EXPERIMENTAL STUDY OF AN ADAPTIVE BASE ISOLATION SYSTEM FOR BUILDINGS

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SUMMARY

The research presented herein investigates the ability of an adaptive seismic isolation system to protect structures subjected to a variety of earthquake ground motions. The isolation system consists of sliding isolation bearings in combination with an adaptive hydraulic damper. The damping capacity of the hydraulic damper can be modified in real-time to respond to the effects of the earthquake ground motion. The results of the research have shown that, for a variety of earthquake ground motion characteristics, an adaptive sliding base isolation system is capable of simultaneously limiting the response of the isolation system and the superstructure. This paper concentrates on the experimental laboratory implementation of the adaptive isolation system within a scale-model building structure.

INTRODUCTION

Conventional seismic design is generally not acceptable for certain structures that must remain fully functional during a major earthquake (e.g., hospitals, fire stations, and emergency command centers). One approach to protecting such structures involves the installation of special seismic protection systems that ensure essentially elastic behavior of the structure during a major earthquake. For example, a seismic isolation system may be used to decouple the structure response from the ground motion while a supplemental damping system may be used to absorb a portion of the energy transferred into the structure. Alternatively, a hybrid isolation system consisting of base isolation bearings combined with supplemental dampers offers a very reliable and cost-effective approach to mitigating the effects of strong earthquake-induced ground motion. Recent applications of hybrid seismic isolation systems have utilized either elastomeric bearings or friction pendulum sliding bearings combined with fluid dampers (Constantinou et. al., 1998). There are limitations, however, to the performance of hybrid isolation systems. In particular, such systems may not perform well for structures that are prone to a wide variety of earthquake ground motions. For example, the ground motions associated with near-field and far-field earthquakes can be quite different. Thus, the most appropriate seismic isolation system design may be different for each type of ground motion. One approach to addressing the limitations of hybrid isolation systems is to replace the supplemental dampers with adaptive dampers. There are a variety of adaptive control elements for application within hybrid seismic isolation systems (e.g., see Symans and Constantinou (1998)).

Numerous researchers have studied adaptive base isolation systems for seismic protection of buildings. However, a majority of the adaptive isolation systems that have been proposed employ active control devices at the isolation level to control the structural response (Riley, 1996). As an alternative, semi-active control devices which require only a relatively small amount of power for operation could be used. The forces that develop in such devices are induced by the motion of the structure to which they are attached. The number of studies on adaptive isolation systems that employ semi-active control devices is relatively small with most of the work being analytical and/or numerical (e.g., see Fujita et. al. (1994), Nagarajaiah (1994), Yang et. al. (1995), Makris (1997), Johnson et. al. (1998), Sadek and Mohraz (1998) and Symans and Kelly (1999)). In general, it has been recognized that inappropriate levels of supplemental damping in a base isolation system can increase the response of the superstructure (e.g., see Makris (1997) and Kelly (1999)).

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Typically, a numerical study is more practical than an experimental study to evaluate the performance of different seismic protection systems. However, at some point an experimental study must be performed to verify the numerical results. This paper concentrates on an experimental study of the seismic response of a scale-model, steel building frame outfitted with a hybrid seismic isolation system. To the author's knowledge, the work presented herein represents the first experimental study of an adaptive semi-active seismic isolation system within the United States.

DESCRIPTION OF EXPERIMENTAL TEST SETUP

The experimental testing arrangement is shown in Figure 1. A scale-model, steel building frame (test structure) was mounted to a uniaxial seismic simulator. The seismic simulator and test structure have been described in detail by Twitchell (1998). The test structure can either be conventionally founded by fixing it to the simulator platform or can be retrofitted with various base isolation systems. The isolation system utilized in this study consisted of sliding isolation bearings combined with an adaptive fluid damper (see magnified view in Figure 1). The damper was controlled within a real-time, closed-loop feedback control system which utilized the measured response of the structure. A sophisticated data acquisition/control system was used to simultaneously record the measured data and to determine the appropriate level of damping within the isolation system. The desired damping level was determined via control algorithms which were designed to reduce the response of the structure. Additionally, the data acquisition/control system provided the earthquake ground motion signal for operation of the seismic simulator. The response of the structure was measured via accelerometers and displacement transducers. The displacement measurements were transformed to velocity measurements via analog differentiation.

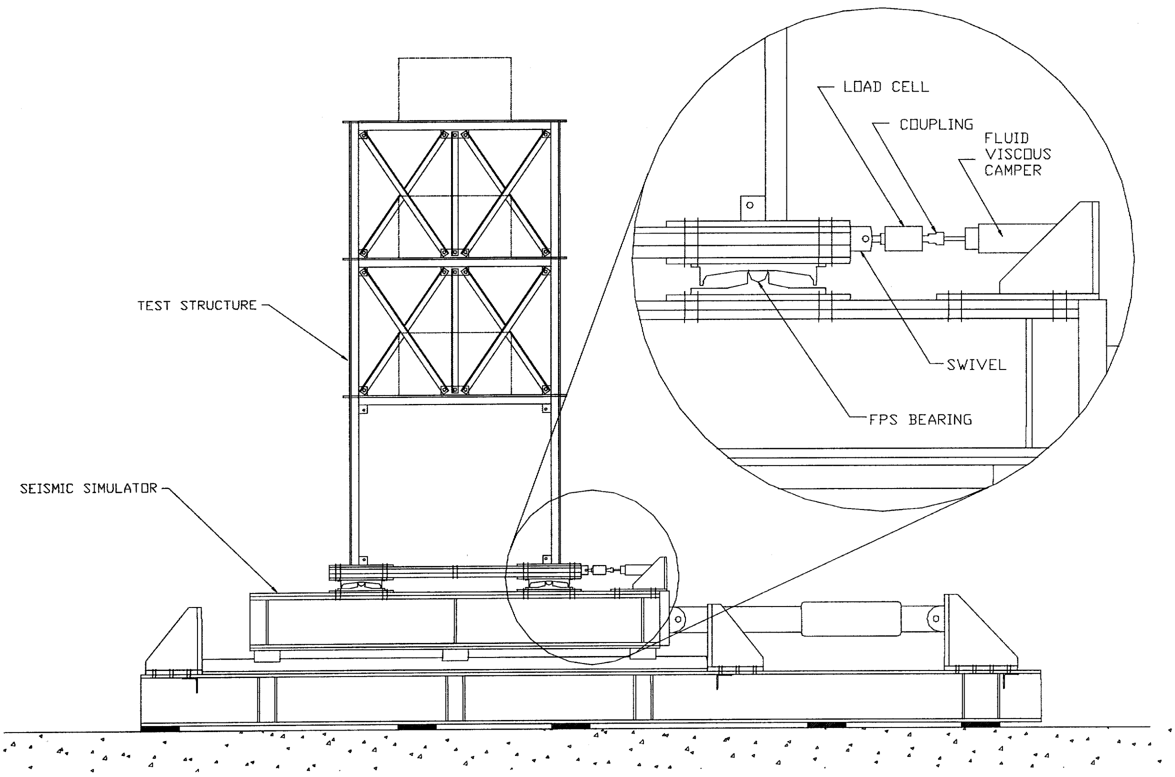


Figure 1 Test Structure Mounted on Seismic Simulator and Retrofitted with Adaptive Base Isolation System.

The test structure used in the experimental study was a 1:4 scale model of a hypothetical prototype structure. The structure is a one-bay by one-bay, three-story, steel moment-resisting frame. As shown in Figure 1, the test structure was rigidly braced at the top two stories so that the structure effectively behaved as a one-story structure. The weight of the test structure was estimated as 31.64 kN. The height of the first-story columns was 102 cm and the second moment of area of each of the columns about its axis of bending was 22.06 cm^4. The structure was tested as a fixed-base structure, a base-isolated structure, and a base-isolated structure with supplemental fluid dampers at the isolation level. As shown in Figure 1, the base-isolated configuration included a rigid basemat between the isolation bearings and the first story columns. The weight of the basemat was 7.76 kN. The dynamic properties of the test structure were determined via experimental system identification methods yielding a natural frequency and damping ratio of 3.95 Hz and 1.11%, respectively.

The adaptive seismic isolation system consisted of sliding bearings combined with an adaptive fluid damper. The sliding bearings were Friction PendulumTM System (FPS) Bearings which are a type of sliding bearing whose sliding surface is spherical (see magnified view in Figure 1). The sliding surface is faced with a highly polished stainless steel overlay and the slider is faced with a low-friction Teflon material. The displacement capacity of the bearings was ± 8.22 cm. The adaptive fluid damper consisted of a fluid-filled cylinder containing a piston which is connected to a piston rod (see magnified view in Figure 1). The damper may be described as an inertial force damper since energy is dissipated as heat as fluid is forced to pass through small orifices at high rates of speed. The damping capacity of the damper was modulated by controlling the size of the orifice. The displacement and force capacity of the damper was ± 3.81 cm and 8.9 kN, respectively.

The data acquisition/control system used in the experimental test program included MATLAB® software (MathWorks, 1997) and dSPACE® hardware and software (dSPACE, 1996). The software and hardware was installed on a desktop PC (Pentium/166 MHz/32 MB RAM). The MATLAB® software consisted of MATLAB (V. 5.2.1), SIMULINK® (V. 2) and REAL-TIME WORKSHOP® (RTW) (V. 3). The dSPACE hardware and software is used for real-time control of dynamic systems that have been designed using SIMULINK. The dSPACE hardware consisted of a Digital Signal Processor (DSP) board, a A/D converter board, and a D/A converter board. The dSPACE software consisted of REAL-TIME INTERFACE® (RTI) (V. 3.0), COCKPIT® (V. 3.1), and TRACE® (V. 3.1).

ANALYTICAL MODELS OF ISOLATION SYSTEM COMPONENTS AND ISOLATED STRUCTURE

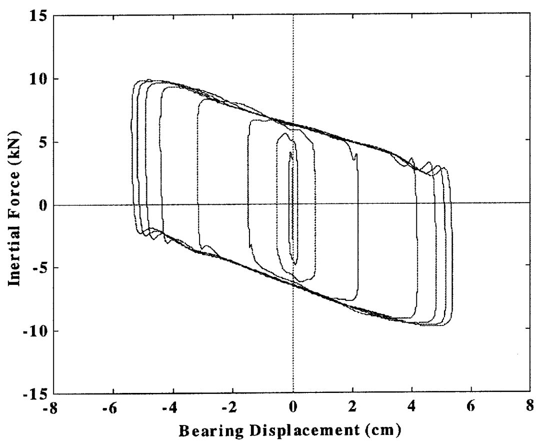
The resisting force developed in the sliding bearings may be written as the sum of a restoring force and a friction force:

$$F = \frac{W}{R}u + \mu W Z \tag{1}$$

where W is the weight of the structure, R is the radius of curvature of the spherical sliding surface (47.35 cm), u is the bearing displacement, μ is the coefficient of friction, and Z is a dimensionless viscoplasticity function that describes the hysteretic behavior of the friction force (Constantinou et. al., 1990). Note that the radius of curvature was selected so as to obtain a fundamental natural period of 2.75 sec at prototype scale. The velocity-dependent coefficient of friction is given by (Constantinou et. al., 1990):

$$\mu = \mu_{\max} - (\mu_{\max} - \mu_{\min})\, e^{-a|\dot{u}|} \tag{2}$$

where μ ranges from $\mu_{\max}$ at large velocities of sliding to $\mu_{\min}$ at very low velocities and a is a constant having units of time per unit length. A typical bearing hysteresis loop which was used to calibrate the analytical model is shown in Figure 2(a). Note that the loop shown in Figure 2(a) was obtained with the bearings installed at the base of the structure. The inertial force shown on the vertical axis of Figure 2(a) is the sum of the inertial forces in the test structure which is equal to the negative of the bearing resisting force. The parameters in Equation (2) were calibrated using a nonlinear regression analysis in which experimental data such as that shown in Figure 2(a) was utilized. The calibration procedure resulted in the following values for the parameters in Equation (2): $\mu_{\max}$ = 0.15, $\mu_{\min}$ = 0.08, and a = 0.2 sec/cm.



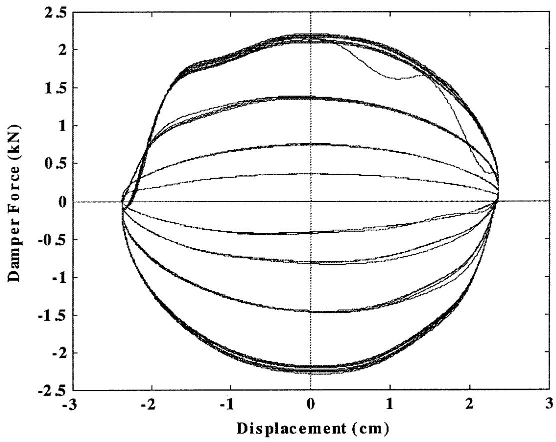


Figure 2 Force-Displacement Hysteresis Loops: (a) Sliding bearing and (b) Adaptive Fluid Damper.

The viscoplasticity function, *Z*, was obtained from the following first-order, nonlinear differential equation (Wen, 1976):

$$Y\dot{Z} + \gamma|\dot{u}|Z|Z|^{\eta-1} + \beta\dot{u}|Z|^{\eta} - A\dot{u} = 0 \tag{3}$$

where the five constants *Y*, *A*, β, γ, and η were calibrated using experimental data. The following values were selected for the constants: A = 1, $\beta = 0.1$, $\gamma = 0.9$, $\eta = 2$, and Y = 0.13 mm. Note that the overdot used in Equation (3) indicates first-order differentiation with respect to time.

The properties of the adaptive fluid damper were determined by subjecting the damper to steady-state sinusoidal motion and recording the resulting force. The size of the damper orifice was modulated via a control valve that was attached to the damper. The voltage supplied to the control valve was incrementally increased from 0 volts (maximum damping) to 3 volts (minimum damping) during each test. A typical force-displacement loop at a frequency of motion of 1 Hz is shown in Figure 2(b). The elliptical shape of the hysteresis loops shown in Figure 2(b) indicates that a suitable model to describe the dynamic behavior of the adaptive fluid damper is given by the simple linear viscous dashpot model with a variable damping coefficient:

$$F_d = C\dot{u} \tag{4}$$

where F_d is the damper force and C is the damping coefficient which can be written in the following form (Symans and Constantinou, 1997):

$$C = C_{\min} + (C_{\max} - C_{\min})e^{(-\zeta V^{\varphi})} \tag{5}$$

where $C_{\min}$ and $C_{\max}$ are the minimum and maximum damping coefficient, respectively, V is the command voltage to the control valve, and ζ and φ are dimensionless constants. The parameters in Equation (5) were calibrated using a nonlinear regression analysis in which experimental data such as that shown in Figure 2(b) was utilized. The calibration procedure resulted in the following values for the parameters in Equation (5): $C_{\min}$ = 36 N-sec/cm, $C_{\max}$ = 150 N-sec/cm, ζ = 0.11 and φ = 4.20.

The equations of motion for the isolated structure can be written in state-space format as

$$\{\dot{x}\} = \begin{bmatrix} [0] & [I] \\ [-[M]^{-1}[K]] & [-[M]^{-1}[C]] \end{bmatrix} \{x\} + \begin{bmatrix} \{0\} & \{0\} \\ \{-[M]^{-1}\{n\}\} & \{-[M]^{-1}\{n\}\} \end{bmatrix} \begin{Bmatrix} F_f \\ F_d \end{Bmatrix} + \begin{Bmatrix} \{0\} \\ -\{n\} \end{Bmatrix} \ddot{u}_g \tag{6}$$

where $\{x\}$ is the state vector, $[M]$, $[K]$, and $[C]$ are mass, stiffness, and damping matrices, respectively, $\{n\}$ is a force location vector, F_f is the friction force developed in the sliding bearings (i.e., the second term on the right-hand side of Equation (1)), F_d is the linear viscous force applied at the basemat by the fluid damper (see Equation (4)) and $\ddot{u}_g$ is the ground acceleration. A more compact form of Equation (6) is given by

$$\{\dot{x}\} = [A]\{x\} + [B]\{f_1\} + [E]\{f_2\} \tag{7}$$

where $[A]$ is the system matrix and $[B]$ and $[E]$ are the input location matrices for input vectors $\{f_1\}$ and $\{f_2\}$, respectively.

CONTROL ALGORITHMS

Three different control algorithms were utilized in the experimental test program. The first two were system-independent while the third was system-dependent. As a result, the third control algorithm typically outperformed the first two and thus will be discussed herein. A description of the first two algorithms is provided by Madden (1999). The Sliding Mode Control (SMC) Algorithm described herein is a system-dependent algorithm (i.e., the control algorithm requires reliable estimates of the properties of the structure). The goal of sliding mode control (a.k.a., the theory of variable structure system (VSS) (Utkin, 1992)) is to design a controller to drive the response of the structure toward a stable surface within the state space and to keep the response on the stable surface. The stable surface is often referred to as the sliding surface because, once the response trajectory is on the surface, the controller is designed to slide the response toward the desired response (i.e., toward the origin of the state-space) (Yang et. al., 1994). For the work described herein, the sliding surface was determined by using the linear quadratic regulator (LQR) method with minimization being imposed on the combined kinetic and potential energy of the structure. After defining the sliding surface, the controller required for driving the state vector onto the sliding surface was determined by Lyapunov's direct method. The damper force must be determined such that rate of change of the Lyapunov function is negative semi-definite which ensures that the response of the system will decrease. As shown in the work by Madden (1999), the damper force may be written as

$$F_d = \alpha G - \delta \Phi \tag{8}$$

where α is a unitless constant (used to ensure that the damper force is not so large that the isolation effect is reduced to the point that significant interstory drifts occur in the structure), δ is the sliding margin (used to ensure that the rate of change of the Lyapunov function is negative semi-definite) and Φ and G are state-dependent scalars. The state-dependent damper force of Equation (8) is divided by the damper velocity to determine the desired damping coefficient (see Equation (4)). The desired damping coefficient is designed to saturate below $C_{\min}$ and above $C_{\max}$. Based on the desired damping coefficient, the required control valve voltage signal is determined from Equation (5).

EXPERIMENTAL VERIFICATION OF ANALYTICAL MODELS

The validity of the analytical models can be assessed by comparison of numerical simulation results with experimental test data. The validation of the analytical models is important since the results of the numerical simulations (as obtained from the solution of Equation (7)) were utilized to draw conclusions about the performance of the adaptive seismic isolation system. Although not discussed in detail herein, the numerical simulations generally showed that, for both far-field and near-field motions, the adaptive system was capable of simultaneously controlling the response of the isolation system and the superstructure. Indeed, when compared with the response of the isolated structure with maximum damping, the adaptive system reduced the interstory drift response while allowing limited increases in the bearing displacements. Further details on the numerical simulation results and their implications are available in the work by Madden (1999). Of course, conclusions drawn from numerical simulations are only as good as the analytical models that are used to perform the simulations. Thus, numerical simulations must be validated via experimental testing.

Five different historical earthquake records were used in the experimental test program. Experimental and numerical results are compared herein only for two of the earthquake records: the S00E component of the El Centro record from the 1940 Imperial Valley earthquake and the NS component of the Rinaldi record from the 1994 Northridge Earthquake. Note that the El Centro record may be regarded as a typical far-field earthquake ground motion while the Rinaldi record represents a near-field, pulse-type ground motion. The results of the numerical simulations and the experimental test data are compared herein for the case of the base-isolated structure with adaptive supplemental damping controlled according to the SMC algorithm. Figure 3 shows the time-histories of the bearing displacement, interstory drift response, isolation system hysteresis loop, and damper force for the structure subjected to 100% of the El Centro record and 35% of the Rinaldi record. As can be seen in Figure 3, the analytical predictions match the experimental results reasonably well. The analytical predictions for the tests with the El Centro record as input (see Figure 3(a)) are generally very similar to the experimental data. In the case where the Rinaldi record was used as input (see Figure 3(b)), the analytical predictions are generally good except that the bearing displacement exhibits a vertical shift (although the shape of the predicted bearing displacement time-history is similar to the experimental data). In general, the comparisons shown in Figure 3 indicate that the analytical models of the isolation system components and the test structure provide reasonable representations of the physical systems. Although the use of adaptive dampers leads to a more complex, nonlinear dynamic system, Figure 3 indicates that the ability to predict the experimental results is not hindered by the increased complexity.

CONCLUSIONS

An adaptive seismic isolation system was developed and implemented within a scale-model building frame. The implementation of such a system was complex due to the requirement for real-time control of the isolation system. The real-time control operations were carried out using a sophisticated data acquisition and control system which allowed for seamless integration of the design and implementation of the control system. Analytical models of the isolation system components and the test structure were developed. In turn, experimental tests were performed to validate the results from numerical simulations which utilized the analytical models. In general, the analytical predictions compared reasonably well with the experimental test data. Furthermore, the numerical simulations generally showed that, for a wide variety of earthquake ground motion characteristics, an adaptive sliding base isolation system is capable of simultaneously limiting the response of the isolation system and the superstructure. To the author’s knowledge, the experimental work presented herein represents the first application of an adaptive semi-active seismic isolation system in an experimental test structure within the United States.

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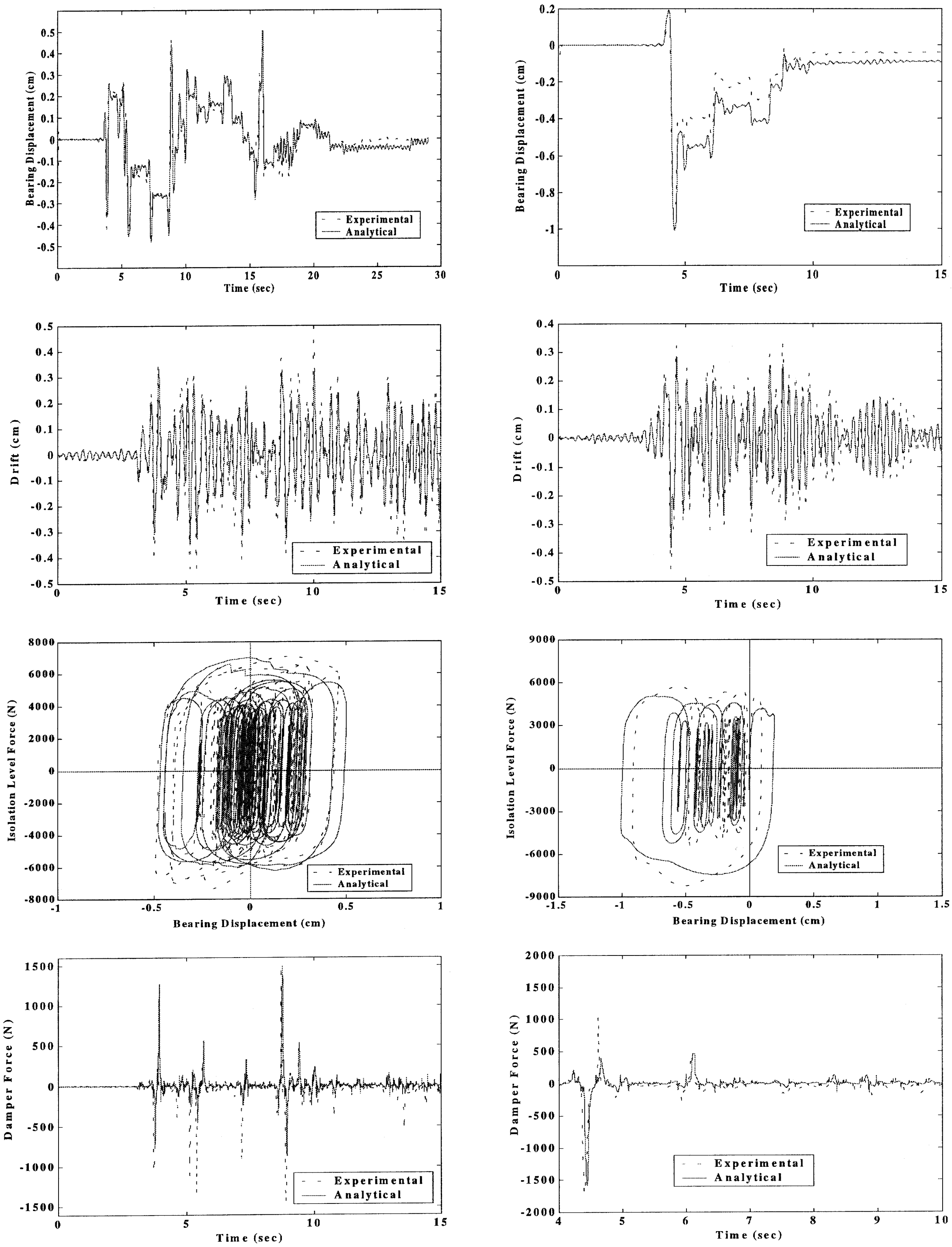

(a) (b)

Figure 3 Experimental and Analytical Results for Base-Isolated Structure with Adaptive Damping (SMC Algorithm) Subjected to (a) 100% of the El Centro Record and (b) 35% of the Rinaldi Record.