the seismic performance of large-scale structure systems or components. The application focuses on slow pseudo-dynamic experiments, which the possible time lag among different laboratories collaboratively performing a distributed pseudo-dynamic experiment is acceptable. Two different approaches, namely, the Database Approach and the Application Protocol Approach, are prototyped to provide different solutions for network communication as well as collaborative framework in the ISEE. Database Approach employs a database server for data exchange and data repository; while the Application Protocol Approach directly uses point-to-point TCP/IP-based communication to transfer experimental data. This paper introduces the framework of the two approaches and the validation experiments.

3.1 Database Approach in ISEE

The ISEE framework with the database approach is composed of three major parts: the Data Center, the Facility Controllers, and the Analysis Engine (as shown in Fig. 9). The Data Viewers and the Cameras are accessory parts of the ISEE framework.

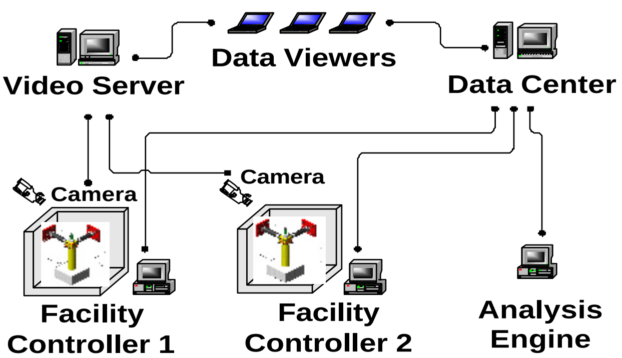

Figure 9 Database Approach in ISEE

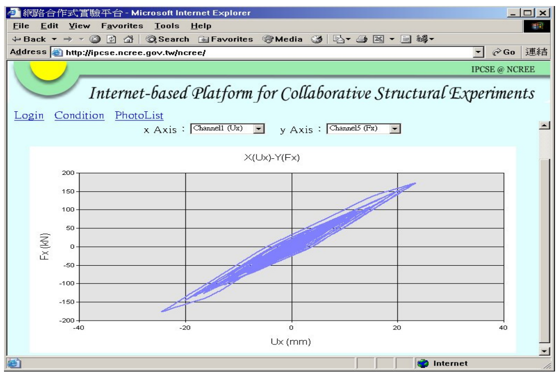

Figure 10 Web representation of real-time experiment data using Database Approach in ISEE

The Data Center

The Data Center serves as a data exchange hub and repository in ISEE database approach. All the experiment data and analysis data are gathered to the Data Center during and after a pseudo-dynamic test. The Data Center employs a database server to facilitate exchange of experimental or analysis data among different ISEE parts (or components) that may reside in laboratories at different geographical locations. The Data Center also provides a WWW (World-Wide Web) interface for viewers to browse the experiment data (Fig. 10) or researchers to setup required experimental parameters for collaborative networked structural tests before the experiment starts. In this work, the Data Center employs the Microsoft SQL Server database and the IIS web server. In addition, for the C++ programs of the Analysis Engine and the Facility Controllers to easily communicate with the Data Center, a C++ class, named SQLAccess, is developed (Hsu, 2002) for incorporation into those C++ programs.

For the flexibility issue, this work uses a three-layer framework to construct the Database Approach (see Fig. 11.) The top layer is the user layer includes components for data viewers or researchers, including www browsers, analysis engine, and facility controllers. The bottom layer is the data layer, which is the database engine. Although the user-layer components get or exchange0020data with the database, they do not communicate with it directly, instead, through a middle layer. All the user layer components are database independent. Researchers maintaining the analysis engine or facility controllers do not need to worry about the detail of access the database. In addition, few extra efforts will be required on the user-layer components if we upgrade or change the database engine, for example, to a distributed or even transnational database system.

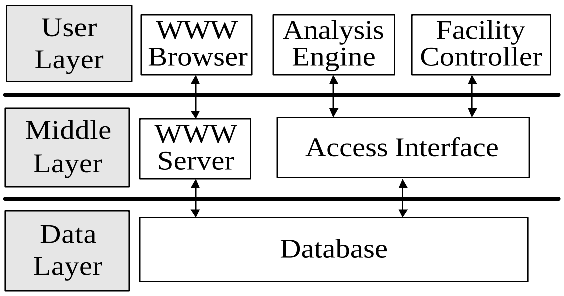

Figure 11 Three-layer framework of the Database Approach

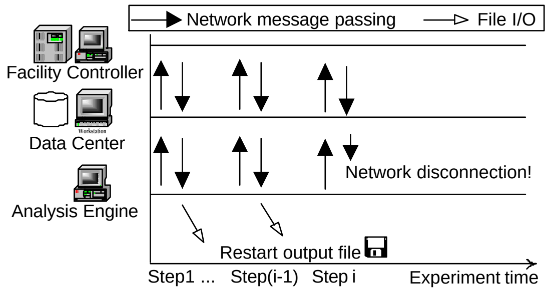

Figure 12a Experiment encountering an accident network disconnection

The Analysis Engine

The Analysis Engine computes the dynamic responses of a structure by considering both the finite element analytical responses and the real experimental responses of the specimen. In a collaborative pseudo-dynamic test, the Analysis Engine performs a finite element dynamic analysis, in which the resisting forces of one or more elements are obtained from the measured specimen resisting forces in the laboratory. The Analysis Engine sends the computed displacements to the Data Center for sharing with the Facility Controller(s) or Data Viewers.

In this work, the Analysis Engine is based on a finite element analysis program, named OpenSees (OpenSees, 2003), which allows researchers to add new components (e.g., new element types or material models). Two new element types, called pseudoGen1 and pseudoGen2, respectively, are implemented and added into the OpenSees framework (both derived from the 'Element' class in OpenSees.) The pseudoGen1 is superceded by pseudoGen2 because the latter one costs less elapsed time for a multiple-sited networked pseudo-dynamic experiment. More detail about the differences between the two types of pseudo-dynamic elements can be found in Tsai et al. (2003.) These pseudoGen elements act as actual specimen components in the finite element model by exchanging displacement and resisting forces with a Facility Controller through the Data Center. When each pseudoGen element is requested to return the resisting forces, it sends the element's displacements to the Facility Controller through the Data Center, waits for the resisting forces returned from the Facility Controller through the Data Center, and returns it to the OpenSees component which sends the request.

A pseudoGen element acts as an actual specimen component in the finite element model by exchanging displacement and resisting forces with a Facility Controller through the Data Center. During each time step of the pseudo-dynamic analysis, the OpenSees calculates a predicted response, including the displacements, velocities, and accelerations of each node. Each pseudoGen element is then requested to return the dynamic resisting force in the predicted response. It gets the predicted displacements, sends them to the Data Center (so that the Facility Controller can push the specimen and measure the stiffness resisting forces), and gets the stiffness resisting forces. The dynamic resisting force of the pseudoGen is assembled with the stiffness resisting force, inertia forces, and the damping force. The inertia forces and damping forces are calculated by multiplying the acceleration and velocity vectors by the element mass and damping matrices, respectively, read from the user-specified file. The stiffness resisting force is the measured specimen resisting force, which reflects the nonlinear behavior of the specimen. After responding the dynamic resisting force, OpenSees calculates the displacement, velocity, and acceleration response of all nodes in the structures.

In this study, the Newmark-based Operator-Splitting (OS) method is employed by the Analysis Engine for the time integration of a pseudo-dynamic experiment. The concept of the OS method (Hughes and Liu, 1978) is to separate the damping and stiffness matrices into the implicit part and the explicit part. In the viewpoint of implementation, the only difference between the Newmark's method and the OS method is that the latter one considers the nonlinear effects only on the unbalanced force, i.e., the parts in Eq. (1), but not on the effective matrix. In a pseudo-dynamic experiment, the explicit part denotes the nonlinear part of the damping and stiffness matrices of the specimen(s), while the implicit part is the rest of the damping and stiffness matrices. The effective matrix (see Eq. 11) does not change during an analysis. There is no nonlinear iteration solution scheme (such as Newton Raphson's iteration) used in this work.

$$\{\Delta a_{i+1}\} = \left([M] + \gamma\Delta t[C] + \beta\Delta t^2\left[K^I\right]\right)^{-1}\left(\{p_{i+1}\} - \{\tilde{f}_{i+1}\}\right) \tag{11}$$

The Facility Controller

The Facility Controller is a software layer that can be used to drive the corresponding experimental facility in the laboratory. In a networked pseudo-dynamic experiment, the Facility Controller gets the displacement data from the Data Center, sends the displacements to the experimental facilities (servo hydraulic actuators), then receives restoring force data and sends them back to the Data Center. The control systems employed in NCREE Lab and NTU Lab are the MTS FlexTest IIm and MTS 407 controllers, respectively.

Network Fault Tolerance

A successful networked pseudo-dynamic experiment relies on network stability. Even a short period of network disconnection during an experiment may cut off the procedure of the experiment. In case of network disconnection during a network pseudo-dynamic experiment, the Analysis Engine and/or all Facility Controllers can not get the data they need, and the experiment will get suspended, even after the network is re-connected. It is not good to re-do a suspended experiment from the beginning if the specimen has been in nonlinearity status which behavior and properties may not be restored. However, typically the network between laboratories is Internet, which connection quality is not the focus of this research. To avoid of the failure of network pseudo-dynamic experiments caused by Internet disconnection, this research focuses on providing fault tolerance mechanism. A network fault tolerance solution is necessary for a network pseudo-dynamic test.

The fault tolerance solution in the Database Approach allows a re-start experiment to link with a previous suspended one. By setting the initial condition (including displacements, velocities, accelerations, material stress-strain histories) to the re-start experiment, we provide a solution so that a broken-off experiment can be followed by a re-start experiment. The initial condition of the re-start experiment is just the final condition of the suspended experiment. After the re-start experiment finishes, a complete experiment result is available by combining the experiment result of the suspended experiment and the re-start experiment.

In this research, both pseudoGen1 and pseudoGen2 element types provide a restart function to link with a previous suspended experiment. During a network pseudo-dynamic analysis, the pseudoGen element(s) export the element resisting forces and displacements step-by-step to restart output files, including the data flowing through the Analysis Engine, Data Center, Facility Controller(s), then back to Data Center, and Analysis Engine in each time step. After the data (of resisting force) flows back to the Analysis Engine, the pseudoGen1 or pseudoGen2 elements append the displacements and forces to a restart file. In case of accident network disconnection, the experiment breaks off (see Fig. 12a), say, at the i-th step, the restart output file would then contain the displacements and forces data of at least the previous (i-1) time steps. Also, the specimens are at the status of the (i-1)-th or the i-th step (depends on where the network disconnection happens.) To restart 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 restart output file of the suspended experiment, instead of the Data Center, from the first step through the (i-1)-th step (see Fig. 12b.) It is supposed that the analysis result before the (i-1)-th step is exactly the same as those of the previous suspended experiment because the resisting forces fed into the Analysis Engine are exactly the same. After the i-th step, the Analysis Engine begins to send and receive data to Data Center, as it does in a normal experiment, until it completes the experiment. If the network disconnection happens again in a restart experiment, the restart solution can be applied again, until the whole experiment completes.

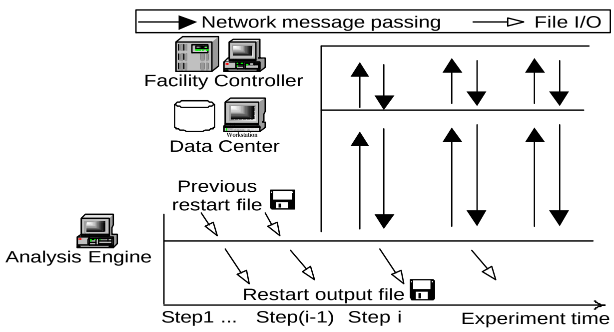

Figure 12b A restart experiment completing a previously disconnected experiment

Figure 13 A real-time video image through a WWW browser

Other Accessory Parts

Anyone on the Internet can access the experimental data from the Data Center using a Data Viewer (actually a WWW browser, such as Microsoft Internet Explorer or Netscape Navigator) without installing any additional software. The viewers can browse the time history curves of displacements or resisting forces, or the hysteresis loop of the displacements and resisting forces of any specimens of any completed or in-progress experiments using the Database Approach of ISEE (for example, see Fig. 10) With proper authorization, users can also get the plain numerical data of these displacements and resisting forces data from the Web page. With proper setup of Cameras and the Video Server, users can also see the real-time video images of the experiments. The Video

Server also provides a WWW interface to the Data Viewers (see Fig. 13)

3. 2 Application Protocol Approach in ISEE

Platform Architecture

The Transmission Control Protocol/Internet Protocol (TCP/IP) suite was designed as an open standard to meet the demand of data transmission on rigorous network conditions (Postel 1981.) It connects a number of different networks designed by different vendors into a network of networks (the Internet). TCP guarantees reliable data transmission by providing services such as acknowledged delivery, error detection, retransmission if necessary, data sequence preservation, and flow control. IP provides addressing, routing, fragmentation and reassembly for data packets. TCP/IP stack thus handles robustly all those tedious works for data transmission between hosts on heterogeneous networks. Simply put, an application protocol is a set of predefined rules that defines the constitution and content of information to be shared and transmitted, as well as the sending/receiving behaviors to be obeyed by the applications.

The Application Protocol Approach proposed a TCP/IP-based platform, the “Platform for Networked Structural Experiments” (PNSE, see Fig. 14) on which data transmission is implemented by transferring predefined data packets defined by a preliminarily proposed application protocol, the “Networked Structural Experiment Protocol” (NSEP), to realize the goal of Internet collaborative structural experimentation. A series of transnational pseudo dynamic tests upon a specimen composed of two double-skinned concrete filled in tube (DSCFT) columns located in two different laboratories were conducted to verify the validness and efficiency of PNSE. The characteristic of environment independency of PNSE was also verified by a series of networked pseudo dynamic tests were also performed upon a full scale 3-story 3-bay concrete filled steel tube (CFT) and buckling restrained braced (BRB) composite frame.

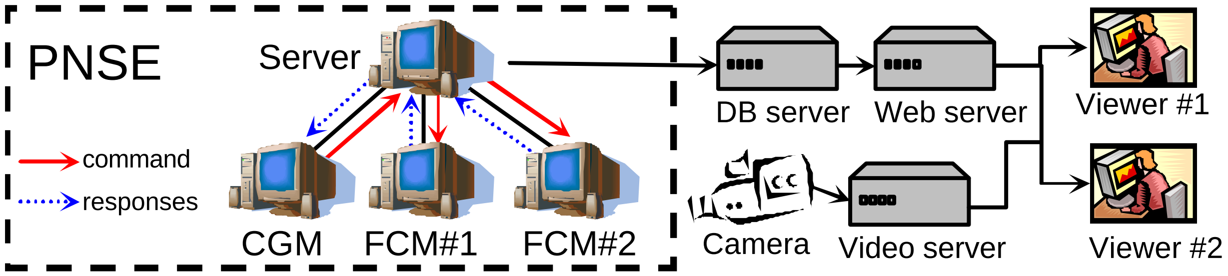

Figure 14 The Architecture of the Application Protocol Approach

Platform for Networked Structural Experiments

This study proposed a platform, PNSE, to meet the goal of networked collaborative structural experimentation. The architecture of PNSE is illustrated in Fig. 14. PNSE concentrates on the core tasks related to successful and robust progression of the networked experiment and excludes functionalities of digital and video data storage and display on the Internet, which can be implemented by commercially available software such as Microsoft SQL server or Windows Media Player. The PNSE is a multi-client system with all the clients connected to the server with a TCP point-to-point connection. The PNSE server is essentially the center of the system and provides services of message dispatch and data delivery for all clients. PNSE has two kinds of clients: the Command Generation Module (CGM) and the Facility Control Module (FCM). The CGM generates command to be imposed on the specimen located at different laboratories by all the FCMs. It can be a numerical integration algorithm in the scenario of pseudo dynamic testing, an input module that queues predefined command profile in the case of quasi-static testing, or simply a remote application with an user interface that allows its users to enter command promptly. The

CGM prepares the commands for all FCMs in a single packet and sends the packet to the server. After receiving the packet, the server forwards them to corresponding FCMs. The FCMs then control the actuators to impose the individual command received from the server on the specimen located in their laboratories. After the command is successfully executed, an FCM measures or calculates the response and sends it back to the server. When the server receives all the packets, it integrates them and sends it to the CGM as a notification of the completion of command execution. Those actions performed by the PNSE server, CGM and FCMs described above constitute a cycle, which is the smallest unit to be executed repeatedly until the collaborative experiment finishes.

On PNSE, human communication is still necessary but not as easy to implement as in a traditional structural laboratory since all the participants (including test operators and interested individuals on the Internet) are scattered around at different locations. However, it is very difficult or even impossible to clearly define all possible events (such as the detailed damage condition of the specimen or any action taken by the laboratory staffs to fix the specimen, etc.) that can occur in a networked structural experiment in the application protocol. To address this issue, a feature of instant discussion is included in the application protocol for all PNSE participants to promptly transfer relevant information about the experiment by means of sending and receiving human readable texts.

Characteristics of PNSE

PNSE is an environment independent platform since it is constructed based on the TCP/IP suite which is supported by almost all currently available operating systems and programming languages. High interoperability can be assured regardless of the diverse environment composed of computer hardware, operating system, and programming language. This suggests only minimum programming work has to be done to incorporate existing numerical analysis programs and facility control programs on PNSE.

The PNSE server sits the central position in the star-topology connection system. However, except for maintaining a simple login procedure for each connection attempt, it does not behave as an “administrator” of the system for any purpose other than security concern. That is, it does not mandate any clients to perform any specific task during the course of the experiment and only serves as a “spokesman” for all clients. For example, the server never actively queries the CGM for command to be executed nor it ever queries the running state of any of its clients. It is the CGM’s responsibility to actively send the command to the server, and similarly, it is every client’s responsibility to send a notification of change of its running state to the server when necessary. Actually, both the PNSE server and clients are stipulated to make “active notifications,” meaning that the one who owns relevant information should actively informs the other side of the connection, when necessary. This stipulation naturally makes the PNSE an event-reflective platform, provided that all significant events that can occur in experiments are clearly defined in the application protocol.

In other words, for any PNSE client, any information that comes from the server is actually originally sent or caused by other clients. This characteristic actually makes the PNSE a truly cooperative platform because every client plays an indispensable role and has its responsibility to behave as stipulated to jointly make the progression of the experiment. This leads PNSE to an event-driven system. The progression of the experiment can be thought of a series of responsive behaviors to all events defined in the application protocol. The characteristic of event-driven enhances the extensibility of PNSE since when events and interactions get more and more complex in the future, all that has to be done is to add more message handler functions in programs without drastically modifying the program architecture.

In addition to make the PNSE an event-driven and a truly cooperative platform, the stipulation of active notification actually increases the overall data transmission efficiency of PNSE. Other than the active notification stipulation proposed in this study, an “information query mechanism

(IQM)" can be an alternative approach to realize an event-reflective platform. This mechanism basically stipulates that the one who need relevant information should actively query for that information from the one who owns it repeatedly until the information is acquired. Techniques utilizing IQM to exchange data over the networks have been employed in other research works due to its simplicity. Examples include accessing shared-used disk files (Sugiura et al. 1998, Yun et al. 2000, and Watanabe et al. 2001) and depositing and retrieving data from a database repository (Tsai et al. 2003). However, IQM generally decreases the overall system efficiency since the polling operations have to be done frequently enough so that information can be acquired promptly enough, but frequent query wastes a lot of time and network resources especially when the information queried has not been updated at the moment of query. As for the active notification stipulation proposed in this study, the system efficiency could be drastically increased since all the PNSE modules (both the server and the clients) have to do is to wait for the information to come automatically without spending any time and network resources to poll from the other side of the connection continuously.

PNSE is designed and constructed in a start-topology connection system to simplify the network topology and hence the communication flow. Instead of connected to any other client, a PNSE client is designed to connect to the server only. Consequently all data packets must be directed to the server first and then can they be dispatched to their destination by the server. This would cause additional time consumed in data transferring but this architecture tremendously simplifies the network communication flow since for each client program it only has to handle information that comes from the server, instead of the many other clients. This design can save large amount of efforts needed in programming especially when events and interactions get more and more complex in the future. Since all the information must be directed to the server first, the PNSE server appears to be the best candidate to publicize all valuable information on the Internet, including the general information (metadata) of the current experiment, all the open signal values, running state of the experiment, running states of all client programs.

In any traditional structural laboratory, due to various reasons such as damage examination, photographing, minor specimen or instrumentation adjustment, or safety concerns, an experiment can be suspended, resumed or even stopped prematurely. In the scenario of virtual laboratory, privilege of change of the running state is still preserved for each participating laboratory, although all the FCMs are stipulated to report any change of its running state to the system.

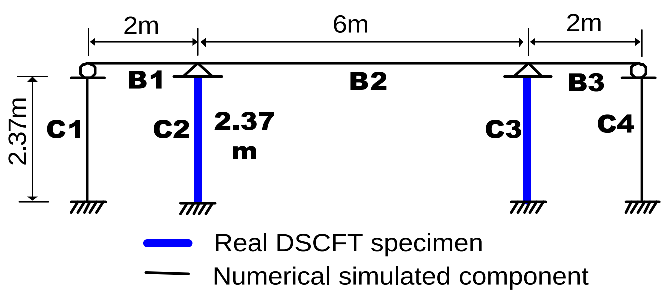

Figure 15 Substructure Pseudo-dynamic DSCFT Tests using Database Approach

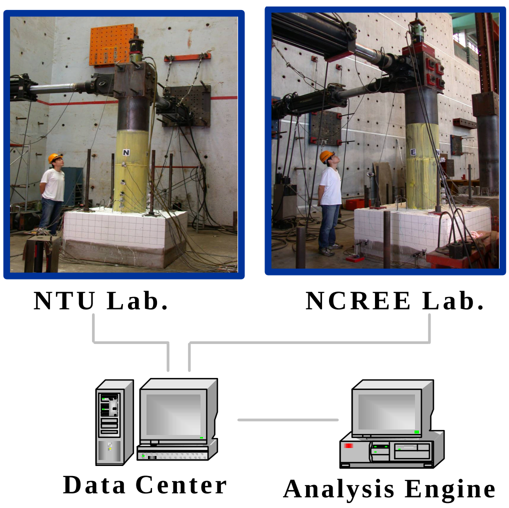

Figure 16 Configuration of the DSCFT Tests using Database Approach

3.3 Experimental Validation

To verify the validness and efficiency of the Database Approach and Application Protocol Approach, a series of domestic and transnational collaborative experiments were conducted upon a bridge with two double-skinned concrete-filled tube (DSCFT) bridge specimens. More details of these tests can be found in (Tsai et al., 2003). The two columns were fixed to the ground and pin-connected to the rigid superstructure with earthquake ground motions along two horizontal directions, hence each pier has two controlled degrees of freedom assigned at the top. Two piers of the structure are constructed and located at National Taiwan University Laboratory (NTU Lab.) and National Center for Research on Earthquake Engineering Laboratory (NCREE Lab,) respectively.

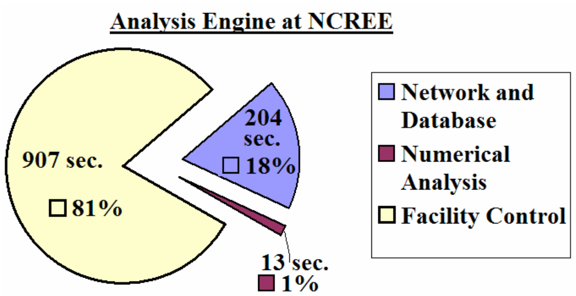

Figure 17a NCREE-NTU Testing Result using Database Approach

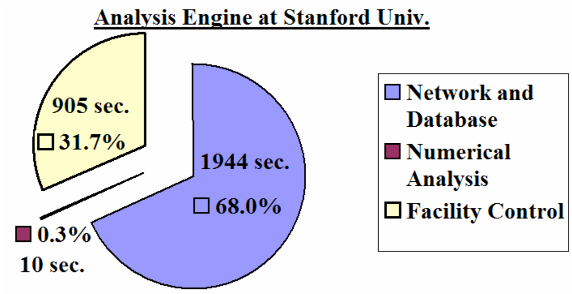

Figure 17b NCREE-NTU-Stanford Testing Result using Database Approach

A series of 1000-time-step substructure pseudo-dynamic tests demonstrates the feasibility of the Database Approach. A four-pier bridge subjected to a bi-directional earthquake is simulated (see Fig. 15), while two of the four piers are real specimens and other components are numerically simulated by the OpenSees-based analysis engine (see Fig. 16.) In average, the time cost on network transmission costs 204 seconds of the total elapsed time of 1124 seconds (see Fig. 17a), less than 20% of total time in domestic tests (across NTU and NCREE, while the Data Center and the Analysis Engine are placed at NCREE.) The network costs less than 70% of total elapsed time in transnational tests, (see Fig. 17b) in which the Analysis Engine is moved to Stanford University in USA.

A series of transnational pseudo-dynamic tests are also conducted using Application Protocol Approach for a two-pier bridge system (see Figs. 18 and 19.) In the tests, the server resided in Stanford University, while the CGM runs at the NCREE Lab. A 1999 Chi-Chi earthquake motion is selected as the excitation, which PGA is reduced so that the specimens keep in elastic status for the networked tests. The test results reasonably agrees with the one obtained from pure numerical analysis, indicating that all signals including commands and responses were correctly transmitted over the Internet. Time consumed for a data packet to make a round trip between NCREE and Stanford is 0.17 seconds in average, which is nearly the same as the network performance tested by using an operating system ping-pong network testing program (0.16 seconds.)

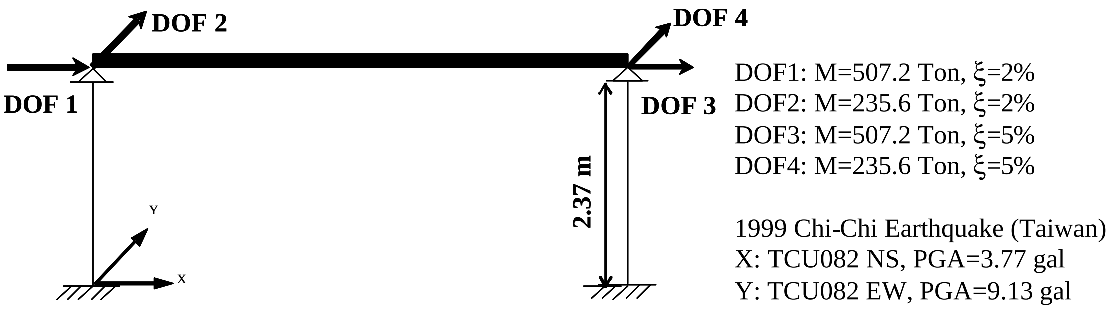

Figure 18 Pseudo-dynamic DSCFT Tests using Application Protocol Approach

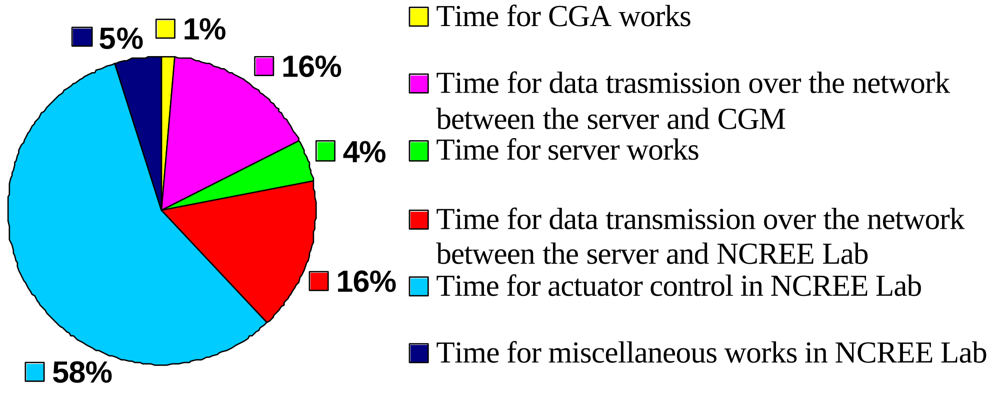

Figure 19 A Restart Experiment Completing a Previously Disconnected Experiment

3.4 Summary

An Internet-based environment, called ISEE, has been prototyped in this work for collaborative networked structural experiments among geographically distributed structural laboratories. Two approaches, the Database Approach and the Application Protocol Approach, have been prototyped and employed to provide different solutions for network communication as well as collaborative framework in ISEE. The Database Approach employs a database server with a World-Wide Web service as a data center to serve as a data exchange and repository center, and all network communications are performed by calling SQL commands. The Application Protocol Approach develops a communication protocol based on TCP/IP suite for direct exchange of messages in ISEE. Several networked pseudo-dynamic tests have been conducted to investigate the feasibility and efficiency of ISEE. The tested experiment sites include the NCREE Lab and the NTU Lab. A series of networked experiments using Database Approach and Application Protocol Approach, which the components of the experiments are placed at the NTU Lab, NCREE Lab and Stanford University (in USA) has been completed and validates the feasibility of the ISEE for future networked collaborative pseudo-dynamic experiments.

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