# Real-Time Hybrid Simulations of a Large-Scale Steel Frame Building with Magneto-Rheological Dampers

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**SUMMARY:**
Real-time hybrid simulations of a steel frame building with large-scale magneto-rheological (MR) dampers are conducted to evaluate the performance of various structural control algorithms in reducing the response of a structure under earthquake loads. A 3-story steel frame building with two large-scale MR dampers is designed based on a simplified design procedure (SDP) to satisfy specified performance objectives for selected seismic hazard levels. The two large-scale MR dampers are comprised of the experimental substructure and the remaining structural system is modeled analytically using nonlinear structural elements. Various damper control strategies, including passive and semi-active control are included in the simulations to control the response of the 3-story building under seismic loading. Five ground motions scaled to the design basis earthquake (DBE) are used for the real-time hybrid simulations. The assessment of the performance involved comparing the statistics of the response of the structure for the various controllers. Results from the real-time hybrid simulations are presented and discussed, and comparisons are made with nonlinear time history analysis using OpenSees.

*Keywords: real-time hybrid simulation, magneto-rheological damper, semi-active control*

## 1. INTRODUCTION

Various control strategies for structures with MR dampers are evaluated in this paper through real-time hybrid simulations. MR dampers are one of the more popular semi-active devices. The MR damper can be controlled by adjusting the input current into the damper. Many researchers have studied the behavior of structures with MR dampers, using semi-active control strategies to mitigate seismic hazards. Most of these studies are comprised of numerical simulations with small-scale MR dampers. Thus, there is a need to investigate the behavior of structures with large-scale MR dampers for earthquake hazard mitigation of the civil infrastructure.

In this paper a 3-story building with two large-scale MR dampers is used for the evaluation of the structural control strategies. The 3-story building is designed based on the simplified design procedure (SDP) considering a strength requirement and drift limit (Chae 2011). Five different ground motions are selected and scaled to the design basis earthquake (DBE). Five different control strategies that include passive and four different semi-active controllers are selected and evaluated. The performance of each control method under the DBE ground motions is assessed by comparing the statistics of the response of the structure obtained from the real-time hybrid simulations. The real-time hybrid simulation results are validated by comparing them to numerical simulations using OpenSees (2010).

## 2. PROTOTYPE 3-STORY BUILDING

The 3-story building used for the study is shown in plan and elevation in Figure 2.1. The building has two perimeter moment resisting frames (MRFs) and internal braced bays with MR dampers (called damped brace frames (DBFs)) along each of side of the building at the 2nd and 3rd stories. The structure is designed using the simplified design procedure developed by Chae (2011) to achieve a performance objective of 1.5% story drift and 2.5% story drift under the DBE and maximum considered earthquake (MCE), respectively. The MCE ground motion is represented by a response spectra that has a 2% probability of exceedance in 50 years, and the DBE ground motion is 2/3rd the intensity of the MCE ground motion. (FEMA 2003). The 3-story building was scaled using a scale factor of 0.6 for the study since a reduced scale model of the building will be constructed and tested in the laboratory in future research studies.

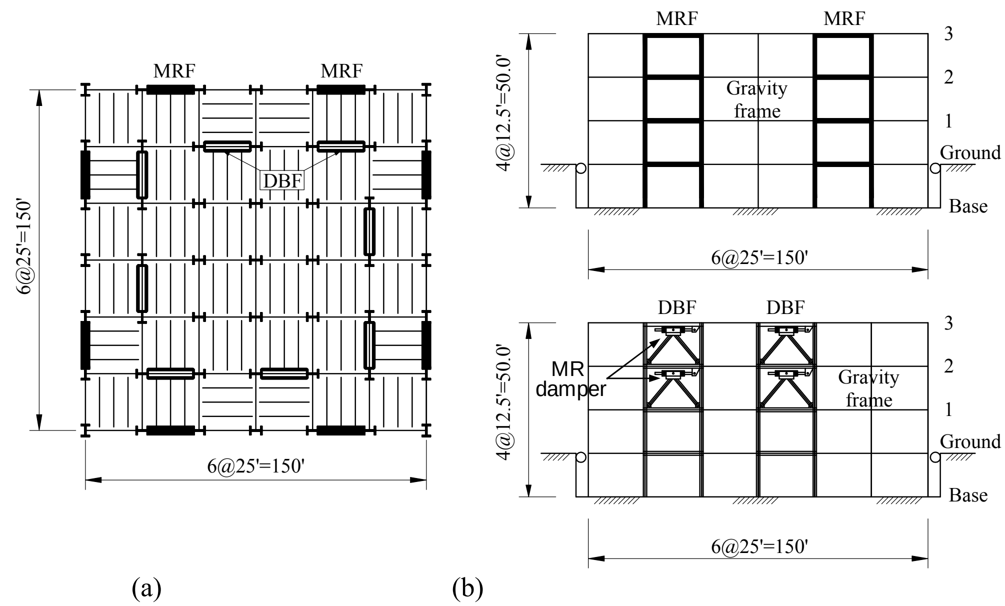


**Figure 2.1.** Prototype 3-story building structure for real-time hybrid simulations: (a) floor plan; (b) elevation

The members of the MRF are proportioned using a weak beam-strong column design. Yielding is expected to occur predominately at the ends of the MRF beams and at the base of the columns in the first story of the MRF and DBF under the DBE. The beams and diagonal bracing members in the DBF have pin-ended connections. The member size for the 0.6-scale building is summarized in Table 2.1.

**Table 2.1.** Member size for 0.6-scale building

| Story (Floor Level) | MRF | | DBF | | | Gravity Frame | |
|---|---|---|---|---|---|---|---|
| | Column | Beam | Column | Beam | Diagonal bracing | Column | Beam |
| 1 | W8X67 | W18X46 | W10X33 | W10X30 | - | W8X48 | W8X40 |
| 2 | W8X67 | W14X38 | W10X33 | W10X30 | W6X20 | W8X48 | W8X40 |
| 3 | W8X67 | W10X17 | W10X33 | W10X30 | W6X20 | W8X48 | W8X40 |

## 3. REAL-TIME HYBRID SIMULATIONS

The real-time hybrid simulations of this study are conducted at Lehigh NEES Real-Time Multi-Directional (RTMD) Equipment Site. Figure 3.1 shows a schematic of the real-time hybrid simulations for this study. Real-time hybrid simulation combines physical testing and numerical simulation, such that the dynamic performance of the entire structural system can be considered during the simulation. In this paper, the MR dampers are modeled as an experimental substructure while the remaining part of the structural system is modeled analytically (and referred to as the analytical substructure). During the real-time hybrid simulation, the coupling between the experimental and analytical substructures is achieved by maintaining compatibility and equilibrium at the interface between these substructures.

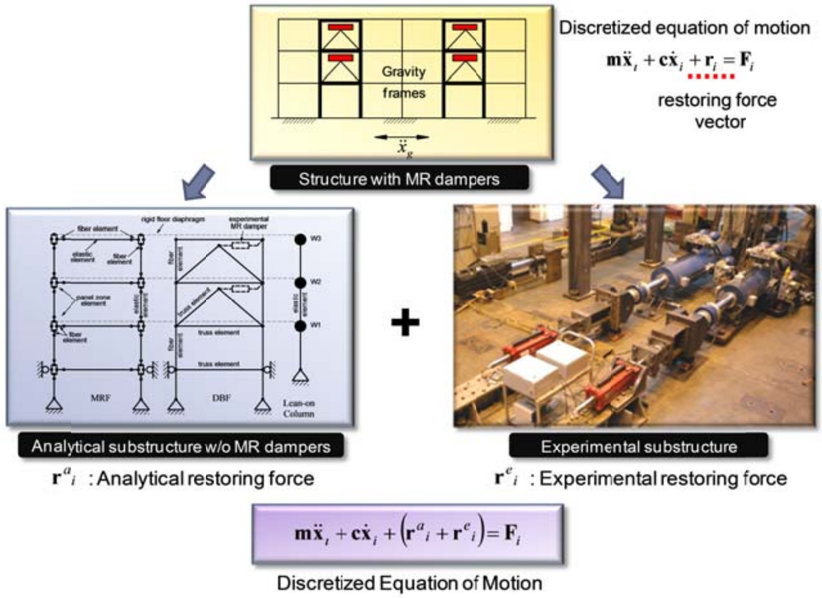


**Figure 3.1.** Schematic of real-time hybrid simulation for a structure with MR dampers: analytical and experimental substructures

The analytical and experimental substructures, the integration algorithm, the servo-hydraulic actuators, and associated controllers combine together to form the frame work for a real-time hybrid simulation. The explicit unconditionally stable CR integration algorithm (Chen and Ricles 2008) is used to solve the equations of motion. The robust nonlinear finite element code HybridFEM (Karavasilis et al. 2009) is used to develop the analytical substructure and interface it with the experimental substructure. In order to minimize actuator delay due to the dynamics of hydraulic actuators that are used in the simulations, the inverse compensation method (Chen and Ricles 2010) is employed for the control of the actuators during the real-time hybrid simulations. The sampling rate for the control of actuators and collection of data is 1024Hz.

### 3.1. Analytical Substructure

Taking advantage of symmetry, it is necessary to consider only one-quarter of the floor plan of the prototype structure in the real-time hybrid simulations. In Figure 3.1, the MRF, gravity frames, and the DBF within the one-quarter of the floor plan are modeled analytically. The structural model for this analytical substructure is shown in Figure 3.2. The beams are axially restrained in the DBF by the floor diaphragm (which is assumed to be rigid in-plane) at each floor level. The gravity load frames are represented by a lean-on column with P-Δ effects. At each floor level the inertial force due to the floor mass is transferred to the MRF and DBF through the rigid floor diaphragm connected to the lean-on column.

The beams and columns of the MRF structure are modeled with a distributed plasticity displacement-based beam-column element with five fiber sections along the element length. Each fiber is modeled with a bilinear stress-strain relationship with a small post-yielding stiffness. The beam-column joints are modeled using a panel zone element, where shear and symmetric column bending deformation modes are considered (Seo et al. 2009). The gravity loads from the tributary gravity frames at each floor level are applied to the lean-on column to account for the P-Δ effect of the building. Only horizontal ground motions are applied to the building; hence, only a horizontal mass is defined at each floor level, and located at the lean-on column. The first three natural periods of the scaled structure used in the simulations are $T_1$= 0.94sec, $T_2$ = 0.30sec and $T_3$= 0.13sec. Rayleigh damping is used to model the inherent damping of the building with a 5% damping ratio for the 1st and 2nd modes. More details about the structural modeling can be found in Chae (2011).

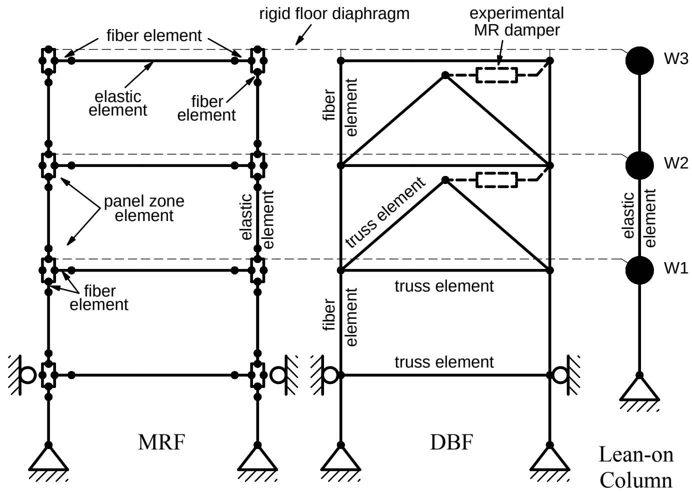


**Figure 3.2.** Analytical substructure model for real-time hybrid simulations (dampers of experimental substructure indicated for clarity)

## 3.2. Experimental Substructure

The two large-scale MR dampers for the experimental substructure were manufactured by Lord Corporation. Figure 3.3 shows the experimental test setup for the real-time hybrid simulations. The length and available stroke of each damper are 1.5m and ±279mm, respectively. Each damper can generate a force of about 200kN at a piston velocity of 0.1m/sec under a current input of 2.5A.

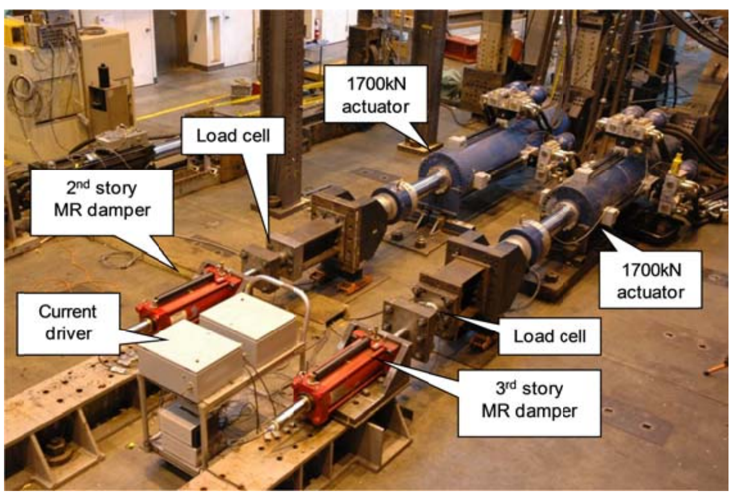


**Figure 3.3.** Experimental substructure with two MR dampers

The experimental setup consists of two primary parts: i) a hydraulic actuator and test fixtures to control the movement of the MR damper; and ii) electrical hardware to supply an appropriate current to the damper for the control of the damper force. The MR damper is connected to the hydraulic actuator through a stiff horizontal steel section. This is done in order to extend the arm of the actuator piston to accommodate the spacing of anchor locations for threaded rods that secure the damper and actuator to the laboratory strong floor. The maximum force capacity of the actuator is 1,700kN; with the actuator having the ability to generate approximately 500kN of force at a piston velocity of

1.0m/sec with three servo-valves. Each servo-valve has a maximum flow rate of 2082 lpm (550 gpm) at 20.7MPa (3000 psi). A 534kN load cell is installed between the horizontal steel section and the damper piston to directly measure the force developed in the damper. The current going into the damper is controlled by a pulse width modulation (PWM) type current driver manufactured by Advanced Motion Controls (30A8). The PWM servo-amplifier can supply current to the electrical circuit up to 30A by driving the DC motor at a high rate of switching frequency (22kHz).

## 4. CONTROL ALGORITHM

In this study, four different semi-active controllers are used: i) linear quadratic regulator (LQR); ii) sliding mode control (SMC); iii) decentralized bang-bang (DBB) control; and iv) phase angle control (PAC). A more detailed description and design procedure for these semi-active control algorithms applied to the 3-story building structure can be found in Chae (2011). The maximum command current input to the damper $I_{max}$ is 2.5A. For the passive control of an MR damper, a constant current of 2.5A is supplied to the damper, while an on-off type command current (i.e., either 0.0A or 2.5A) is used for the semi-active controllers.

## 5. GROUND MOTIONS

Five ground motions among 44 far-field ground motions in FEMA P695 (ATC 2009) were selected for the real-time hybrid simulations and are listed below in Table 5.1. The ground motions are scaled to the DBE level using the procedure by Somerville et al. (1997). Since the structure is scaled down with a geometric scale factor of 0.6, the time axis for the ground motion is scaled by √0.6 during each real-time hybrid simulation to satisfy similitude laws, where the scaled structure is assumed to have the same material properties and amplitude of acceleration as the prototype structure. Response spectra of these scaled ground motions are shown in Figure 5.1.

**Table 5.1.** Ground motions for real-time hybrid simulations

| EQ name | Year | Station | DBE scale factor |
|---|---|---|---|
| Superstition Hills | 1987 | Poe Road (temp) | 1.71 |
| Duzce, Turkey | 1999 | Bolu | 0.64 |
| Landers | 1992 | Coolwater | 2.15 |
| Imperial Valley | 1979 | El Centro Array #11 | 1.95 |
| Northridge | 1994 | Canyon Country-WLC | 1.16 |

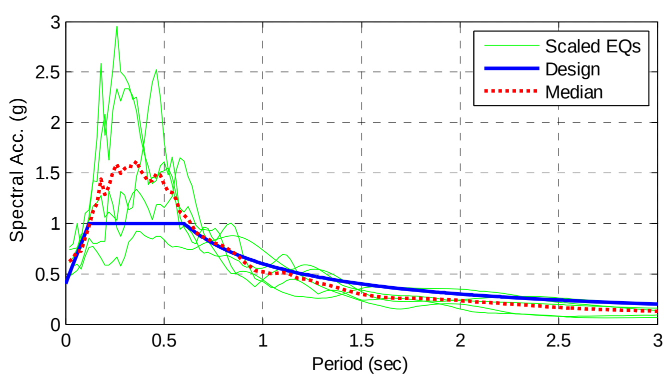


**Figure 5.1** Response spectrum of ground motions scaled to DBE

## 6. REAL-TIME HYBRID SIMULATION RESULTS

The five different ground motions and five different control strategies considered in the real-time hybrid simulations to evaluate the performance of the structural control strategies resulted in a total of 25 real-time hybrid simulations being conducted. A more rational assessment of the control strategies is based on the statistics of the response results for the various ground motions to account for the record-to-record variability of ground motions.

**Table 6.1.** Comparison of median maximum story drift from real-time hybrid simulations (RTHS) and numerical simulations (OpenSees)

| Control | | Median maximum story drift (%) | | |
|---|---|---|---|---|
| | | 1st story | 2nd story | 3rd story |
| No damper (OpenSees) | | 1.10 | 1.77 | 2.49 |
| Passive | RTHS | 1.17 | 1.33 | 1.52 |
| | OpenSees | 1.18 | 1.36 | 1.48 |
| LQR | RTHS | 1.11 | 1.37 | 1.63 |
| | OpenSees | 1.16 | 1.40 | 1.53 |
| SMC | RTHS | 1.14 | 1.34 | 1.52 |
| | OpenSees | 1.15 | 1.37 | 1.49 |
| DBB | RTHS | 1.16 | 1.34 | 1.55 |
| | OpenSees | 1.15 | 1.38 | 1.51 |
| PAC | RTHS | 1.15 | 1.38 | 1.63 |
| | OpenSees | 1.13 | 1.37 | 1.52 |

**Table 6.2.** Comparison of median maximum absolute acceleration from real-time hybrid simulations (RTHS) and numerical simulations (OpenSees)

| Control | | Median maximum absolute acceleration (g) | | |
|---|---|---|---|---|
| | | 1st floor | 2nd floor | 3rd floor |
| No damper (OpenSees) | | 0.65 | 0.68 | 0.67 |
| Passive | RTHS | 0.51 | 0.56 | 0.63 |
| | OpenSees | 0.46 | 0.56 | 0.61 |
| LQR | RTHS | 0.47 | 0.52 | 0.58 |
| | OpenSees | 0.45 | 0.52 | 0.62 |
| SMC | RTHS | 0.47 | 0.56 | 0.62 |
| | OpenSees | 0.45 | 0.52 | 0.60 |
| DBB | RTHS | 0.51 | 0.56 | 0.63 |
| | OpenSees | 0.44 | 0.55 | 0.61 |
| PAC | RTHS | 0.50 | 0.56 | 0.60 |
| | OpenSees | 0.51 | 0.53 | 0.60 |

The median of the maximum story drift and maximum absolute acceleration from the real-time hybrid simulations are given in Tables 6.1 and 6.2, respectively. When the building has MR dampers installed, it is seen that the performance of the building is improved for all control algorithms. These results clearly show the benefit of using dampers to suppress the vibration of the building. However, the median maximum story drifts for the various semi-active controllers do not show significant differences. The median maximum first story drift for the passive control case is slightly larger than that for the semi-active control cases, while the median maximum second and third story drifts are slightly lower for the passive control case than for the semi-active control cases.

Similar to the story drift results, no significant difference between the results for the various controllers is observed in the median maximum absolute accelerations. The maximum absolute acceleration is used to evaluate the non-structural component behavior and potential damage in the building. For the maximum absolute acceleration, the LQR controller has a slightly better performance than the passive control for all three floors. The median value of the maximum absolute acceleration at the 3$^{rd}$ floor level, where the maximum acceleration is observed, is about 7.5% less than that for the passive control case. However, the maximum 3$^{rd}$ story drift for the LQR controller is increased by about 7.2% compared to the passive control case, illustrating a trade-off between the maximum displacement and maximum absolute acceleration response.

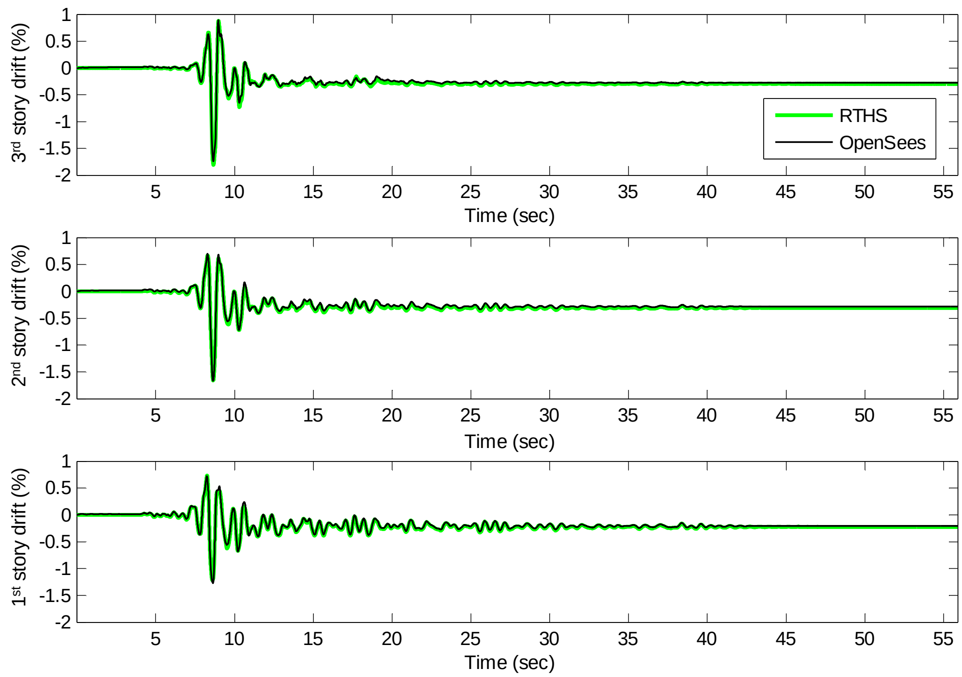


**Figure 6.1.** Comparison of story drifts between RTHS and OpenSees; Duzce EQ ground motion, LQR control

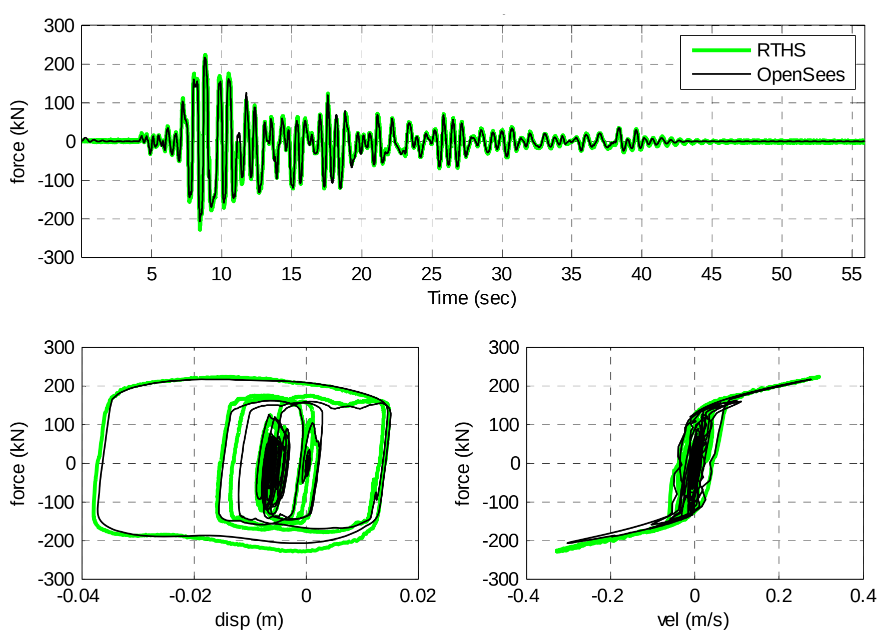


**Figure 6.2.** Comparison of the 2nd story MR damper response (Duzce ground motion; LQR Control)

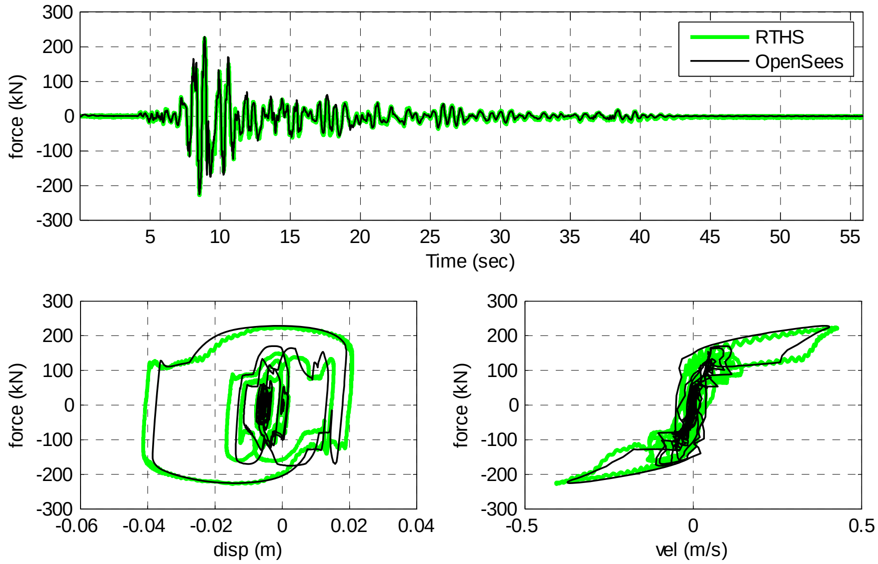


**Figure 6.3.** Comparison of the 3rd story MR damper response
(Duzce ground motion; LQR Control)

Numerical simulations were also conducted using OpenSees with the Maxwell Nonlinear Slider (MNS) MR damper model (Chae et al. 2012a and 2012b) to check and compare with the results from the real-time hybrid simulations. The median responses from the numerical simulations are included in Tables 6.1 and 6.2. Good agreement is observed between the real-time hybrid simulation results and the numerical simulation results. Figures 6.1 through 6.3 compare the story drift and the response of MR dampers when the structure is subjected to the 1999 Duzce, Turkey earthquake. In the comparison, the LQR controller is used for the control of the MR dampers. Again, the results from real-time hybrid simulation show good agreement with the results from OpenSees, validating the results of the real-time hybrid simulations of this study. More comparisons between the real-time hybrid simulation and OpenSees can be found in Chae (2011).

## 7. CONCLUSIONS

In this paper real-time hybrid simulations were performed on a 3-story building with MR dampers to assess the effectiveness of various structural control algorithms on enhancing structural performance under seismic loading. Real-time hybrid simulations were conducted, and the results were validated through numerical simulations with OpenSees. In order to account for record-to-record variability in the ground motions, five different ground motions were selected and scaled to the DBE hazard level, and the response of the building was studied with this ensemble of ground motions. The statistical results for response from the real-time hybrid simulation showed that the overall performance of semi-active controllers is similar to the passive controller for the 3-story building used in this study. No significant improvement of the structural performance was observed by using the semi-active control algorithms compared to using passive control.

It should be noted however that the conclusions made in this paper is based on the 3-story building structure with a limited number of input ground motions and semi-active controllers. To derive more general conclusions on the performance of semi-active controllers, it is necessary to use a larger number of ground motions and to include more semi-active controllers that can consider the nonlinearity of structural systems. Moreover, the effect of user-defined variables in the semi-active control algorithm, such as **Q** and **R** in the LQR (Chae 2011), need to be investigated because the performance of semi-active controllers can be different, depending on the values for the elements in these weight matrices. Finally, the geometry of the structure (e.g., building height, floor plan, plan layout of lateral load resisting frames) needs to be investigated.

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