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Application of Hybrid Simulation to Investigate the Seismic Behavior of Steel Moment Frame Structures through Collapse

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ABSTRACT
Hybrid simulation combines numerical and experimental methods for cost-effective, large-scale testing of structures under simulated dynamic earthquake loads. Particularly for experimental seismic collapse simulation of structures, hybrid testing can be an attractive alternative to earthquake simulators due to the limited capacity of most facilities and the difficulties and risks associated with a collapsing structure on a shaking table. To further enhance the capabilities of hybrid testing, an innovative substructuring technique for hybrid simulation of structures subjected to large deformations is applied and verified experimentally using a reduced scale four-story moment-resisting frame that was previously tested to collapse on an earthquake simulator. Some of the challenges encountered with numerical errors in hybrid simulations involving complex numerical models are discussed and recommendations are made to mitigate their effect on the simulation results. In particular, the selection of integration algorithms and integration time step are critical to achieving accurate simulation results. The developed hybrid testing techniques and lessons learned from the small scale tests are applied to experimentally evaluate the seismic response of half-scale experimental substructures that demonstrate the reliability of hybrid simulation through collapse.

KEYWORDS: *Hybrid simulation, Collapse, Experimental errors, Substructuring*

1. INTRODUCTION

The need for assessing the collapse of structures stems from the key objective of seismic design provisions for buildings, which is life-safety or more specifically collapse prevention during a major earthquake. While several analytical tools have been proposed for collapse assessment of structures subjected to seismic excitations (Sivaselvan and Reinhorn 2006; Lignos and Krawinkler 2011), there remains a need for more realistic experiments to large levels of loading near collapse (Villaverde 2007; Nakashima 2008). Experimental data from large scale system level collapse simulations is essential to fully validate and improve the analytical tools that generally rely on empirical and mechanical component-level models to capture global system behavior. Very few experimental facilities have the capabilities to examine the behavior of large-scale structures to collapse with notable experiments of steel buildings including Suita et al. (2008). Limitations in the majority of the testing facilities combined with the cost of testing complete full-scale structures have motivated alternative large-scale testing methods such as hybrid simulation with substructuring (Schellenberg et al. 2008; Wang et al. 2012).

In order to develop and verify the applicability of hybrid simulation to examine system-level behavior of structural systems to collapse, studies on a reduced scale steel moment resisting frame (SMRF) structure are first conducted and compared to results for previous shake table tests of the same structure. These hybrid simulations utilize substructuring technique for multi-story frame structures (Hashemi and Mosqueda 2014), that allows for testing large frame subassemblies with a limited number of actuators while maintaining adequate boundary conditions. The influence of error propagation in simulation results due to experimental hardware, numerical stability and substructuring technique were carefully examined. As in previous studies, it is found that reliable results from a hybrid simulation requires careful mitigation of both numerical and experimental errors (Mosqueda et al. 2007). The lessons learned from these tests are then applied to successfully conduct hybrid simulations of the seismic behavior of half-scale subassemblies representative of SMRF structures.

2. VALIDATION OF HYBRID SIMULATION TO COLLAPSE

A series of hybrid simulation tests were conducted on a 1/8 scale model of a four-story two-bay steel special moment resisting frame. The same frame was previously tested on a shake table and examined extensively in numerical studies (Lignos et al. 2011), providing benchmark data to evaluate the results from the hybrid simulations. The hybrid simulations include complex structural models with significant geometric and material nonlinearities in order to capture the response through collapse and thus introduce many challenges including the interaction between numerical and experimental subassemblies, and numerical and experimental error propagation.

2.1. Structural Model

The 1/8 scale model consists of aluminum beams and columns connected to cruciform solid aluminum joint elements. The connections simulate plastic hinge elements. While the aluminum elements remain elastic, sacrificial steel plate coupons are inserted at plastic hinge locations to provide repeatable nonlinear simulations. Previous shake table experiments at the Structural Engineering and Earthquake Simulation Laboratory at University at Buffalo (UB-SEESL) evaluated numerical collapse predictions for steel moment frames by explicitly addressing P-Δ effects and component deterioration (Lignos et al. 2011). The scale model shown in Figure 2.1 was subjected to the Northridge 1994 Canoga Park earthquake record at five sequentially increasing intensities with scale factors of 0.4, 1.0, 1.5, 1.9 and 2.2, representing Service Level Earthquake (SLE), Design Basis Earthquake (DBE), Maximum Considered Earthquake (MCE), Collapse Level Earthquake (CLE) and Final Collapse Level Earthquake (CLEF), respectively.

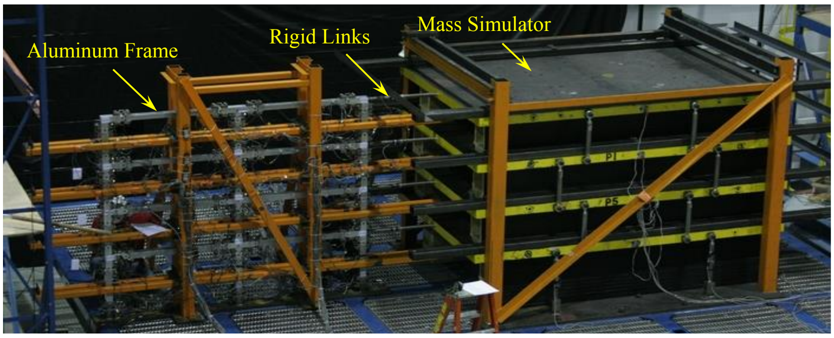


Figure 2.1 Photograph of 1:8 scale moment frame on shake table

The structural model was simulated numerically in OpenSees (2012) by Eads et al. (2013) and then modified by Hashemi (2013) for these hybrid simulation studies. A concentrated plasticity model was used with the frame members modeled as elastic elements with nonlinear rotational springs at their ends with the hysteretic behavior of the plastic hinges governed by a modified version of the Ibarra–Medina–Krawinkler (IMK) deterioration model (Lignos and Krawinkler 2011). In the shaking table tests, the P-Δ effect is transferred through horizontal links from the gravity simulator to the test frame, which is equivalent to the use of a leaning column. Experimental identification of viscous damping in the shake table experiment was challenging due to the presence of friction in the test setup including the mass simulator connections. To better simulate the energy dissipation mechanism, in combination with viscous damping, a friction element was added per story at both ends of the leaning columns, and modeled as a rotational spring with elastic perfectly-plastic behavior (Lignos et al. 2011).

2.2. Substructuring Strategy and Experimental Setup

A key challenge in substructuring is the interface between the analytical and experimental subassemblies where equilibrium and displacement compatibility should be satisfied. While some facilities are capable of controlling MDOF at the boundaries of physical specimens (Hashemi et al. 2015; Mahmoud et al. 2013), they are mainly used for experimental and numerical substructures that share one or two node at their interface. For more general applications to frame structures, an overlapping substructuring technique proposed by Wang et al. (2012) and improved by Hashemi and Mosqueda (2014) can provide accurate results through collapse while maintaining a simple experimental setup. This substructuring technique is employed here with the experimental substructure consisting of the lower 1.5 stories of the substructure as shown in Figure 2.2. The numerical model however, extends to include the first floor beams, thus creating an overlap between experimental and numerical substructure. More details on this approach and discussion of issues that arose during testing related to flexibility of the reaction frame and load cells used at the boundary of the structure are discussed in Hashemi (2013).

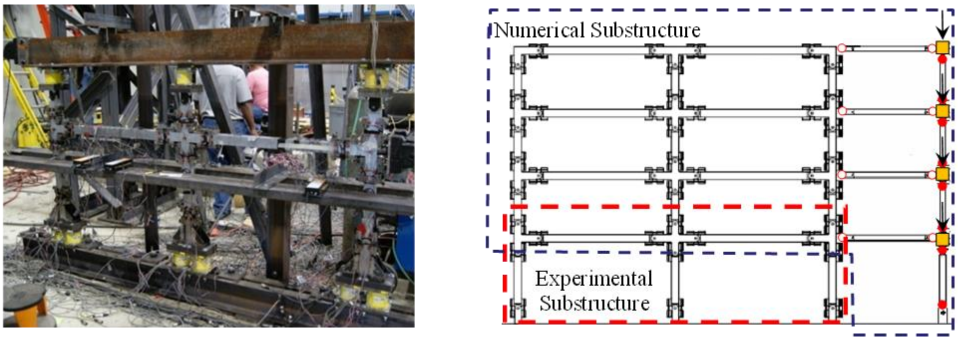
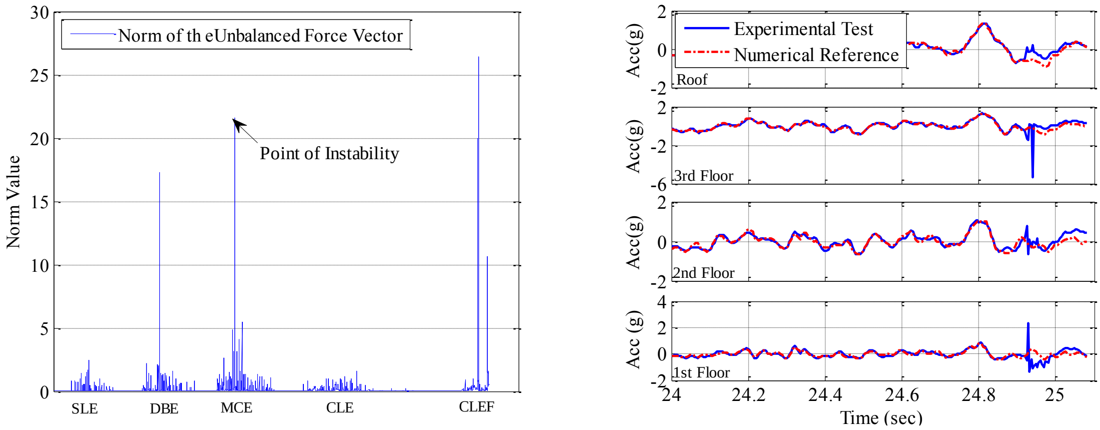


Figure 2.2 Illustration of substructure hybrid simulation for 1/8 scale moment frame model

2.3. Numerical Errors

Simulation of structural response through collapse requires highly nonlinear behavior that can challenge numerical algorithms. In hybrid simulation, a time-stepping integration method is used to solve the equation of motion. Iteration strategies often employed in pure numerical simulations to converge at an acceptable solution are not practical to implement in a hybrid simulation due to the path-dependent behavior of the experimental substructure. Alternatively, implicit integration algorithms with a fixed number of monotonically increasing iterations have been proposed. However, the convergence criteria used in pure numerical simulations are not strictly enforced with fixed number of iterations before advancing to the next step in order to keep the continuity of the simulation. Therefore, selection of the integration time step and number of iterations can be critical to determining the stability and accuracy of the simulation. In some of the earlier tests conducted as part of this series, numerical instability occurred and was later traced to large numerical errors. In an actual hybrid simulation, the integration method went unstable during the third ground motion intensity (MCE) at the time instant of 24.92s. Figure 2.3(a) illustrates the level of unbalanced forces in pure coupled-numerical simulation that shows significant increases at the exact time of instability. These norm of these unbalanced forces represent the equilibrium error in the structure that is often used as convergence criteria. Despite this large error, no numerical instability or even loss in accuracy was observed for the pure numerical simulations. Unfortunately, this data was not collected during the actual hybrid tests. Note that the norm of the unbalanced force vector is calculated from both linear forces and moments making it difficult to interpret the amplitude or units. Figure 2.3(b) shows the history of relative acceleration at each floor where the large spikes are indicative of potential instability in the simulation although similar spikes were not evident in displacements. Accordingly, prior to conducting the actual hybrid simulation experiment, a sensitivity study is recommended through numerical simulations in order to evaluate different integration parameters.



a) Unbalanced force in numerical simulation   b) Acceleration time histories from hybrid test

Figure 2.3 Large unbalanced forces predicting potential instability in hybrid simulation

In an effort to reduce the unbalanced forces, numerical simulations were conducted to examine the sensitivity of the integration parameters including time step and number of iterations. A careful balance was selected to limit the errors while also limiting the duration of the simulation. Based on the results presented in Figure 2.3, an effort was made to reduce the unbalanced force error below one unit. This value was selected because as will be show later, it was difficult to achieve smaller values considering feedback from experimental measurements. Additional improvements were also made to the numerical model to reduce these errors, particularly for very stiff elements such as the friction springs used to model damping. The yield force and initial stiffness were recalibrated to reduce these values while increasing the viscous damping without having a significant influence on the simulation results.

2.4. Simulation Results

A successful hybrid simulation with 1½ story of the moment frame as the physical substructure was conducted to experimentally validate hybrid simulation of framed structures through collapse. The final model included the substructuring strategy and careful examination of unbalanced forces in pretest numerical simulations. In the hybrid simulations, the test frame was subjected to the five sequential ground motions with increasing intensities using records from the measured shake table accelerations. The Implicit Newmark Method with fixed number-of-iterations as implemented in OpenSees was used as the integration scheme (Schellenberg et al. 2009; Shing et al. 1991). The time steps and number-of-iterations were selected to minimize the potential of instability while maintaining the duration of the hybrid simulation within reasonable time limits. For the MCE test and above, a time step of 0.00156s was used with up to 8 iterations in order to prevent large unbalanced forces in the pretest numerical simulations. In terms of the accuracy, the results of the hybrid simulations are compared with the shake table results as the reference. Figure 2.4 compares the first-story drifts for all 5 sequential hybrid simulation tests. It can be seen that with careful error control as implemented in this test, reliable results can be achieved. In particular, the hybrid simulation as implemented can trace the dynamic response of the test frame reasonably well from the onset of damage through collapse. Collapse in both the experimental hybrid simulation and shake table tests occurred at the same time instance in the ground motion. Also, similar peak displacements and resisting forces were achieved when comparing the results.

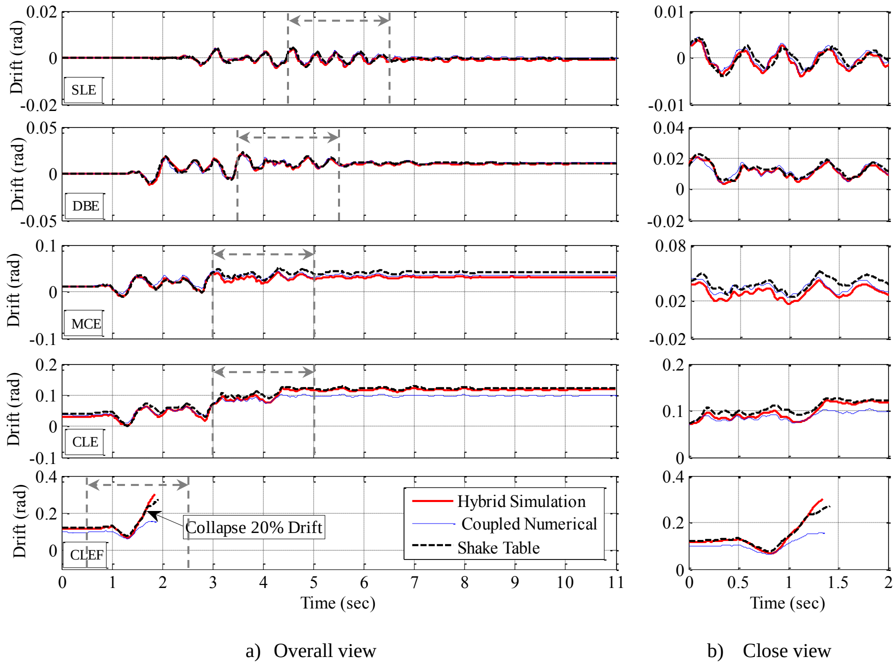


Figure 2.4 Comparison of first story drifts for 5 sequential ground motion intensities

The stability of the simulation was monitored by the norm of unbalanced forces while using a fixed number-of-iterations as presented in Figure 2.5. While a formal stability margin is difficult to specify, the level of the norm unbalanced force vector was kept constantly below 1unit in the numerical simulations. By comparison, the hybrid simulation unbalanced force norm is consistently higher and just under one unit due to the experimental errors such as the random noise in the measurements. It should be noted that this trend was not evident when comparing the displacement or energy norm that are also commonly used as convergence criteria.

3. HYBRID SIMULATION TO COLLAPSE WITH LARGE SCALE SUBSTRUCTURES

Hybrid simulations were implemented at UB-SEESL to examine the seismic behavior of two half-scale subassemblies representative of moment and gravity frames from the onset of damage through collapse. Only sidesway collapse mechanisms are considered, where dynamic instability results from second-order P-Delta effects fully overcoming the shear resistance of a structural system at large lateral deformations. The same four-story office building considered in the previous studies was used here as the prototype building structure. However, the frames examined here are in the orthogonal direction and correspond to three bay frames. The seismic-force-resisting system consists of SMRF located around the perimeter of the building with fully-restrained reduced beam sections (RBS) in both principal directions. For these tests, ½ scale experimental substructures are considered with more realistic construction details. The large-scale subassemblies span 1½ bays by 1½ stories of the frame structures and are subjected to realistic seismic loading conditions. Only selected test results from the moment frame are provided here with more details available in Del Carpio et al. (2014).

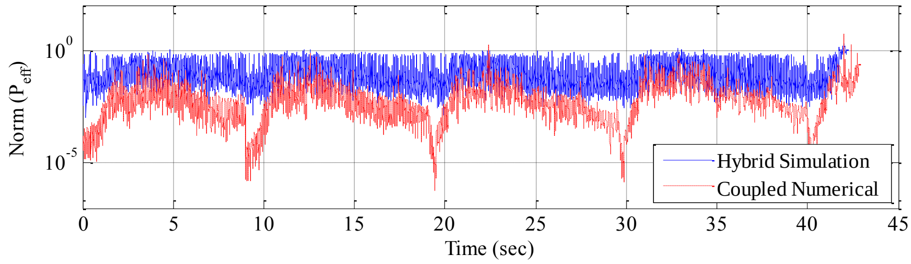
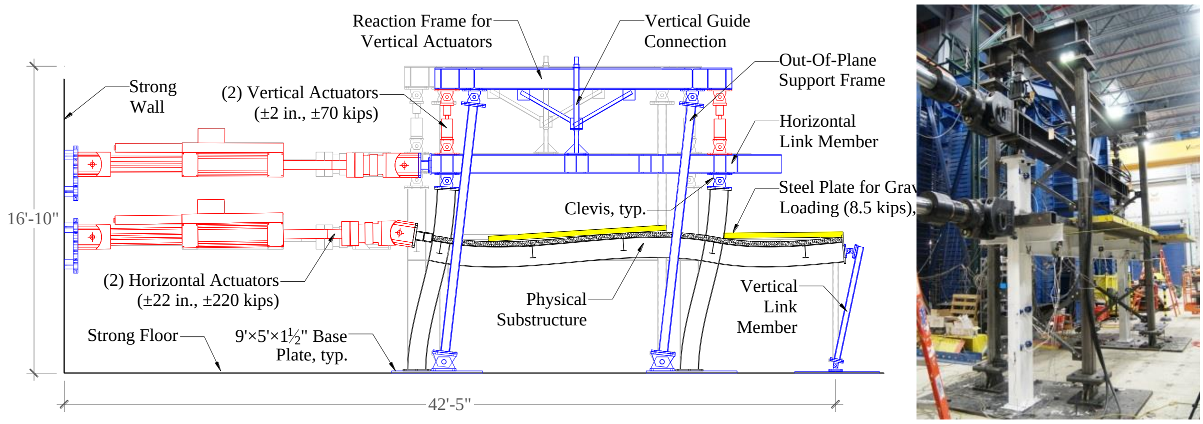


Figure 2.5 Comparison of unbalanced forces in integrator for hybrid and coupled pure numerical simulation



(a) Elevation of hybrid simulation test setup for collapse (b) Photograph

Figure 3.1 Experimental substructure setup for horizontal and vertical loading on specimen

3.1. Experimental Substructure

The test setup shown in Figure 3.1 was designed to apply lateral as well as vertical forces on the physical substructures during a hybrid simulation. Clevises are conveniently provided in the experimental setup as indicated to simplify the boundary conditions with the numerical substructure. In particular, rotations and moments at the boundaries are not fully enforced since they are difficult to apply with linear hydraulic actuators and are part of the substructuring strategy. The cantilever portion of the first-story girder is underpinned using a vertical link member as shown to limit vertical deflection at the tip. A support frame surrounds the physical substructures and provides out-of-plane support. Seismic loading is applied through two horizontal actuators controlling the lateral displacements at the first and mid-second story levels of the physical substructures. The horizontal link member shown in Figure 3 transfers the lateral loads from the top horizontal actuator to the top of the physical substructure columns connected by pins. Gravity loads at the elevated first floor level of the physical substructures are simulated using steel plates for dead weight simply supported on the beams. Additional gravity loads on the columns of the physical substructure from upper stories as well as earthquake-induced variations from overturning forces are applied with two vertical actuators.

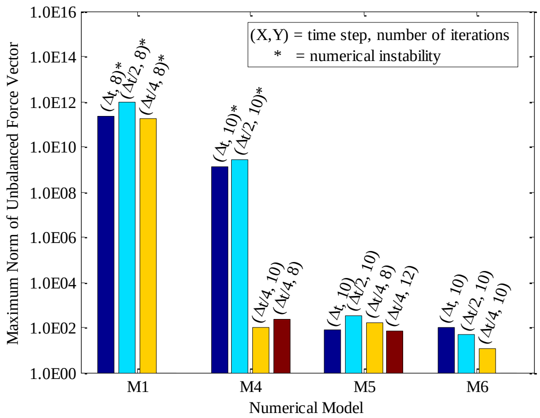
3.2. Numerical Substructure

The numerical substructure for the SMRF consisted of the 3 bay by 4 story frame plus a leaning column modeled in the OpenSees platform using a concentrated plasticity approach, similar to the approach described in Section 2.1. For large scale connections, the hysteretic model was previously calibrated by Lignos and Krawinkler (2011) using an extensive database of structural steel components. This one-dimensional hysteretic model does not account for axial force-bending moment (P-M) interaction (as currently implemented in OpenSees). However, this is a reasonable assumption to simulate the response of columns in low-rise structures with low levels of column axial forces as demonstrated by recent collapse tests (Lignos et al. 2013). Geometric nonlinearities are included using the P-Delta formulation in OpenSees since the simplicity of this formulation as compared to the corotational provides more stable simulations.

3.3. Integration Algorithm

The modified implicit Newmark method for hybrid simulation (INM-HS) as implemented in OpenSees was selected to integrate the equations of motion of the substructured hybrid models. Analytical studies with this numerical model (Del Carpio et al. 2014) showed that even when using sufficiently-small time steps for accuracy purposes, this integration algorithm can become unstable due to the complexity of the numerical models and the large levels of nonlinear response distributed in the physical and highly-detailed numerical substructures. Although the stability criteria do not commonly dictate the choice of the time step when considering accuracy, it was observed in these studies that large unbalanced forces can accumulate and result in unstable simulations when performing a fixed number of iterations.

Figure 3.2 shows how modifications to various modeling parameters can lead to significant reductions in the magnitude of unbalanced forces thus improving the stability and robustness of the simulations. Some of the modifications explored include: (i) softening the elastic stiffness of rotational springs of the one-component model (plastic-hinge elements) using a value of "n=1" instead of "n=10" , where "n" is used to distribute the elastic stiffness (ii) using the P-Delta transformation instead of the corotational to account for second-order effects, and (iii) using algorithmic damping in the integration method as it has been reported to improve the convergence of iterative schemes (Chung and Hulbert 1993). For the latter, the integration method developed by Hilber et al. (1977) as modified in OpenSees for hybrid simulation with fixed number of iterations similar to Schellenberg et al. (2009) was utilized (noted as HHT-HS). These modifications were implemented in several conventional numerical models of the half-scale moment frame in Del Carpio et al. (2014). Four of those models are summarized in Figure 3.2. These numerical models were subjected to 200% of the Los Gatos Presentation Center (LGPC) station to result in a highly nonlinear response of the frame structure and therefore challenge the performance of the integration methods.



Numerical Model	Geometric Transf.	Stiffness Factor "*n*"	Integration Method
M1	Corotational	10	INM-HS
M4	Corotational	1	HHT-HS
M5	P-Delta	1	HHT-HS
M6	P-Delta	1	INM-HS

Figure 3.2 Results of unbalanced forces for various modeling and integration parameters

The maximum norm of the unbalanced force vector is presented for the four numerical models using the integration methods for hybrid simulation with different time steps and number of iterations (the time step is presented as a fraction of the time step of the scaled ground motion sampling rate "Δt=0.0035" s). Model M1 becomes unstable, as indicated before, even when using small time steps for accuracy purposes. On the other hand, softening the elastic stiffness of the plastic-hinge elements in model M4 significantly decreases the unbalanced forces and prevents numerical instabilities for the smallest time step considered (Δt/4). More consistent improvements on the stability of the simulations are observed in model M5 with the P-Delta formulation in addition to the softened plastic hinges. Although the corotational formulation is theoretically more accurate, only minor differences in response are observed towards collapse for these particular models. Also, a comparison of the unbalanced forces for models M5 and M6, which differ only in the use of algorithmic damping in the former, indicates that the use of algorithmic damping does not render favorable results. The consistency of this observation was verified for these particular models with different combinations of modeling parameters. Figure 3.2 also shows that decreasing the time step of the simulations does not always results in smaller unbalanced force errors, partly due to the random nature of these errors. In view of these observations, the P-Delta formulation and rotational springs with reduced initial stiffness are implemented in the numerical models for hybrid simulations. For the collapse test with the LGPC scaled at 200%, a time step of $\Delta t/3 = 0.001167$s was used with 8 iterations. These parameters were slightly reduced for lower level simulations to minimize the duration of the tests.

3.4. Hybrid Simulation Results

The hybrid simulations were successfully conducted with the previously-described hybrid models, test setup, substructuring algorithm, integration algorithms and parameters. Sidesway collapse with a mechanism forming over the lower-three stories was observed in the series of hybrid simulations, consisting of the LCPC record applied at 25%, 100%, 160%, and 200%. At the end of each test, an additional 1.0 sec. of highly-damped free vibration (50% damping ratio) was added to rapidly damp the vibration of the hybrid models before the initiation of the next test. The collapse hybrid simulation (HS01-200%) was stopped when a stroke of 20 in. was reached at the top horizontal actuator, corresponding to 15% story drift in the physical model. Figure 3.3 compares the roof drift ratio (RDR) of the two series of hybrid simulations with the reference numerical results from pre-test simulations. Maximum RDRs are indicated for each hybrid simulation. The close agreement in response indicates that the response of the four-story steel moment frame building structure can be predicted with similar levels of accuracy with the hybrid and fully-numerical simulation methods. The largest differences are observed in the residual RDRs at the end of the HS01-160% and HS02-200% tests. This can be attributed to the sensitivity of the type of hysteresis on residual drifts (Ruiz-Garcia and Miranda 2006). In this case, the inelastic response in the numerical portion was simulated with multi-linear springs (i.e., non-smooth hysteretic models). Despite such differences, the oscillation cycle at which collapse occurred was closely predicted in the first series of hybrid simulations. Detailed results of the distribution of damage can be found in Del Carpio et al. (2014).

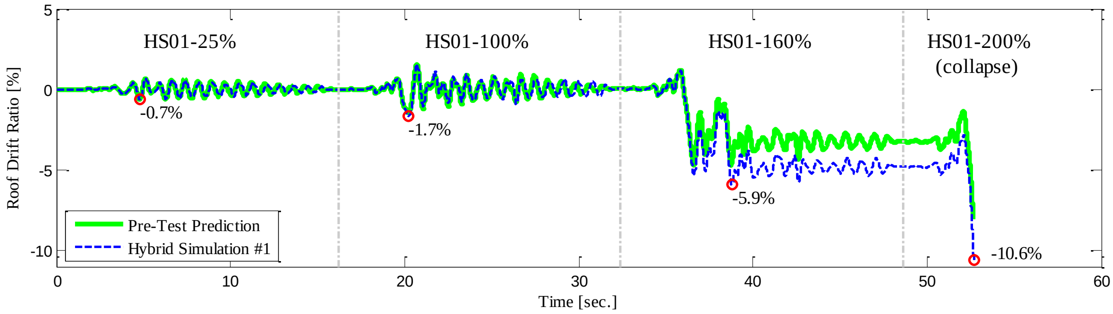


Figure 3.3 Response of hybrid simulations compared with numerical prediction

4. CONCLUSIONS

Hybrid simulation with substructuring was investigated and implemented as a cost-effective alternative for large-scale system-level testing of structural frame subassemblies to simulated dynamic earthquake loading through collapse. An evaluation of the test method indicated that the performance of the integration method for hybrid simulation can be greatly challenged when employed with large and complex numerical substructures experiencing highly nonlinear response. However, careful consideration and mitigation of errors can lead to reliable simulation results as validated in tests of a 1/8 scale frame yielding similar results for both shake table and hybrid simulations. The hybrid framework was then implemented to examine the seismic response of a half-scale subassemblies of a moment frame from the onset of damage through collapse with detailed numerical substructure models. The substructuring technique for multi-story frame structures included varying axial forces on the columns of the physical specimens. The hybrid test method was found to be reliable and provided insight into experimental behavior of structural subassemblies under realistic seismic loading. The observed behavior of the frame structures with damage distributed throughout the various components highlights the benefits to this hybrid test approach with large subassemblies towards better understanding component interaction and system-level behavior. These tests also provide valuable data to assess the ability of analytical tools to trace the response of a steel moment frame building structure near collapse.

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