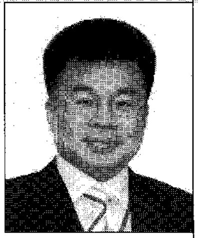
내진평가를 위한 하이브리드 실험과 멀티플랫폼 해석방법

Hybrid Simulation and Multi-platform Analysis for the Seismic Assessment of Complex Structures



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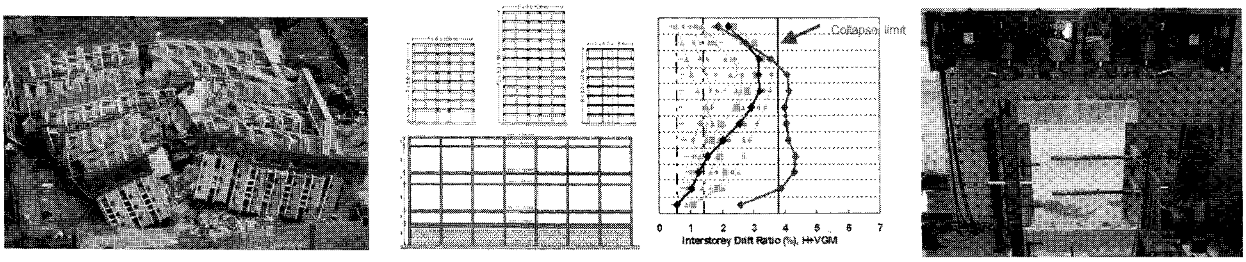
1. Introduction

Recent seismic events exposed the built environments to severe loading resulting in structural damage and jeopardizing the safety and economic viability of societies around the world. Examples include the Kashmir Earthquake, Pakistan (2005, M_w 7.6), Sichuan Earthquake, China (2008, M_w 7.9), Haitian Earthquake (2010, M_w 7.0), Maule Earthquake, Chile (2010, M_w 8.0), Tohoku Earthquake, Japan (2011, M_w 9.0), and Christchurch Earthquake, New Zealand (2011, M_w 6.3). Particularly, the Haitian Earthquake where unengineered structures performed poorly and the Maule Earthquake in Chile where structures adhering to seismic design code had much improved performance, are prime examples of the importance of understanding and designing for the performance of structures under severe hazards1). Thus, to better protect the built environment, earthquake engineers must optimize the use of available assessment tools.

Historically, three methods of assessment have been available, namely, field observation, numerical analysis, and experimental testing. Although field observation can provide with more realistic data of the structural behavior under seismic load, generalizing findings from field observation is challenging due to uncertainty in the collected data. Thus,



Field observation

Numerical analysis

Experiment

Figure 1. Seismic assessment methods

structural engineer community typically investigates the structural behavior under extreme loads by utilizing either numerical analysis or experimental testing. However, assessment of complex structural systems using these methods is still challenging to develop effective mitigation, response and recovery measures. Neither modern laboratory testing nor advanced computer simulations are able to respond to this challenge. Laboratory testing is restricted by issues of scale (e.g., a high-rise building and a long-span bridge) while computer simulation is inadequate in representing all components of complex system[2]. Moreover, one single laboratory cannot have the features of all others. An analysis platform has been developed to solve the only specific problem within complex structural systems and thus has a unique feature when dealing with the narrow problems. Thus, either laboratory testing or numerical analysis has inherent weakness in assessing the complex system.

Recently, by recognizing the relative merits of different laboratory testing facilities and analysis software packages, structural engineering community make an attempt to combine various testing facilities or analysis packages in order to effectively solve the complex problems. In contrast to using one analytical platform and one experimental facility, multiple analytical platforms are utilized and distributed testing exists. These approaches have been subject to extensive research in recent years[3)~9)]. Therefore, this article presents these efforts in USA by introducing hybrid simulation and multi-platform analysis.

2. Hybrid Simulation

2.1 Overview of Hybrid Simulation

Hybrid simulation, also called substructure pseudo-dynamic testing, is a type of experimental testing within civil engineering that provides the capability to isolate and physically test critical components of a structure in an efficient manner. The loading applied to the structure is determined by numerical integration of the dynamic equations of motion[3)]. The method provides an exceptionally attractive option for assessment of complex interacting systems, combining physical testing with numerical simulation. As shown in Figure 2, the hybrid simulation allows the well-behaved and better understood regions to be singled out and analyzed computationally, while regions of particular interest or complexity are treated experimentally. Through the interaction of the physical and analytical substructures during the simulation, the response of the entire structure can be obtained. The hybrid simulation has been adopted and extended by many researchers through the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) which consists of fourteen shared-use equipment sites located throughout the USA [5)~7)]. In the following sections, a couple of examples from recent research efforts are introduced.

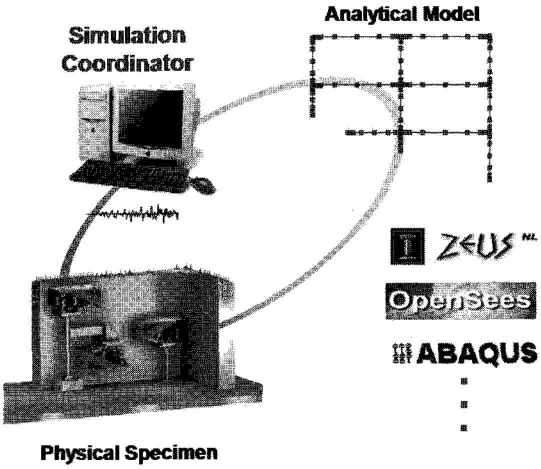


Figure 2. Overview of hybrid simulation

2.2 Effect of Vertical Ground Motion on RC Bridge Columns

This experimental program aimed at assessing the effect of vertical earthquake ground motion on reinforced concrete bridge columns[7)]. Two hybrid simulations with and without vertical excitation of earthquake ground motion which had not previously been tested. As shown in Figure 3, one of the bridge columns was evaluated experimentally while the rest of structure was simulated analytically. The horizontal ground motion was used as the only input for the first specimen while the second specimen was subjected to combined horizontal and vertical components of ground motion. Through these tests, the significant effect of vertical ground motion on RC bridge columns was investigated and confirmed (Figure 4). More details can be found at Kim et al. (2011)[7)].

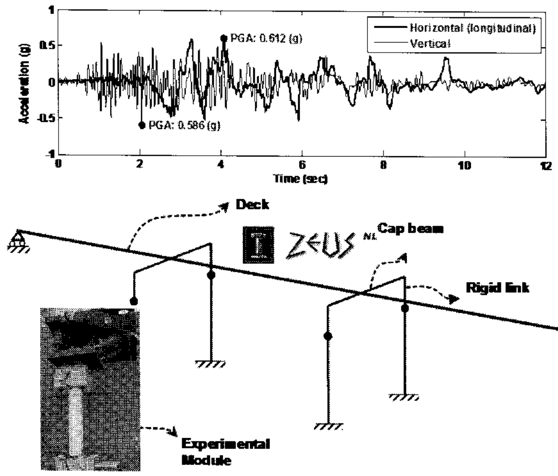


Figure 3. Input ground motions and substructure

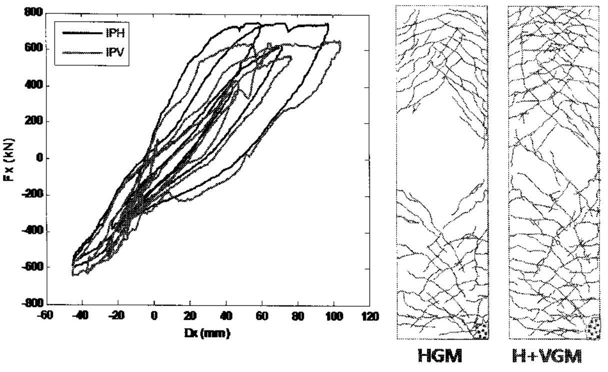


Figure 4. Lateral responses and crack comparison

2.3 Multi-Site Soil-Structure-Foundation Interaction Test

The Multi-Site Soil-Structure-Foundation Interaction Test (MISST) which was one of the earliest to utilize the cyberinfrastructure of the NEES; collaborating partners included University of Illinois at Urbana-Champaign (UIUC), Lehigh University (Lehigh), and Rensselaer Polytechnic Institute[8]. The project demonstrated the application of hybrid simulation to a complex bridge system. The MISST structure was partitioned into five distinct modules distributed to 3 geographically separate NEES equipments sites as shown in Figure 5. Two of the 5 substructured components were experimentally tested while rest of structures were analytically simulated.

As indicated in Figure 6, despite the brittle nature of the test piers, the simulation was able to continue on well past the initial shear failures observed at both the Illinois and Lehigh sites. Furthermore, the redistribution of forces between the two sites with the bridge piers as either of the two suffered partial failure shows that full interaction was taking place between the geographically distant sites.

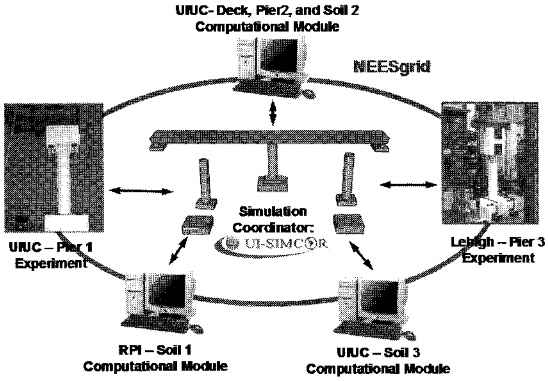
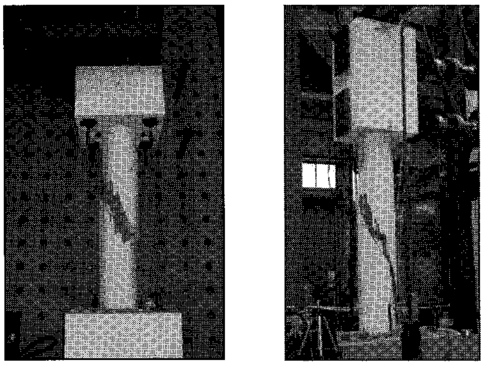


Figure 5. MISST test



Column 1 - UIUC **Column 3 - Lehigh**

Figure 6. Specimens after MISST test

2.4 Mutli-Site Real-Time Hybrid Simulation of MR Dampers

Real-time hybrid simulation (RTHS), also called real-time dynamic substructuring or real-time pseudo-dynamic testing, is a relatively new method of testing made more feasible by the recent advances in computing power, digital signal processing, and hydraulic control. In RTHS the physical component is tested in hard real time such that any rate dependencies of the physical component are fully captured. When the restoring force depends also on the velocity and acceleration (damping and inertia forces) of the physical specimen, care must be taken to ensure that displacements enforced on the physical specimen are accurately imposed in time. Thus, RTHS has

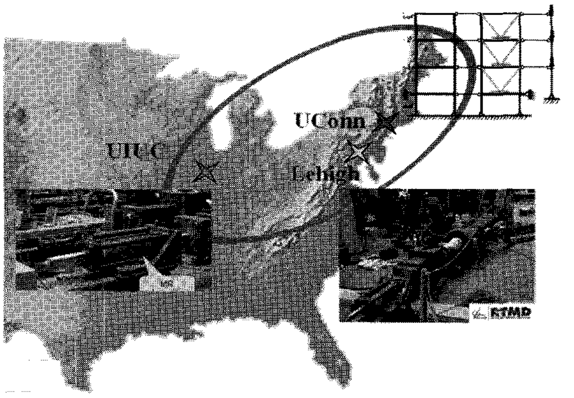


Figure 7. Multi-site RTHS

been proposed to fully capture strain, damping, and inertial effects by computing each numerical integration time step of the experiment in exactly that amount of time[10)~14)].

Recently, attempt to conduct the Multi-site RTSH (MRTHS) was made between the University of Connecticut (UConn), UIUC and Lehigh with a three-story steel building controlled by two Magneto-Rheological (MR) dampers[9)]. Two MR dampers were placed on the first and second story, respectively. As shown in Figure 7, one MR damper was experimentally simulated at UIUC and another MR damper was tested at Lehigh while rest of structure was analytically simulated.

The major challenge with geographically distributed RTHS is the accommodation of large communication time delays present in sending data over large distances - including the internet. Modern local controllers and hybrid simulation algorithms typically run at a rate of around 1000 Hz (1 msec). Recent multi-site tests conducted between the NEES facilities at Lehigh and UIUC encountered network time delays in one direction (geographically located approximately 1200 km apart) of 25-50 msec[9)]. Due to this large delay, testing in real-time (which would allow for testing rate dependent physical components) cannot be accomplished with traditional methods and algorithms. Thus, a Smith prediction-based approach is adopted to accommodate the communication time delay present in multi-site testing as shown in Figure 8.

The Smith predictor uses an analytical model of the physical component to compensate for the delay and provides an estimated current physical restoring force. Kim et al. (2011)[9)] reported that for a modeling error of 10% and network delay of 50 msec a peak response error of 5% can be achieved compared to single site RTHS. Figure 9 shows the comparison between single site RTHS (SRTHS) and MRTHS for semi-active control and indicates that results from both simulations match well.

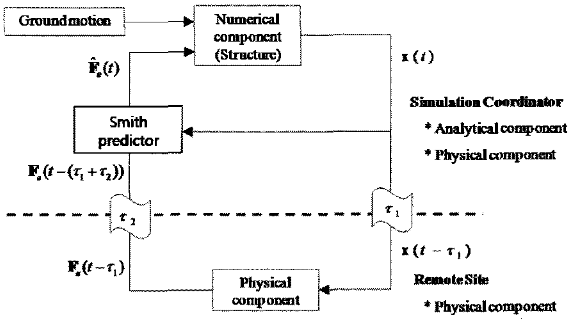


Figure 8 Proposed MRTHS framework

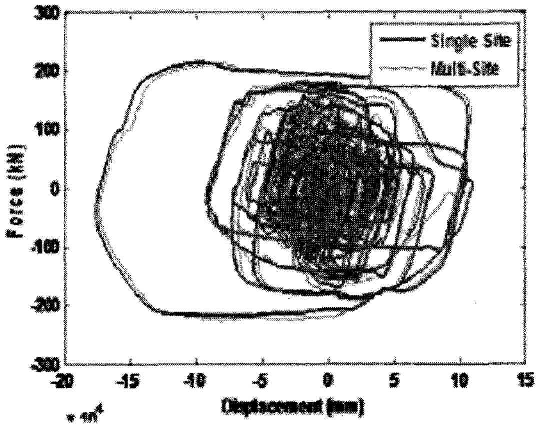


Figure 9 Single site RTHS and MRTHS

4. Multi-Platform Analysis

4.1 Overview of Multi-Platform Analysis

Many state-of-the-art analysis platforms in the research field have unique features. By utilizing these unique features of analytical capabilities, a complex structure can be more realistically modeled and more reliable results can be obtained. The concept of multi-platform simulation is developed in conjunction with hybrid simulation. As described previously, in hybrid simulation a structure is subdivided into several modules that are either physically tested or computationally simulated. UI-SimCor[2)] was developed for this purpose, which is capable of coordinating

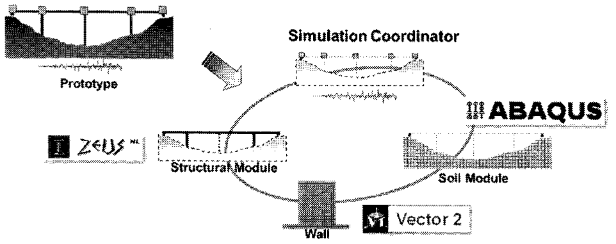


Figure 10. Overview of multi-platform analysis

the synchronized simulation of Zeus-NL[15], OpenSees[16], FedeasLab[17], Abaqus18), Vector2[19], and other software and hardware. The multi-platform may be run on one or more processors, thus making use of clusters of computers in a more effective manner.

4.2 High-Rise Building with wall system

The structural system of a high-rise building is not a direct extension of low-rise structure due to its more complex configurations and the needs to resist much larger external loads. Thus, normal analytical methods for low-rise building do not work well for the capacity evaluation of a high-rise structure. The following example presents the application of multi-platform simulation to analyze a complex high-rise structure.

Figure 11 shows the example of multi-platform analysis for an actual RC high-rise building, Tower C03 at Dubai, United Arab Emirates[20]. Frame in Figure 11 includes dual core walls and beam-column frame. It is analyzed using two analysis platforms: VecTor2 and ZEUS-NL. The former, VecTor2, is capable of analyzing an RC continuum based on the Modified Compression Field Theory[21]. The latter, ZEUS-NL, utilizes fiber-based frame elements.

The shear significant lower regions of the walls, 1st - 10th stories of the building, are modeled as RC continuum elements in VecTor2, while the remaining parts of the walls and frame are simulated with fiber-based beam-column elements in ZEUS-NL. Figure 12 presents two sets of displacement response histories at two different floor levels (1st and roof stories), using a record from the Kobe earthquake (1995). The analysis results from the multi-platform simulation are compared with those from the frame analysis of skeletal model in ZEUS-NL. At lower levels of the building, the drifts computed from the multi-platform simulation are much larger than those from the pure ZEUS-NL model, while at roof story they are close to each other. The large difference at the lower level results from shear deformation, as considered by concrete continuum model in VecTor2. Further detailed information about this multi-platform simulation is available at Ji et al. (2009)[20].

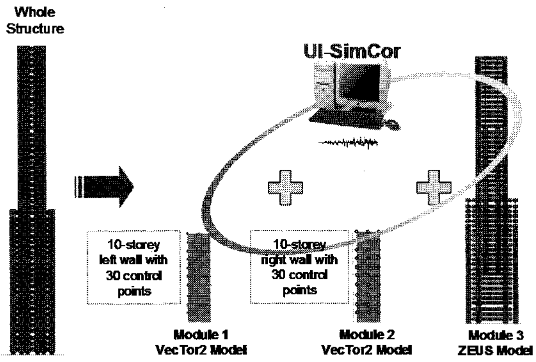


Figure 11. Multi-platform analysis of a high-rise complex structure[20]

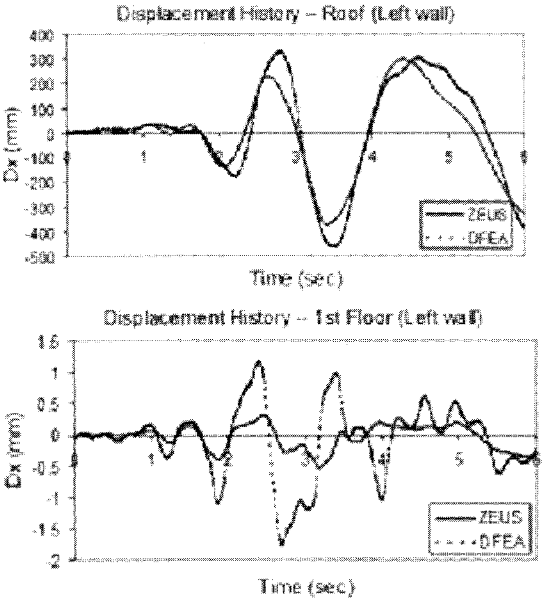
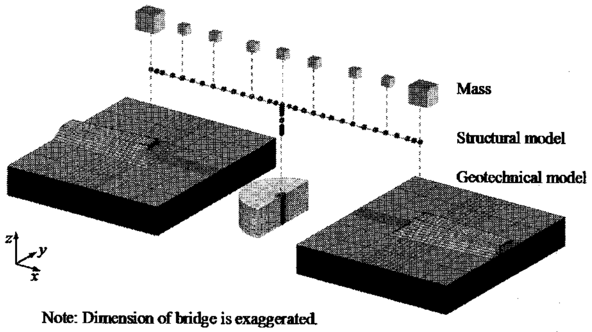


Figure 12. Lateral displacement history[20]

4.3 Meloland Road Overcrossing Bridge with Soil-Structure Interaction

As part of a study for soil-structure interaction, the Meloland Road Overcrossing (MRO) Bridge was modeled with the best applications for each structural component[22]. As illustrated in Figure 13, OpenSees is used to model geotechnical environment including embankments, piles, and



Note: Dimension of bridge is exaggerated.

Figure 13. Multi-platform analysis for MRO bridge[22]

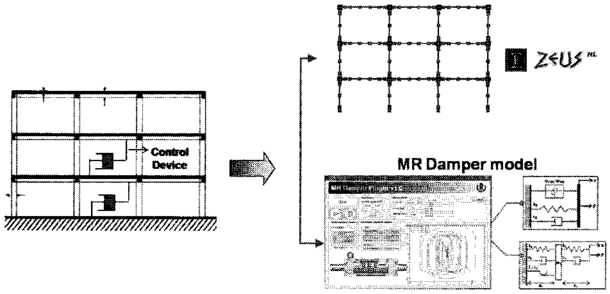


Figure 14. Multi-platform analysis for RC building with MR dampers

foundations with state-of-the-art soil material models. ZEUS-NL is used to model super structures. The structural model in ZEUS-NL and the geotechnical model in OpenSees is combined with UI-SimCor. The bridge is equipped with 32 channels of accelerometers and measured several sets of earthquake ground motions. Thus, the multi-platform simulation is verified with measured responses from instrumented bridge. Further detailed information about this bridge analysis is introduced in Kwon and Elnashai (2008)[22].

4.3 RC Building Controlled by MR dampers

It has been shown over the last few decades that the implementation of MR dampers in civil structures is an effective way to reduce the dynamic response of structures to various dynamic loading conditions. In practice, the MR damper's dynamic characteristics are typically modeled in a MATLAB/Simulink environment which provides the proper framework to estimate the damper's nonlinear dynamic characteristics. A number of models have been produced in this environment that accurately depict the damper's behavior under numerous loading conditions. However, creating a structural model with nonlinear material properties is neither simple nor practical in a MATLAB/Simulink environment without approximating the material behavior as bilinear. More reliable models of these structures can be produced using nonlinear finite element analysis tools such as Abaqus, OpenSees or ZuesNL, that perform significantly better in reproducing the dynamic response of structures comprised of nonlinear materials. These tools unfortunately are not ideal for modeling the complex nonlinear behavior of the MR dampers nor their control algorithms. Therefore, recently, MR damper plugin has been developed by author. The MR damper plugin is to facilitate communication between MATLAB/Simulink and a finite element analysis tool, such that each component is able to be modeled in its preferred environment and that these components are able to communicate the necessary information at each time step to run a successful multi-platform analysis. Currently, seismic Assessment of three-story RC structure controlled by MR dampers by utilizing the multi-platform analysis is underway. This analysis accounts for more complex inelastic behavior of the structure and a schematic overview is shown in Figure 14. This work is expected to overcome difficulties in the analytical assessment of structural control strategies for complex and nonlinear structures.

5. Closure

In this article, recent efforts to efficiently assess complex structure systems under seismic loading are presented by introducing hybrid simulation and multi-platform analysis with several research examples. Hybrid simulation can utilize multiple experiment facilities and various software packages to investigate the behavior of complex structures. Also, multi-platform analysis can allow structural engineers to employ various analysis platforms each of which has a unique feature for modeling a specific component of the complex system. Therefore, hybrid simulation and multi-platform analysis have a great potential for seismic assessment tools and are recommended when dealing with a complex structural system under extreme loadings.

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