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Multi-directional Seismic Behavior Assessment of a Tall Building using Real-Time Hybrid Simulations

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ABSTRACT

Large-scale multi-directional real-time hybrid simulations (RTHS) are used to assess the maximum considered earthquake (MCE) seismic performance of a 40-story steel building equipped with supplemental nonlinear viscous dampers. These dampers are placed between outrigger trusses and the perimeter columns of a building that was part of the inventory for the California Tall Building Initiative (TBI) PEER study. The analytical substructure for the RTHS consists of a 3-D nonlinear model of the building while the experimental substructure consists of a full scale nonlinear viscous damper. Other dampers in the structure are analytically modelled using an online explicit model updating scheme where the physical damper is used to obtain the parameters of the analytical damper models during the RTHS. The displacement, residual drift, and ductility demand are found to be reduced by adding the dampers to the outrigger, but only in the direction of the plane of the outriggers. Higher modes, including torsional modes, contribute to the 3-D seismic response.

Introduction

With the quest to construct taller buildings in earthquake-prone regions, the seismic performance of such structures is of considerable interest. To protect structural systems from earthquake and wind hazards, researchers and engineers have developed several passive, semi-active, and active control devices to improve the system's performance. This paper describes a study that investigates the effectiveness of supplemental nonlinear viscous dampers placed in the outrigger system of a tall building under earthquake loading.

Description of the Prototype Building

A 44-story steel building is used in this study that is part of the California TBI [1] conducted by the PEER Center. The building is located in Los Angeles, California and has a height of 166 m and a footprint of 51.8 by 32.6 m, with four stories below the ground level. Six buckling restrained braced frames (BRBF) are located in the E-W and N-S directions to resist lateral loads. The braces have a yieldable core of 70% the brace length. The columns are constructed of steel tubes filled with concrete. The beams are wide flange steel sections with gravity connections at their ends. Outrigger trusses are located at the 20th, 30th, and 40th stories in the N-S direction and extend from the core to outrigger columns located at the four corners of the building. The original design of the building had the outriggers pinned to

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the perimeter columns [1]. In the current study the design is modified to include nonlinear viscous dampers placed between each outrigger truss and the perimeter columns, similar to that proposed in [2], resulting in adding dampers at 12 different locations of the building [3]. The building was originally designed with the seismic performance objectives that include drift limits of 0.5% under the serviceability limit earthquake and 3% under the MCE, respectively, in accordance with AISC 7-05 [4].

Real-Time Hybrid Simulation Configuration

Figure 1 shows the real-time hybrid simulation configuration for the tall building study. The building is modelled numerically via an analytical substructure while one nonlinear viscous damper is modeled physically in the laboratory using an experimental substructure. The remaining dampers are modeled numerically using model updating and included in the analytical substructure. The analytical substructure is created using the finite element method. The earthquake ground accelerations are applied to the structure as an effective force along the height of the building. By solving the equations of motion in real-time, the command displacement to the actuator is calculated and imposed onto the experimental substructure to capture the rate dependency of the nonlinear viscous damper. The measured damper force along with the computed member forces of the analytical model are used as a restoring forces to integrate the equations of motion using the MKR-α algorithm [5]. The response of the analytically modeled nonlinear viscous dampers at other locations of the building is performed using an explicit non-iterative nonlinear Maxwell Model formulation that enables performing the state determination of the model in real-time [6]. The parameters of the analytically modeled dampers are obtained based on the measured response of the physical damper and model updating using the unscented Kalman filter [7]. These identified parameters are used to predict the damper response at other locations of the building in each time step of the RTHS.

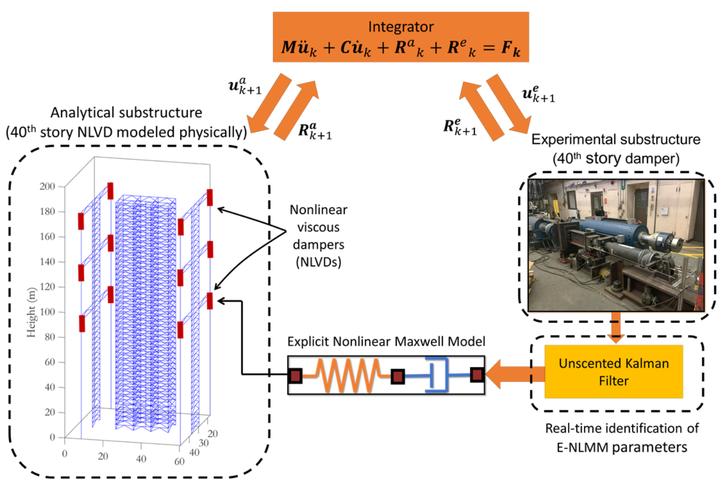

Figure 1. Schematic of real-time hybrid simulation configuration with on-line model updating

Analytical Substructure of the Real-Time Hybrid Simulation

The 3-D analytical model of the building is modeled using the HyCom-3D software [8] as shown in Figure 1. The columns and beams are modeled using elastic beam-column elements. The buckling restrained braces are modeled using nonlinear truss elements. A lean-on column is placed at the center of each floor where its node is considered as the master node of the floor level. All other nodes at each floor level are slaved to their master node to simulate rigid floor diaphragms. The column nodes at the ground level are restrained in both horizontal directions to simulate the restraint provided by the foundation. At each floor level the mass is lumped at the master node, and includes translation mass in both horizontal directions and rotational inertia associated with the distributed floor mass. The resulting analytical substructure model included 3,974 degrees of freedoms which is challenging to run in real-time. Therefore, a super element is used to condense all linear elements in the model, namely the beams and columns, resulting in 1,428 degrees of freedom while enabling the nonlinear behavior of the BRBFs and outrigger trusses of the building to be captured. The beams and columns of the building are expected to be free from damage under earthquakes, thus making it appropriate to model them using linear elastic elements.

The analytically modeled dampers in the model are based on the explicit nonlinear Maxwell Model (E-NLMM) which provides an explicit non-iterative solution of the constitutive relations [6]. The unscented Kalman filter (UKF) is used to identify the model parameters of each damper in real time based on the response of the experimentally modeled damper. The initial mean of the state variables for the dashpot coefficient C_d, stiffness K_d, and exponent α of the E-NLMM used by the UKF are 90,800 kN/m, 671 kN.(sec/m)$^{\alpha}$ and 0.45, respectively. The measurement noise is a Gaussian random variable with a mean of 0 kN and standard deviation of 8 kN. Additional details are found in [6].

Experimental Substructure of the Real-Time Hybrid Simulation

The experimental substructure for the RTHS includes a full scale nonlinear viscous damper manufactured by Taylor Device Inc. having a 600 kN capacity and ±125 mm stroke. The damper is connected to a 1,700 kN dynamic hydraulic actuator via a load beam and a load cell. The experimental substructure physically models the damper located at the N-W corner of the 40th story between the outrigger and the perimeter column. Since four parallel dampers are placed between the perimeter column and truss at each location, the measured damper force is multiplied by a factor of four to simulate four identical dampers acting in parallel.

Ground Motion Selection and Scaling

The two horizontal components of the 1989 Loma Prieta earthquake ground motion recorded at the Saratoga Aloha Avenue Station are used in the RTHS presented herein. The TBI selected seven ground motions to study the seismic response where the Loma Prieta ground motion is one of these. Following the ground motion scaling procedure laid out in the TBI case studies [1], the records are scaled to the target uniform hazard spectrum for the MCE hazard level (2,475 year return period) over a period range of interest. The scaling factor for the Loma Prieta ground motion is 1.89 [1, 9]. Additional RTHS were performed using the complete ensemble of ground motions and presented in [10].

Real-Time Hybrid Results

Figure 2 shows the time history roof displacements in the E-W and N-S directions from the RTHS with dampers. The peak roof displacement is greater in the E-W direction compared to the N-S direction, where the latter is associated with the plane of the outriggers. The force-deformation hysteretic response of the bucking restrained braces at 1st story orthogonal BRBFs are included in Fig. 2. The E-W brace exhibited greater deformations with a ductility of 3.0 compared to a value of 2.0 in the N-S brace. The damper force-deformation hysteretic response is also shown in Fig. 2, where the force capping due to the high velocity in the nonlinear viscous damper is evident in the figure. The peak lateral floor displacements along the height of the building is shown in Fig. 3 where it is compared with the base case simulation (i.e., no dampers in the outriggers). A reduction is shown to occur in the peak floor displacement in the N-S direction when the dampers are added. The reduction ranges from 3.3% at story 22 to 18% at story 28. The dampers do not appear to improve the building response in the E-W direction.

The response of the dampers at the 40th story is shown in Fig. 4 where the N-W damper is physically modeled. The time history of the identified damper parameters are shown in Fig. 5, where the parameters are normalized by their initial values. These parameters are used to predict the response of the other 11 dampers, including the N-E, S-W, and S-E corners at the 40th story whose results (N-E, S-W, and S-E corners) are shown in Fig. 4.

An examination of the frequency decomposition of the roof displacement (not shown herein) indicated that the building's response included both translation and torsional modes, with the translation modes in the N-S direction only contributing to the damper deformations.

Conclusions

Multi-directional large-scale real-time hybrid simulations are used to assess the multi-directional seismic behavior of a 40-story building located in Los Angeles, CA that is subjected to the maximum considered earthquake. The building is outfitted with supplemental nonlinear viscous damper between the outrigger trusses and the perimeter columns, where one of the dampers is modeled physically via the experimental substructure of the real-time hybrid simulation. The other dampers are modeled numerically using an explicit real-time online model updating scheme. A 3-D nonlinear model of the building is used to create the analytical substructure for the real time hybrid simulations. It is found that the nonlinear viscous dampers increase the damping in the direction associated with the plane of the outriggers, where the peak roof displacements are reduced by a range of 3% to 18% over the height of the building. The response of the dampers has been shown to consist of contributions of both translational and torsional modes of the building. The model parameters of the analytically modelled dampers are shown to vary over the course of the simulation, which illustrates the importance of using online model updating to obtain an accuracy response prediction.

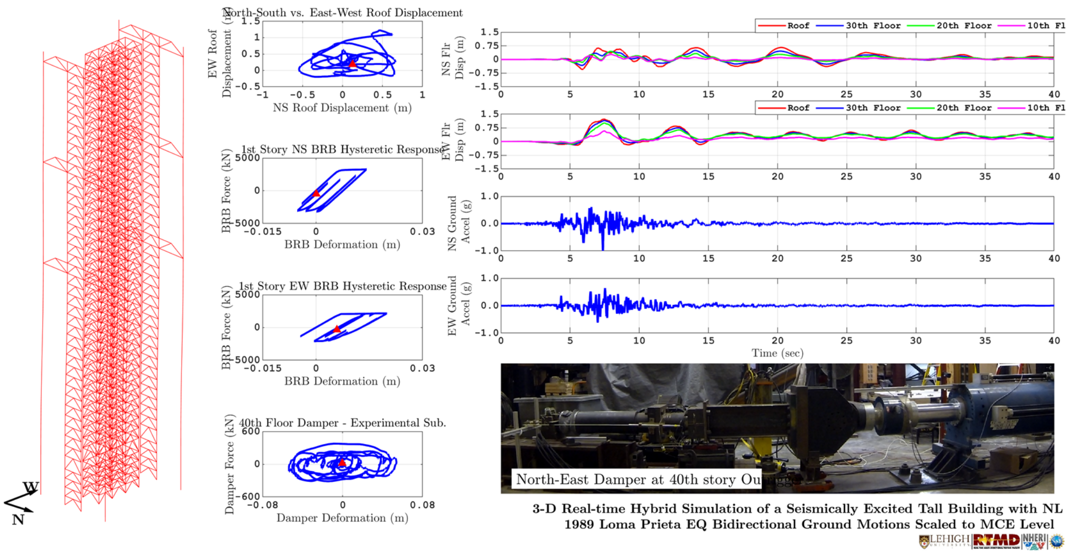

Figure 2. Real-time hybrid simulation results [10, 11].

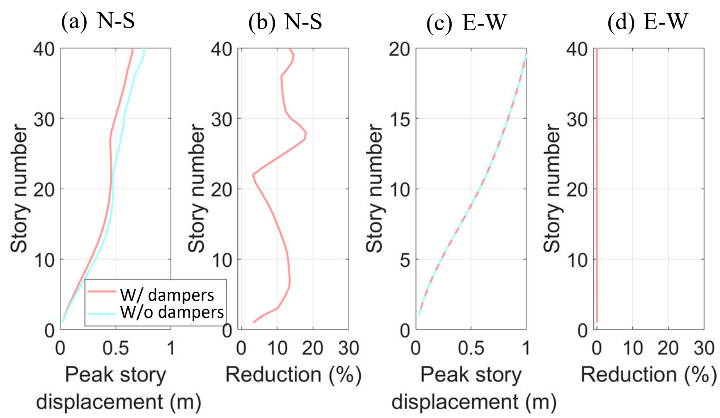

Figure 3. Peak lateral floor displacements and associated reduction

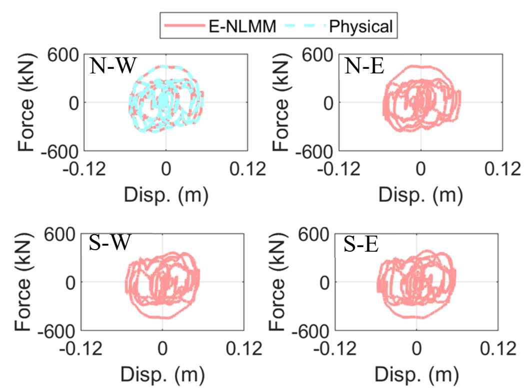

Figure 4. Response of dampers at the four corners of the 40th story

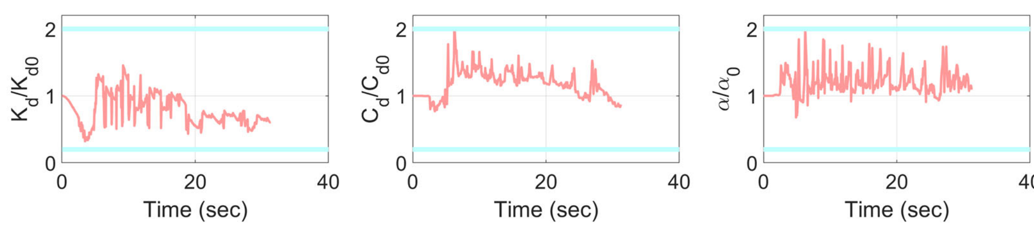

Figure 5. Identified parameters of the explicit nonlinear Maxwell model along with their ceiling limits.

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