12th National Conference on Earthquake Engineering
Salt Lake City, Utah
27 June - 1 July 2022
Hosted by the Earthquake Engineering Research Institute

Real-time Hybrid Simulation of Pulse-type Ground Motions Effects on Steel Building with Nonlinear Viscous Dampers

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ABSTRACT

This paper investigates the effects of near-fault pulse-type ground motions on the structural response of a 3-story steel structure with nonlinear viscous dampers using the real-time hybrid simulation (RTHS) testing method. The real time loop of action and reaction between the experimental and numerical partitions executed in the RTHS enabled the accurate capturing of the velocity pulse effects of pulse-type ground motions. An ensemble of 10 natural pulse-type ground motions at the design basis earthquake (DBE) level is used for the RTHS. The accuracy of RTHS under high velocity loading is demonstrated, and thereby, is a validated method for experimentally investigation of the complicated structural behavior of structures with rate-dependent damping devices. The test results showed that the dampers are essentially effective in earthquake hazard mitigation effects involving pulse-type ground motions. The average peak story drift ratio under the set of pulse-type ground motions is 1.08% radians with a COV value less than 0.3, which indicates that the investigated structure would achieve the ASCE 7-10 seismic performance objective for Occupancy Category III structures under the DBE level pulse-type ground motions.

Introduction

Advanced damping technology has been demonstrated promising for seismic response mitigation to enable performance-based seismic engineering, and therefore, is believed can be utilized to mitigate the effects of pulse-type ground motions on structural response. Pulse-type ground motions have a pulse in the velocity time history which is usually referred to as the forward-directivity effect [1]. It has been demonstrated that pulse-type ground motions are more likely to cause structural damage than ordinary far-field ground motions [2-3]. Nonetheless, there is a knowledge gap in understanding the complex behavior of advanced damping devices when integrated into structures, particularly under pulse-type ground motions. Effective implementation of these advanced rate-dependent damping devices requires real-time large-scale testing for performance validation. The recently developed RTHS method allows complex structural systems with large-scale, nonlinear hysteretic structural elements, and rate dependent components to be tested by substructure partition.

This paper presents an experimental investigation of rate-dependent structural response under pulse-type ground motions using the RTHS method that has vast potential to capture the velocity pulse effects of ground motions through the loop of action and reaction between the experimental and numerical partitions executed in real-time. The biggest challenges of the RTHS implementation for the investigation include: (i) imposing high-velocity loading resulted from the DBE level pulse-type ground motions for multiple actuators; and (ii) using large-scale structure with rate-dependent dampers as the experimental substructure and enable synchronization between the experimental and numerical substructures under velocity pulse.

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Dong B. Real-time Hybrid Simulation of Pulse-type Ground Motions Effects on Steel Building with Nonlinear Viscous Dampers. *Proceedings of the 12th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Salt Lake City, UT. 2022.

Pulse-type Ground Motions

Naturally recorded pulse-type ground motions representing the DBE hazard level without amplitude scaling are selected for the RTHS via a wavelets-based procedure developed by Baker [4]. The DBE hazard level represents an intensity that has the annual probability of exceedance of 10% in 50 years. An ensemble of 10 pulse-type ground motions that represent the DBE hazard of the building site were identified from the PEER NGA database, and are given in Table 1. These ground motions are from earthquake events that were recorded within 15km of the closest distance to the fault (R_{rup}). The pulse periods of these ground motions are within the range of 1.0-3.0s, which results in the value of T_p/T_1 falling in the range of 1.0-3.0 and leads to high seismic demand on the test structure used in the RTHS. The fundamental periods of the test structure for the RTHS is 1.02s. Also, the ground motions have early arriving pulses in the velocity time history and have peak ground velocity (PGV) greater than 30cm/s. The peak ground accelerations (PGA) of the ensemble of ground motion ranges from 0.25g to 0.60g, representing moderate to large earthquake intensities.

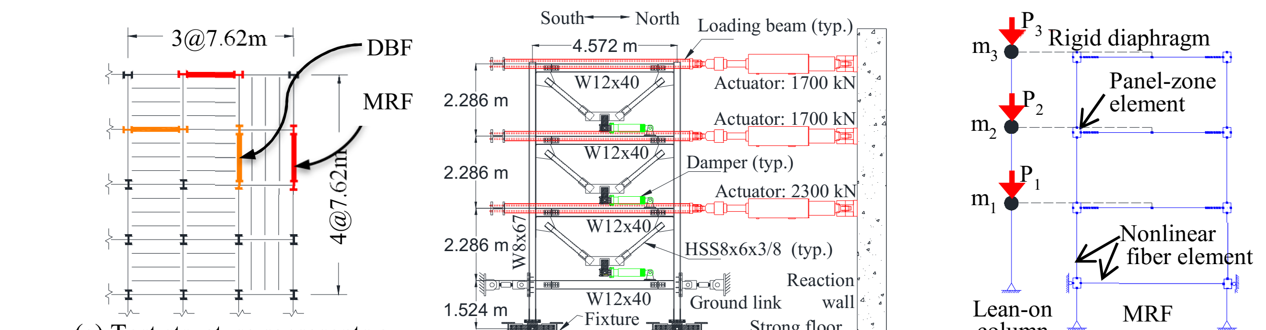
Table 1. Ensemble of pulse-type ground motions for RTHS

No.	Earthquake Event	Fault Mechanism	Station	Record	R_{rup} (km)	T_p (s)	PGA (g)	PGV (cm/s)
1	1979 Imperial Valley	Strike slip	El Centro Array #4	H-E04140	7.1	2.3	0.49	37.4
2	1979 Imperial Valley	Strike slip	El Centro Array #6	H-E06140	1.4	2.7	0.41	64.9
3	1979 Imperial Valley	Strike slip	El Centro Array #8	H-E08140	3.9	2.1	0.60	54.3
4	1979 Imperial Valley	Strike slip	El Centro Differential Array	H-EDA360	5.1	1.7	0.48	40.8
5	1986 North Palm Springs	Reverse Oblique	North Palm Springs	NPS210	4.0	1.3	0.59	73.3
6	1989 Loma Prieta	Reverse Oblique	Gilroy Array #3	G03090R	12.8	2.6	0.37	44.7
7	1989 Loma Prieta	Reverse Oblique	Saratoga-Aloha Ave	STG000	8.5	1.8	0.51	41.2
8	1989 Loma Prieta	Reverse Oblique	Saratoga-W Valley Coll.	WVC000	9.3	2.5	0.26	42.5
9	1994 Northridge	Reverse	LA Dam	LDM064	5.9	2.8	0.51	63.7
10	1994 Northridge	Reverse	Newhall-W Pico Canyon Rd.	WPI316	5.5	2.1	0.33	67.5

RTHS Program

The test structure simulates the lateral force-resisting system (LFRS), supplemental damping system, and gravity system of a quarter of a prototype office building located in the Los Angeles metropolitan area, as shown in Fig. 1(a). The LFRS is a single-bay moment-resisting frame, referred to herein as MRF, and the damping system is a single-bay brace frame with nonlinear viscous dampers, referred to herein as DBF. The seismic area tributary to a pair of MRF and DBF is one-quarter of the total floor area of the building. The prototype building was designed with the philosophy that the MRFs are designed to satisfy 75% of the strength criterion of ASCE 7-10 and the DBFs with dampers are used to reduce structural seismic response. The design details of the MRF and DBF can be found in [5]. During the RTHS, the experimental substructure is the DBF with the dampers (Fig. 1(b)), while the numerical substructure is the remaining part of the structure consisting of the MRF and the associated gravity system, represented by a high-fidelity FE model shown in Fig. 1(c) [5]. Both the MRF and DBF are scaled using a factor of 0.6. The gravity system tributary to the MRF and DBF is represented by a lean-on column with gravity loads and seismic mass lumped at each floor level.

During the RTHS, the DBF was horizontally loaded at each time step by three servo-hydraulic actuators with target displacement demands (x_t). The imposed target displacement demands were determined from the integration of the equations of motion of the test structure. The unconditionally stable explicit CR algorithm [6] was used for this purpose with a time step of 3/1024 seconds. To enable the target displacements to be accurately imposed onto the experimental substructure, the adaptive time series (ATS) compensator [7] which compensates for any variable delay and amplitude error through real-time updating of compensator coefficients was used. The measured displacements of the experimental substructure (x_{sm}) was used as the feedback to control the RTHS. A detail description of the RTHS framework can be found in [8].

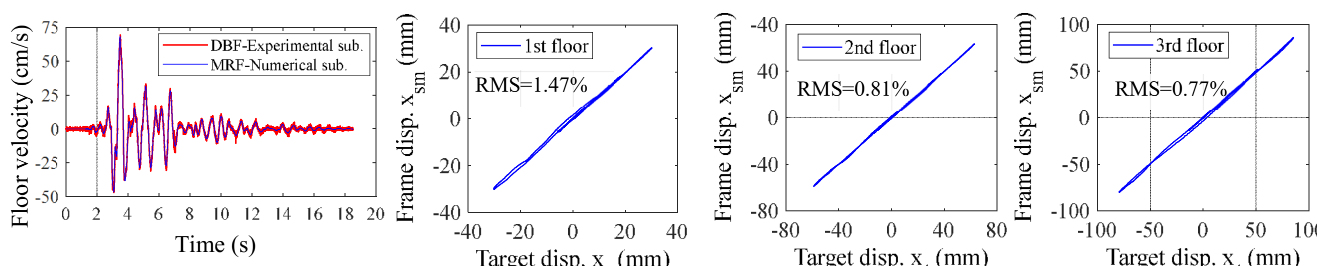


(a) Test structure represents a quarter of a prototype building
(b) Experimental substructure, DBF
(c) Numerical substructure

Figure 1. Test structure for RTHS

RTHS Accuracy Evaluation

The adequacy of the RTHS method for seismic simulation with the DBE level velocity pulses is evaluated in terms of the synchronization between the experimental and numerical substructures during the RTHS under the record NPS210 which has the largest PGV in the selected ground motion ensemble. The comparison of floor velocity response between the DBF and MRF is shown in Fig. 2(a). The response is well in agreement with each other though noise exist in the floor velocity of the DBF. A high peak floor velocity of 70cm/s was reached in the 3rd floor. Fig. 2(b) shows the synchronization subspace plots where x_t is plotted against x_{sm}. The relationship between x_t and x_{sm} is nearly a straight line as seem in the figure. The error between x_t and x_{sm} are quantified by the normalized root mean square (RMS) error, which is 1.47%, 0.81%, and 0.77% for the 1st, 2nd, and 3rd floor, respectively. These small errors demonstrate synchronization achieved between the substructures and the target displacement demands (x_t) generated from the integration algorithm were accurately imposed on the experimental substructure in real time. Therefore, the RTHS is accurate for studying seismic response of structures with nonlinear damping devices under pulse-type ground motions.



(a) Velocity demand in RTHS (3rd floor)
(b) subspace plots of floor displacements

Figure 2. Synchronization of substructures in RTHS with record NPS210

Structural Response Evaluation

The peak story drift response and residual story drift response of the test structure were obtained. The average peak story drift ratio is 0.95%, 1.08%, and 0.85% radians in the 1st, 2nd, and 3rd story, respectively, with value of coefficient of variation (COV) less than 0.3. The reduction of story drift response is over 55% from the predicted story drift of 2.22%, 2.62%, and 2.48% radians in the 1st, 2nd, and 3rd story of the test structure without dampers, respectively, using the equivalent lateral force procedure of ASCE 7-10. Except for the record NPS210, the residual story drift response for other records are less than 0.2% radians which is negligible small to induce unrepairable structural damage. The results suggest the nonlinear viscous dampers appear to be effective in structural response reduction for near-fault pulse type ground motions, and structures could have story drift response within the allowable story drift limitation of 1.5% radians for structures in Occupancy Category III of ASCE 7-10 under the DBE level pulse-type ground motions.

To evaluate the efficiency of the dampers in protecting the test structure, the energy input from the ground motion (E_{INP}), the associated energy dissipated by the dampers (E_{VD}), and the energy absorbed and dissipated due to the frame action of the MRF and DBF (E_{MRF} and E_{DBF}) are compared in Fig. 3. As can be seen, a substantial portion of seismic energy is input to the structure during the few seconds in the early part of the earthquake when the velocity pulse occurs. The dampers are able to dissipate most of the seismic energy, notably about 85% for the H-E06140 record and 75% for the NPS210 and LDM064 records. However, a time lag occurs between the energy dissipation and energy input, which causes small spikes of energy developed in the MRF. These spikes of energy correspond to the peak story drift response of the test structure, and the dampers are effective in terms supplying sufficient energy dissipation and thereby provide an effective means to protect the structure from pulse-type ground motions.

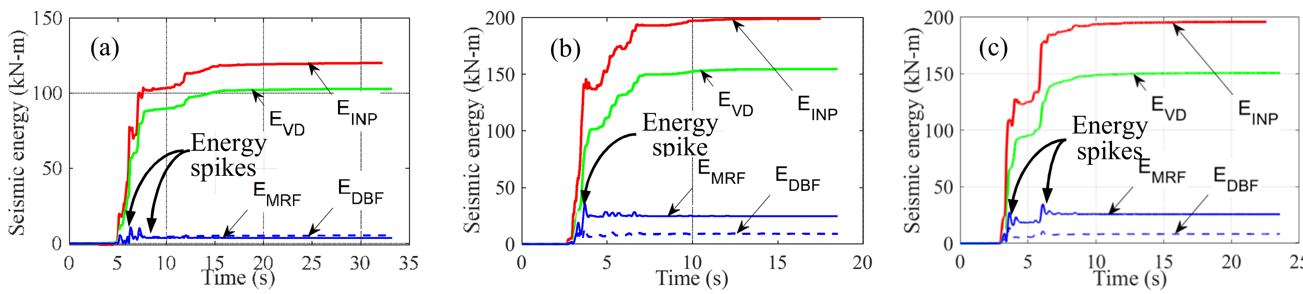


Figure 3. Seismic energy input and dissipation for records: (a) H-E06140, (b) NPS210, and (c) LDM064

Conclusions

The main conclusions include: (1) RTHS is accurate for studying seismic response of structures with nonlinear damping devices under pulse-type ground motions. (2) The nonlinear viscous dampers are efficient in seismic energy dissipation and thereby effective in reducing peak story drift and residual story drift for structures subjected to DBE level pulse-type ground motions. (3) The test structure meets the ASCE 7-10 seismic performance objective for Occupancy Category III structures when subjected to DBE level pulse-type ground motions, and validates that the MRF in the test structure can be designed with a reduced base shear strength.

Acknowledgements

The author would like to gratefully thank Dr. Richard Sause and Dr. James M. Ricles for their support and comments. The grant support (Award No. CMS-0936610) provided by National Science Foundation under the George E. Brown, Jr. Network for Earthquake Engineering Simulation Research (NEESR) program for the simulation performed at the NHERI Lehigh University Real-Time Multi-Directional (RTMD) earthquake simulation facility is gratefully acknowledged.

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