Real-Time Multi-Directional Hybrid Simulation of Building Piping Systems

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ABSTRACT :

Observations during past earthquakes have demonstrated the seismic vulnerability of nonstructural components. Damage to these components can significantly reduce the functionality of essential facilities. Real-time hybrid simulation combines experimental testing and numerical simulation, and therefore provides an excellent technique for the dynamic testing of complete systems rather than testing components or subsystems. In this paper, a real-time multi-directional hybrid simulation of a system of nonstructural components is presented. In the simulation, a building piping system in a three-story moment resistant frame is subjected to bi-directional earthquake ground motions. The pressurized piping on the third story is selected as the experimental substructure, while the rest of the structure is modeled analytically. The Lehigh University Real-Time Multi-Directional Seismic Simulation Facility is used for the study. To ensure accuracy and stability during the simulation, the newly developed unconditionally stable explicit CR integration algorithm and inverse compensation method for actuator delay are used. The two horizontal components of the 1994 Northridge earthquake ground motion recorded at Canoga Park are scaled to the MCE seismic hazard level. Real-time hybrid simulation is performed to evaluate the seismic performance of the components of the piping system, including the bracing, joints, and piping members. The simulation results indicate that adequate piping joints and carefully designed bracing can enable the nonstructural piping system to perform well under strong earthquakes. The experimental study presented in this paper demonstrates the application of real-time hybrid simulation to the seismic testing of nonstructural components.

KEYWORDS: Real-time hybrid simulation, nonstructural component, nonstructural system, actuator delay compensation, integration algorithm

1. INTRODUCTION

Non-structural components of a building are often referred to as those systems , parts, elements or components that are not part of the structural load-bearing system, but are subjected to loading from the building response to natural hazards such as earthquake. Sample data from typical office, hospital and hotel construction (Taghavi and Miranda 2003) indicates that the investment in nonstructural components and building contents is far greater than that for structural components and framing. Observations during past earthquakes have demonstrated the seismic vulnerability of nonstructural components. Although building structures generally performed well during past earthquakes, the inferior performance of nonstructural components might reduce the overall performance of the building system (Filiatrault et al. 2002). Damage to these systems can significantly reduce the functionality of essential facilities such as hospitals and emergency response facilities. With the development of performance-based earthquake engineering, harmonization of the performance levels between structural and non-structural components is necessary. Although the structural components of a building may achieve an immediate-occupancy performance level during a seismic event, failure of nonstructural systems inside the building can lower the performance level of the entire building system.

A great deal of research effort has been devoted over the past 40 years to the development of rational methods for seismic analysis of non-structural elements. Earlier efforts focused on the safety of critical equipments such as piping and control systems in important structures such as nuclear power plants. The 1906 San Francisco and 1933 Long Beach earthquakes exposed the vulnerability of masonry parapets and exterior walls to earthquake loading. It was then recognized that non-structural components should also be designed for lateral force. Currently, most of the design provisions are based on the equivalent lateral force method, where the non-structural component is designed for a lateral seismic force that is a fraction of its weight. In almost all earthquakes, it was found that the performance of engineered (or code-conforming) nonstructural components that have been properly designed and installed is far superior to the performance of nonstructural components installed without seismic engineering. (Reitherman and Sabol 1995).

One of the simplified methods developed to determine the seismic design forces on the nonstructural components in a building structure is the so-called floor response spectrum technique. In this approach, the acceleration time-history at the base of nonstructural components in the structure is obtained by a time-integration analysis of the building response. The acceleration response spectrum of this acceleration time-history is then computed to obtain a floor response spectrum from which spectral acceleration demand on nonstructural building components can be obtained. The floor response spectrum approach has three major limitations: (1) the dynamic interaction between the nonstructural components and the building structure is neglected; (2) nonstructural components that have multiple attachment points along the building height can not be properly considered; and (3) floor response spectra are valid only for linear systems.

Shake table testing is therefore often used for the seismic evaluation of nonstructural components and systems. A minimum response spectrum is specified for the horizontal and vertical directions by the current provisions such as IBC 2003, ATC 2004 and ATC 2005. Shake table testing can provide a realistic simulation of the seismic demand. However, the cost of constructing the structural system on a shake table for testing can be significant although only the nonstructural components are under investigation. Moreover, the structure is often scaled since very few shake tables have the capacity to apply earthquake forces to full-scale structures. Real-time hybrid simulation is an alternate approach, which divides a structural system into experimental substructure(s) and analytical substructure(s), and enables the complete structural system to be considered. The coupling between the experimental and analytical substructures is achieved by maintaining the compatibility and equilibrium at the interface between these substructures. Real-time hybrid simulation is therefore a viable and economical experimental technique, which has been recently used for investigating the dynamic response of structural systems (e.g., Wu et al. 2005, Jung and Shing 2007, Chen et al. 2008).

Of the different types of nonstructural systems, the seismic performance of piping systems is of special interest. These systems are expected to remain functional following earthquakes in order to mitigate post-earthquake fire hazards. During the 1994 Northridge earthquake, at least 13 hospitals suffered extensive water damage caused by failures of pressurized fire sprinkler and domestic water piping systems (Ayres and Philips 1997). The lack of bracing or inadequate bracing was cited as a major factor in the most significant failures of fire sprinkler systems during the 1994 Northridge earthquake (Fleming 1998). Two methods are currently used to design the bracing for piping systems (Stevenson 1998). The first is the *design by rule method* which determines the spacing between piping supports according to rules which implicitly assure that the stresses and deformations in the supports and piping are within the allowable limits. The second approach is the *design by analysis method*. In this method, the loads on the supports and stress resultants on the piping are computed by applying the seismic forces to the piping system with supports in combination with other loads and then evaluating the demands relative to the allowable stress values or factored resistance. Typically, the *design by rule method* is used for small-diameter piping and for areas of low seismicity.

Recently, new types of piping joints and bracing system have been developed by industry to improve the seismic performance of piping systems. To validate the performance of these devices when subject to strong ground motions, real-time multi-directional hybrid simulations are conducted on a building piping system in a three story moment resisting frame. This paper describes the test procedure, selected results and observations.

2. PROTOTYPE STRUCTURE AND TEST SETUP

The piping system investigated in this research is assumed to reside in a three story symmetrical regular-shaped moment resisting frame. The three-story building was designed specifically for this project, but represents a typical moment resisting frame. Figure 1(a) schematically shows the frame and the piping inside the building. The three story building frame has natural frequencies of 0.74, 0.88, 1.96, 2.26, 2.64 and 3.06 Hz, and is assumed to have Raleigh proportional damping of 2% for the first and fifth modes. For the purpose of performing the real-time hybrid simulations, the piping in the third floor is taken as the experimental substructure and physically tested (Figure 1(b)), while the rest of the piping system and the moment resisting frame are modeled analytically (Figure 1(c)). Since the building is symmetric in plan, the displacements due to torsional motion will be minimal relative to the translational displacements, and therefore torsion is not considered in the tests.

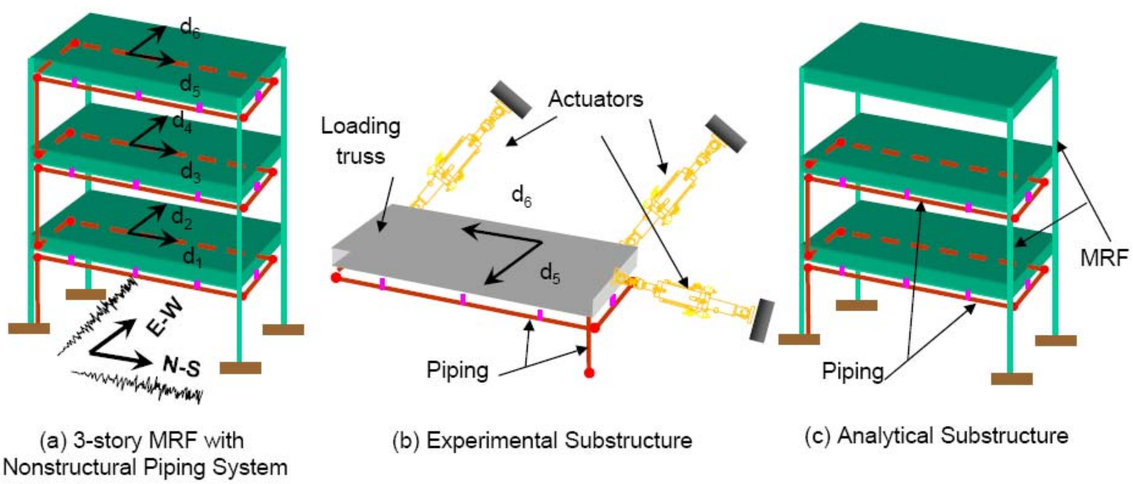

Figure 1 Schematic representation of real-time hybrid simulation of a building piping system

The piping system presented in this paper has a diameter of 406.4 mm (16 inch) and is filled with water pressurized to 1.38 MPa (200 psi). To improve the seismic performance of the piping system, a new type of grooved coupling joint developed by Victaulic Company is used in this research (Figure 2(a)). Rigid and flexible seismic bracing was designed by International Seismic Application Technology per the requirements of IBC2003 (ICC 2003) to attach the piping to the building structure in both the longitudinal and transverse directions of the pipe at various locations (Figure 2(b)). The piping system was supported vertically at multiple locations. Vertical displacement was not considered in this study since vertical accelerations are significantly lower than horizontal accelerations during earthquakes and also piping systems contain vertical support systems consisting of rod hangers and pipe clamps on fixed supports which have a relatively short spacing (compared to lateral supports/bracing).

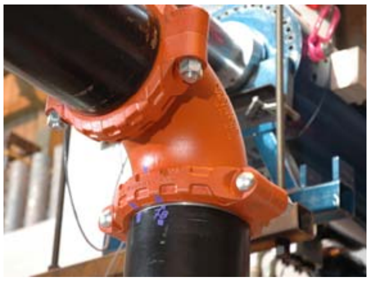

Figure 2(a) Groove coupling joint

Figure 2(b) Flexible seismic bracing

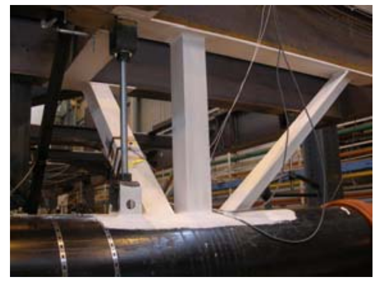

Figure 2(c) Rigid seismic bracing

For the test setup, a horizontal truss served as a rigid floor diaphragm. Controlled bi-directional displacements of the truss simulated the floor diaphragm motion in the real-time hybrid simulation (Figure 3). The truss was designed to support the expected peak lateral acceleration of 3g acting on the water-filled pipe with simultaneous dead load. The truss was sized for stiffness to ensure that its lowest localized natural frequency (approximately 45 Hz) was greater than the highest frequency of interest during the real-time hybrid simulation (around 33.3 Hz). The truss is 3.05 m (10 feet) wide by 12.19 m (40 feet) long, and is comprised of W16x33 chord members and HSS6x6x1/4 web members. The truss was suspended from overhead framing via four hanger rods, each 3.05 m (10 feet) long. The hanger rods are comprised of a 76 mm (3 inch) XS pipe with 50 mm (2-inch) thick heavy welded endplates on each end, into which ball-jointed rod ends were threaded. The suspension system allows the truss to move freely up to 305 mm (12 inches) in any direction with minimal vertical movement from the "swinging" motion.

Figure 3 Photograph of loading truss

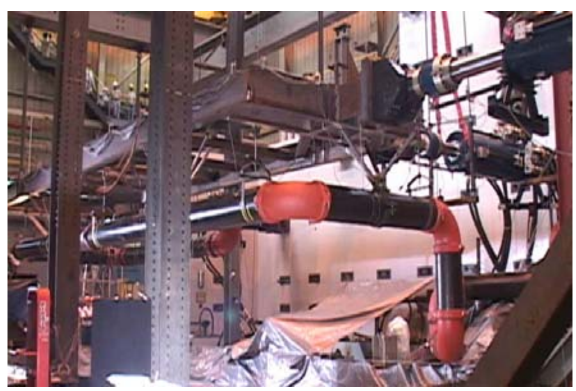

Figure 4 Photograph of test setup

The lower end of the piping system was fixed to the laboratory floor, while the upper end was attached to the horizontal truss used to impose the lateral loading. Three high load rate actuators were attached to the truss, one for longitudinal (i.e., north-south) motion, and two for transverse (i.e., east-west) motion, see Figure 1. Each actuator has a capacity of 1700 kN (380 kips) and a maximum velocity of 1.14 m/sec (45 inch/sec). Figure 4 shows a photograph of the test setup, where the loading frame, piping system, and the actuators are shown.

3. UNCONDITIONALLY STABLE EXPLIIT CR ALGORITHM AND INVERSE COMPENSATION

For the three story moment resisting frame with the piping system shown in Figure 1(a), the equation of motion for the entire structure can be expressed as

$$\mathbf{M}\cdot\ddot{\mathbf{x}}(t)+\mathbf{c}\cdot\dot{\mathbf{x}}(t)+\mathbf{r_a}(t)+\mathbf{r_e}(t)=\mathbf{F}(t) \tag{3.1}$$

In Eqn. 3.1, ***M***, ***C*** and ***K*** are the mass, viscous damping and linear elastic stiffness matrices of the moment resisting frame, respectively; $\ddot{\mathbf{x}}(t)$ and $\dot{\mathbf{x}}(t)$ are the acceleration and velocity response vector, respectively; $\mathbf{F}(t)$ is the external excitation force vector; and $\mathbf{r_a}(t)$ and $\mathbf{r_e}(t)$ are the restoring forces of the analytical substructures (3-story frame and piping on the first and second story) and the experimental substructure (piping on the third story), respectively.

An integration algorithm is used in real-time hybrid simulation to compute the structural response based on feedback restoring forces from the experimental and analytical substructures. Unlike an implicit integration algorithm, an explicit integration algorithm does not involve iteration within a time step and therefore has been used by numerous researchers for real-time hybrid simulation (Nakashima et al. 1992, Wu et al. 2005, Chen et al. 2008). However, the commonly used explicit integration algorithms that include the Newmark explicit method and the central difference method are only conditionally stable and consequently the time step size can become extremely small when the total number of degrees of freedom of the structural system is large, making real-time hybrid simulation difficult. For that reason, the unconditionally stable explicit CR integration algorithm (Chen and Ricles 2008) is used in this paper, of which the variation of displacement and velocity over the time step are defined as

$$\dot{\mathbf{x}}_{i+1}=\dot{\mathbf{x}}_i+\Delta t\cdot\boldsymbol{\alpha}_1\cdot\ddot{\mathbf{x}}_i \tag{3.2a}$$

$$\mathbf{x}_{i+1}=\mathbf{x}_i+\Delta t\cdot\dot{\mathbf{x}}_i+\Delta t^2\cdot\boldsymbol{\alpha}_2\cdot\ddot{\mathbf{x}}_i \tag{3.2b}$$

where Δt is the integration time step; $\boldsymbol{\alpha}_1$ and $\boldsymbol{\alpha}_2$ are integration parameter matrices; $\dot{\mathbf{x}}_{i+1}$ and $\mathbf{x}_{i+1}$ are the velocity and displacement response vector at the $(i+1)^{th}$ time step, respectively; and $\ddot{\mathbf{x}}_i$, $\dot{\mathbf{x}}_i$ and $\mathbf{x}_i$ are the acceleration, velocity and displacement response vector at the $(i)^{th}$ time step, respectively. Eqns. 3.2a and 3.2b indicate that the CR integration algorithm is explicit for both the displacement and velocity, making it well suited for application to real-time hybrid simulation. The integration parameter matrices α_1 and α_2 are determined using Eqn. 3.3 in matrix form, where

$$\boldsymbol{\alpha}_1=\boldsymbol{\alpha}_2=4\cdot\left[4\cdot\mathbf{M}+2\cdot\Delta t\cdot\mathbf{C}+\Delta t^2\cdot\mathbf{K}\right]^{-1}\cdot\mathbf{M} \tag{3.3}$$

A linear ramp generator is used in this study to smoothly impose the command displacement from the integration algorithm to the experimental substructure. The integration time step Δt is divided into n substeps, i.e., $\Delta t = n\ \delta t$, where δt is the sampling time of the servo-controller. The command displacement sent to the servo-controller for the $(i+1)^{th}$ time step is interpolated over the course of the time step by the linear ramp generator as

$$d_{i+1}^{c(j)}=\frac{j}{n}\cdot(x_{i+1}^e-x_i^e)+x_i^e \tag{3.4}$$

where j is the substep index of the ramp generator that ranges from 1 to n; x_{i+1}^e and x_i^e are command displacements for the experimental substructure calculated by the integration algorithm for the $(i+1)^{th}$ and i^{th} time steps, respectively; and $d_{i+1}^{c(j)}$ is the displacement command for the servo-hydraulic actuator at the j^{th} substep of the $(i+1)^{th}$ time step.

Unlike conventional hybrid simulation, command displacements in a real-time hybrid simulation are imposed by servo-hydraulic actuator(s) at a real-time scale. Due to their inherent servo-hydraulic dynamics, an actuator will introduce a time delay resulting in a desynchronization of the measured restoring force(s) of the physical substructure(s) with respect to the real-time hybrid simulation system. This time delay is often referred to as actuator delay, which can be ignored in a conventional hybrid simulation. In real-time hybrid simulation however actuator delay has been found by numerous researchers (Wallace et al. 2005, Chen and Ricles 2008) to be detrimental to the accuracy and stability of the simulation if not compensated properly.

Various compensation methods have been proposed to minimize the effect of actuator delay in a real-time simulation including linear acceleration extrapolation method (Horiuchi et al. 2001) and derivative feedforward compensation method (Jung and Shing 2007). An inverse compensation scheme proposed by Chen (2007) is utilized to minimize actuator delay in the real-time hybrid simulation, where the inverse compensator is defined by the following discrete transfer function:

$$G_c(z) = \frac{\alpha \cdot z - (\alpha - 1)}{z} \qquad (3.5a)$$

Applying the inverse discrete z-transform to the above inverse compensation leads to

$$d_{i+1}^{p(j+1)} = \alpha \cdot d_{i+1}^{c(j+1)} - (\alpha - 1) \cdot d_{i+1}^{c(j)} \qquad (3.5b)$$

where $d_{i+1}^{p(j)}$ is the predicted displacement to be sent to the servo-controller in real-time hybrid simulation to ensure that the actuator command displacement is achieved by the actuator. Eqn. 3.5b indicates that the predicted displacement in inverse compensation can be calculated using the current and previous substep interpolated command displacements $d_{i+1}^{c(j+1)}$ and $d_{i+1}^{c(j)}$.

4. REAL-TIME MULTI-DIRECTIONAL HYBRID SIMULATION RESULTS

A series of tests were performed to evaluate the performance of the piping system, of which the real-time multi-directional hybrid simulation results are presented in this paper. The two horizontal components CNP106 and CNP196 of the 1994 Northridge earthquake ground motion recorded at Canoga Park, CA were scaled to the MCE level (with peak ground acceleration of 0.36g and 0.42g) and applied in the N-S and E-W directions of the test setup, respectively, see Figure 1.

Figure 5 presents a comparison of the command and measured displacement response of the three servo-hydraulic actuators in the real-time multi-directional hybrid simulation. The East-West actuators have the maximum and minimum displacement of 68.93 mm (2.71 inch) and -66.98 mm (-2.64 inch), respectively. The North-South actuator reaches the maximum and minimum displacement of 61.28 mm (2.41 inch) and -66.85 mm (-2.63 inch), respectively. Good tracking of the actuators can be observed for all three actuators in Figure 5, indicating that the inverse compensation method negated the actuator delay in the real-time hybrid simulation. The loads measured in the actuators in Figure 6 are shown to be very small indicating that the nonstructural piping system does not transmit significant reaction force to the building structure.

During the hybrid simulation, there was no observable damage to the pipe system and pressure was maintained. It was observed that both the input motion generated by the actuators and the response of the piping system was characterized by low frequency content. A few of the bracing connections loosened slightly, but the integrity of the braces was maintained.

Upon dismantling of the piping system, the pipe groove couplings were examined for damage. Some of the couplings were observed to have been slightly ovalized. However, these couplings were subsequently pressure tested and were found to have maintained their integrity. The results of these tests indicate that piping systems connected with these new groove couplings are very robust and are not sensitive to the performance of the seismic bracing. It should be noted however, that proper design and installation of seismic bracing is important towards ensuring good seismic behavior of the piping system.

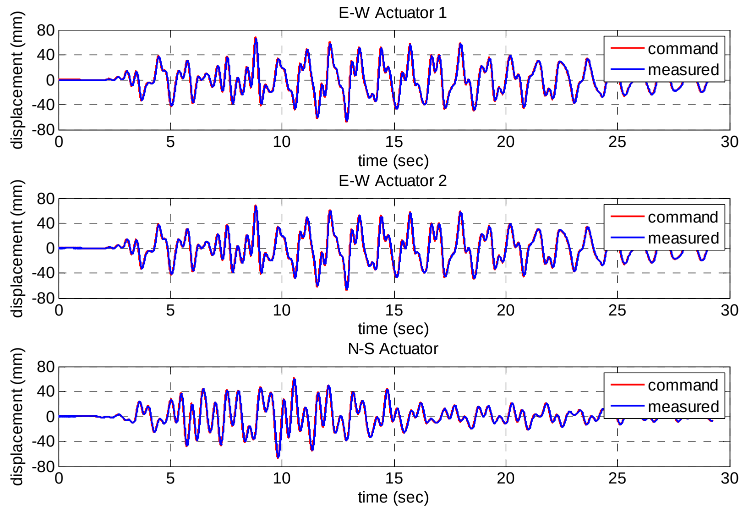

Figure 5 comparison of command and measured displacement response in real-time hybrid simulation

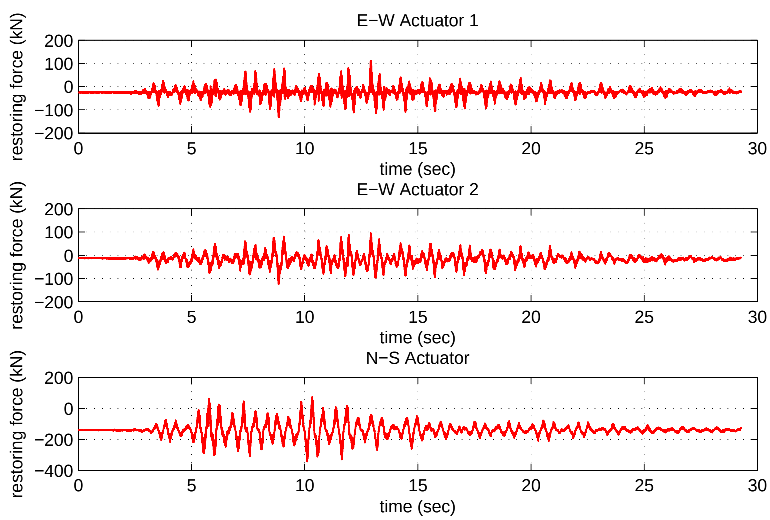

Figure 6 measured restoring forces in real-time hybrid simulation

5. SUMMARY AND CONCLUSIONS

Real-time hybrid simulation techniques are applied to investigate the seismic performance of a nonstructural piping system in a three story building structure. The piping system in the third story is separated as the experimental substructure and the frame with the remaining part of the piping system are modeled analytically. The explicit CR integration algorithm is used to compute the structural response and the inverse compensation is utilized to minimize the effect of actuator delay.

The pipe groove coupling joint and the seismic bracing exhibited excellent performance in the real-time hybrid simulation. No damage was observed in the piping system and the pressure in the pipe was maintained. These results indicate that carefully designed bracing and joint details can enable the piping system to sustain severe seismic demand. The comparison between the command and measured displacements show accurate actuator control in the real-time hybrid simulation. The application of real-time hybrid simulation for nonstructural components has been demonstrated, and offers a viable means to evaluate the seismic performance of nonstructural components and systems and to develop performance-based design criteria.

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