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HYBRID SIMULATION OF MOMENT FRAMES WITH DEEP COLUMNS EXPERIENCING AXIAL SHORTENING

Claudio Sepulveda[1], Gilberto Mosqueda[2], Chia-Ming Uang[2], Gulen Ozkula[3], Kung-Juin Wang[4], Chung-Che Chou[5], Po-Chia Huang[6], Cheng-Wei Huang[6], Mao Cheng[7] and Tracy Becker[8]

1. Research Assistant, University of California San Diego, California, USA
2. Professor, University of California San Diego, California, USA
3. Assistant Professor, Dept. of Civil Engineering, Tekirdağ Namik Kemal University, Tekirdağ, Turkey
4. Principal Engineer, National Center for Research on Earthquake Engineering, Taipei, Taiwan, R.O.C
5. Director General, National Center for Research on Earthquake Engineering, Taipei, Taiwan, R.O.C
6. Research Assistant, National Center for Research on Earthquake Engineering, Taipei, Taiwan, R.O.C
7. Research Assistant, University of California Berkeley, California, USA
8. Professor, University of California Berkeley, California, USA

Email: csepulve@eng.ucsd.edu

ABSTRACT

Wide flange steel column elements have been commonly used for steel moment frames in seismic regions. To economically comply with drift limit requirements, the moment of inertia of the section is increased by choosing slender and deep sections. However, deep columns are susceptible to local buckling and subsequent axial shortening when subjected to a combination of high axial forces and cyclic lateral loads. The interaction between the shortening columns and the surrounding structural framing system can result in a redistribution of axial loads, which has not been examined in detail. Here, this interaction is studied through a hybrid simulation of a full-scale steel moment frame subassembly using advanced hybrid simulation algorithms with new capabilities developed for this test. A new mixed displacement and force control framework is implemented to capture the coupled nature of the column axial behavior during shortening. The lateral behavior of the frame is highly dependent on the moment frame with reduced beam sections considered in this study. The experimental cruciform subassemblage includes beam-to-column connections and this measured plastic hinge response is utilized through online model updating to update parameters in the nonlinear numerical beam models. Preliminary tests are presented for these ongoing experiments.

Keywords: Hybrid simulation, steel moment frames, axial shortening, online model updating

INTRODUCTION

Building design codes currently impose maximum drift requirements for buildings (ASCE 2022). The use of deeper and thinner sections for columns has been common practice to meet drift requirements with an economical solution. However, deep columns are susceptible to localized buckling that can result in axial shortening. A series of experiments have been carried out on individual column members to characterize this phenomenon under quasi-static load patterns of axial loads and lateral drifts (Ozkula et al., 2021; Elkady and Lignos, 2017). Such quasi-static testing of isolated columns and subassemblies have shown the importance of the axial load, inelastic deformation, and boundary conditions on the axial shortening severity (Chansuk et al., 2021; Chou et al., 2022). Nevertheless, the impact of column shortening on the system-level behavior of the frame has only been addressed through pure numerical simulation (Wu et al., 2018), without experimental system-level testing verification. This project aims to experimentally assess the system behavior of moment frame structures with deep columns by conducting hybrid simulations including full-scaled cruciform subassemblies. To include axial shortening in the hybrid simulation, a new mixed displacement and force control method is proposed and implemented to achieve equilibrium of forces and displacement compatibility. Moreover, to overcome the limitations in the experimental setup, an overlapping substructuring method is used to simplify the boundary conditions of the physical substructure. In addition, an online model updating scheme is included to that utilized data measured during the test to update parameters of hysteretic models for the reduced beam section.

HYBRID EXPERIMENTAL AND NUMERICAL MODEL

Hybrid simulation or pseudodynamic testing (Mahin et al., 1985) is a technique where the complete structural model is divided into different substructures. At least one of the substructures is experimental, while the rest of the system is simulated using a numerical model. All substructures interact with each other sharing displacements and forces through the degrees of freedom at the boundary conditions of each subsystem (Shing and Mahin, 1984). Similar to a shake table test, it can be used to experimentally evaluate a structural system under a given ground motion record. Although a shake-table test can be considered a more realistic way to replicate the real behavior of a structure subjected to seismic loads, hybrid simulation is a cost-effective alternative because only the key components or subsystems are tested in the laboratory. With inertial and other rate dependent force simulated numerically, the test can be performed at a slower velocity, reducing laboratory equipment requirements, and allowing for large scale testing as demonstrated here.

For this project, the prototype structure considered is a steel moment frame with 18ft height at the first story plus five floors at 14ft each over four bays each spanning 26ft. Column sections are W24x131 and beams are W27x94 for the first three stories, while for the upper stories columns are W24x117 and beams are W27x84. Reduced beam sections (RBS) are designed for beam-column connection. Figure 1 shows the prototype structure and a scheme of the numerical model used for the numerical substructure.

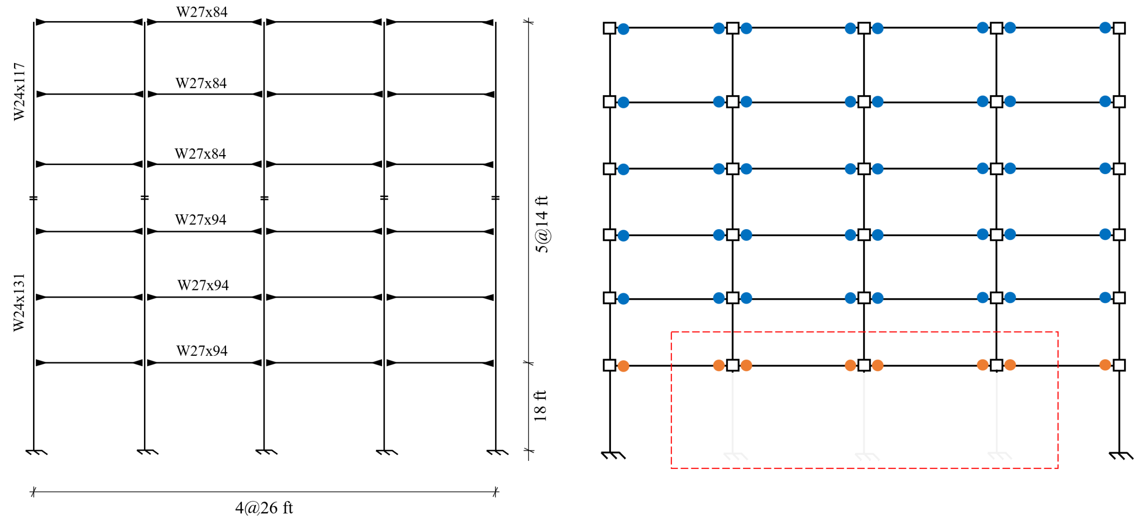


Figure 1. Prototype structure and numerical model

The numerical nonlinear substructure is modeled in OpenSees (McKenna et al., 2009) for the hybrid simulation. Columns are modeled using distributed plasticity elements with a displacement-based formulation. The panel zone deformation is simulated using the parallelogram approach (Gupta and Krawinkler, 1999) with a rotational spring in one of the corners. Beams are modeled considering an elastic beam-column element for the middle section with each end having rigid offsets plus a lumped plasticity spring. Above the second story (blue hinges in Figure 1) the beam hinges are simulated using Ibarra-Medina-Krawinkler (IMK) model (Ibarra et al., 2005). However, for beam hinges at the first story, a modified version of Bouc-Wen model (Cheng and Becker, 2021) are used with the ability of having updatable parameters to be used in the online model updating scheme explained later. Figure 2 shows a schematic of the typical numerical elements used.

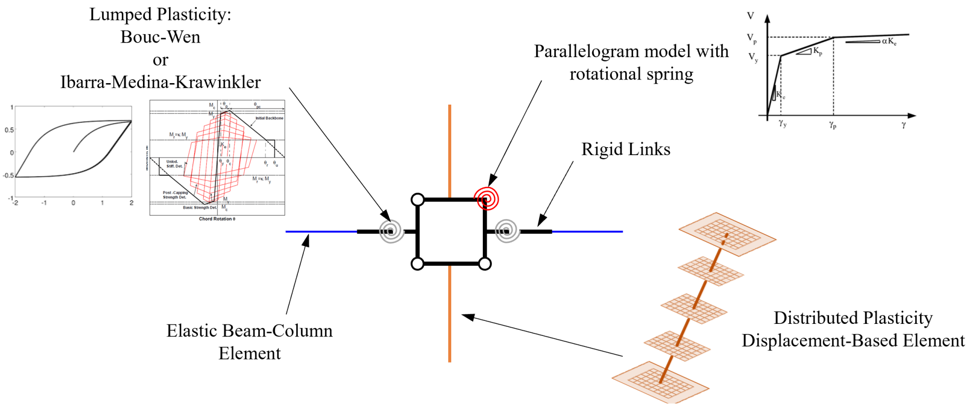


Figure 2. Details of the numerical model

SUBSTRUCTURING METHOD AND EXPERIMENTAL SETUP

The physical substructure is a cruciform beam-column subassembly depicted in Figure 3. The column is one and one-half story heigh with a pair of parallel pinned-connected actuators located on top of the specimen to control the horizontal displacement of the system. The control point of the actuators in the horizontal and vertical direction is located at the top end of the first story column to ensure displacement compatibility at the first floor level with the numerical substructure. Since axial shortening is expected at the base of the column and the specimen is an interior column, one vertical pinned-connected actuator controls each beam end following the vertical displacement measured at the vertical control point. Axial forces are applied by the four hydraulic jacks located on top of the specimen in force control mode. Preliminary numerical studies indicate that the three interior columns are expected to have similar behavior, thus, the one experimental specimen is selected to represents the three interior columns. To overcome the large number of DOFs at the boundaries of the experimental substructure (rotation and displacements at the member ends) an overlapping substructure approach is implemented for this test (Hashemi and Mosqueda, 2014). In this approach, a zone of the system is overlapped in both domains in order to minimize the effects of limiting the controlled DOFs such as neglecting rotation at the boundaries. For this test, the commanded signals from the numerical substructure are the horizontal displacement at the floor level, and the axial load obtained from the second story column. The feedback signals are the moment M and shear force V calculated at the top end of the first story column in the physical substructure, plus the vertical displacement measured at the same point. This last signal is converted into an equivalent vertical force F_{eq}, to impose a vertical displacement in the numerical model that is compatible with the measured displacement as explained later.

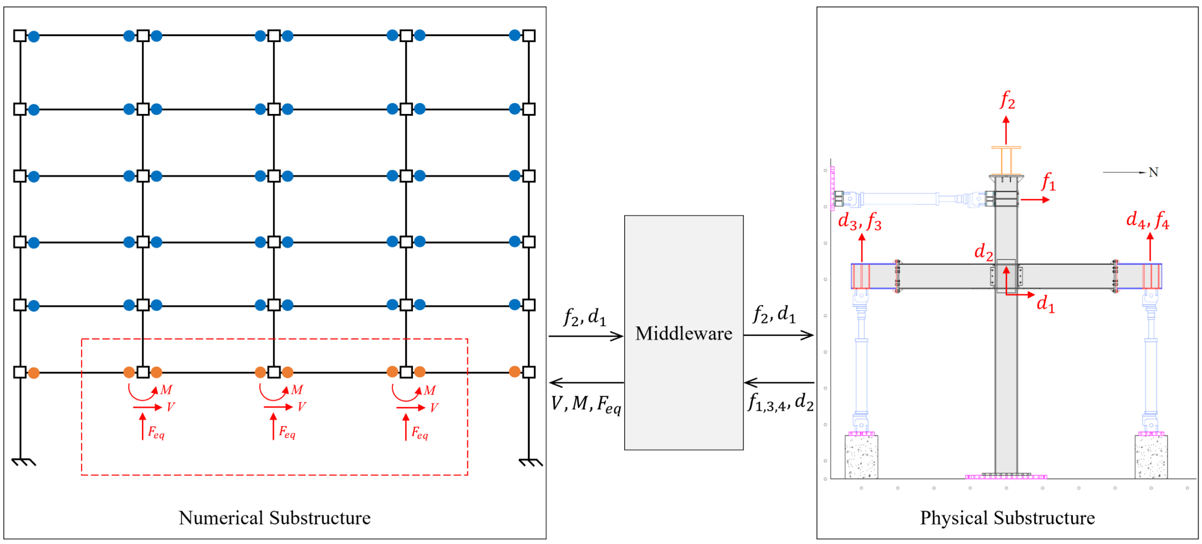


Figure 3. Experimental setup and hybrid loop.

COMUNICATION PROTOCOL

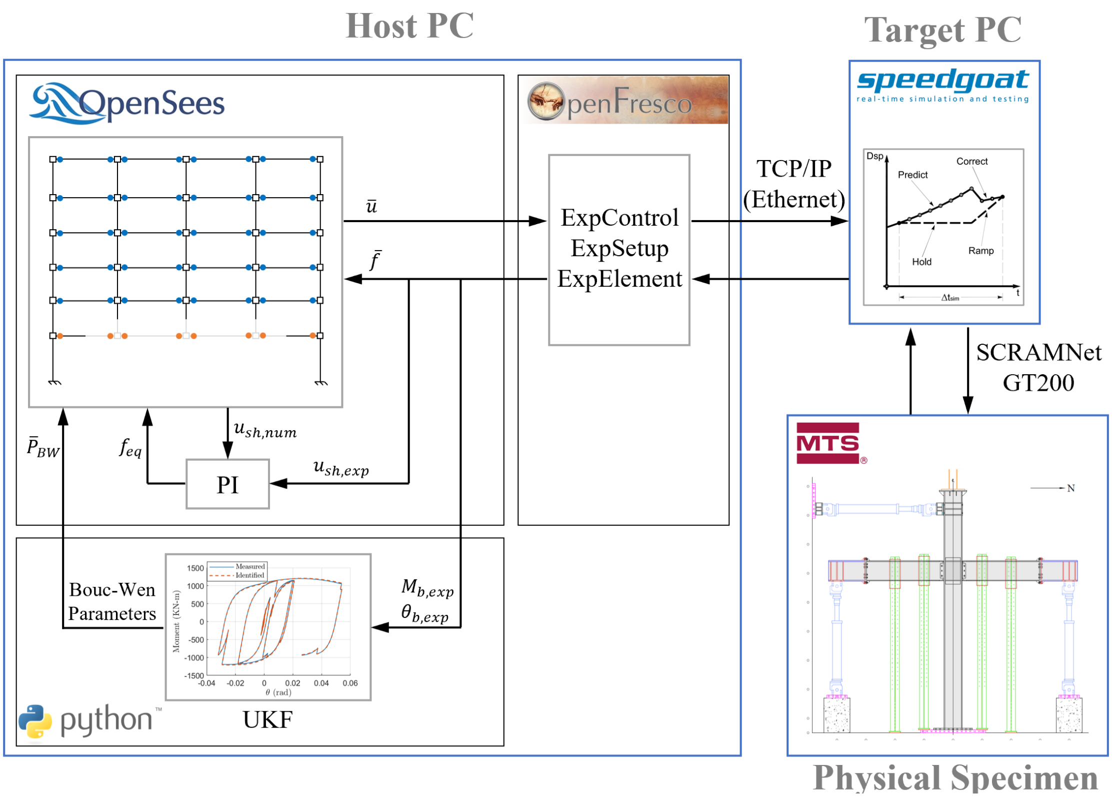


Figure 4. Flowchart of the hybrid simulation with closed-loop-based mixed displacement/force control algorithm and online model updating.

Figure 4 shows a flowchart of the hybrid simulation scheme. The structural analysis software OpenSees (McKenna et al., 2009) is used for the numerical substructure with OpenFresco (Schellenberg et al., 2009) as middleware to connect the numerical domain with the physical domain. OpenFresco exchanges information with a real-time target machine (Speedgoat xPC Target), which converts discrete signal coming from the numerical domain into a more continuous signal series using a predictor-corrector algorithm (Stojadinovic et al., 2016). Then this signal with scaled velocity is sent to the MTS controller to command the actuators. The host PC, running OpenSees, Python and OpenFresco, is connected to the real-time machine through TCP/IP connection (Ethernet), which, in turn, is connected to the MTS actuator controller through a shared memory network (SCRAMNetGT).

In the host PC, where the nonlinear finite elements model is running, two subprocesses are running in parallel. Within the OpenSees model, the vertical displacement measured in the test is transformed into the equivalent force F_{eq} shown in Figure 3 on every integration time-step. In the same computer, an online model updating algorithm is running in Python to update the parameters of the beam hinge in the numerical model. The details of these features are explained below.

ONLINE MODEL UPDATING

In a hybrid simulation, the numerical substructure is typically based on the region that can be simulated more accurately while the experimental substructure consists of components that are more difficult to model. In some cases, the complex behavior can be distributed throughout the whole structure. If components similar to the experiment exist in the numerical model, but experience slightly different deformation pattern, the measured behavior of the specimen can be used to update the model parameters of numerical substructure during the hybrid simulation (Hashemi et al., 2014). A few applications of this technique have been developed and applied recently, including a hybrid simulation carried out at Lehigh University using one nonlinear viscous damper as physical substructure and using the measured data to update the parameters of the rest of the dampers within the numerical substructure (Al-Subaihawi et al., 2022). Cheng and Becker (Cheng and Becker, 2021) developed a modified unscented Kalman filter (UKF) which combines the robustness of the constrained UKF, the ability of learning new features from adaptive UKF, and including an additional weighting on learning based on the magnitude of the input. This weighted adaptive constrained unscented Kalman filter (WACUKF) algorithm was implemented in Python, and able to update parameters in OpenSees through a network socket connection. These past studies have verified the ability to identify and update parameters using a modified Bouc-Wen model. The current version of the hysteretic model used here captures hardening or softening behavior beyond the linear range without influencing its accuracy for smaller deformations.

For the application proposed here, the WACUKF algorithm was used to identify the moment-rotation behavior of the reduced beam section (RBS) assuming that the hysteresis can be represented by the Bouc-Wen model. To obtain the required data from the experiment, the moment is calculated as the actuator force at the beam end multiplied by the distance to the center of the RBS. The relative rotation of the hinge zone is calculated as the difference between two displacement transducers: one of them located at the bottom flange and the other one located on the top flange of the beam. The measured moment-rotation hysteresis is received in the host PC and sent through OpenFresco to OpenSees, and from this stage, both signals are sent to a Python-Based code running the online model updating algorithm. The identified parameters of the Bouc-Wen model are the initial stiffness, yielding moment, and post-yielding stiffness ratio. The rest of the parameters used by Bouc-Wen model are defined offline before the test. These parameters are then sent back to the numerical substructure to update the models of the first story beam plastic hinges. Figure 5 illustrates the process.

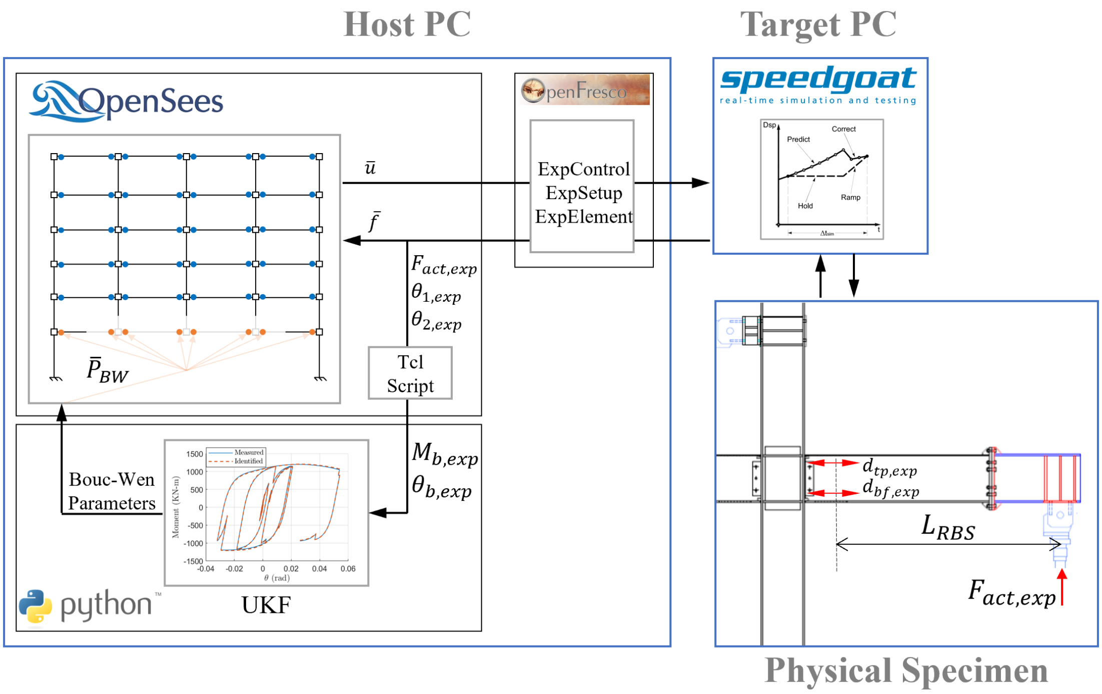


Figure 5. Flowchart of the model updating algorithm

CLOSED-LOOP MIXED DISPLACEMENT/FORCE CONTROL

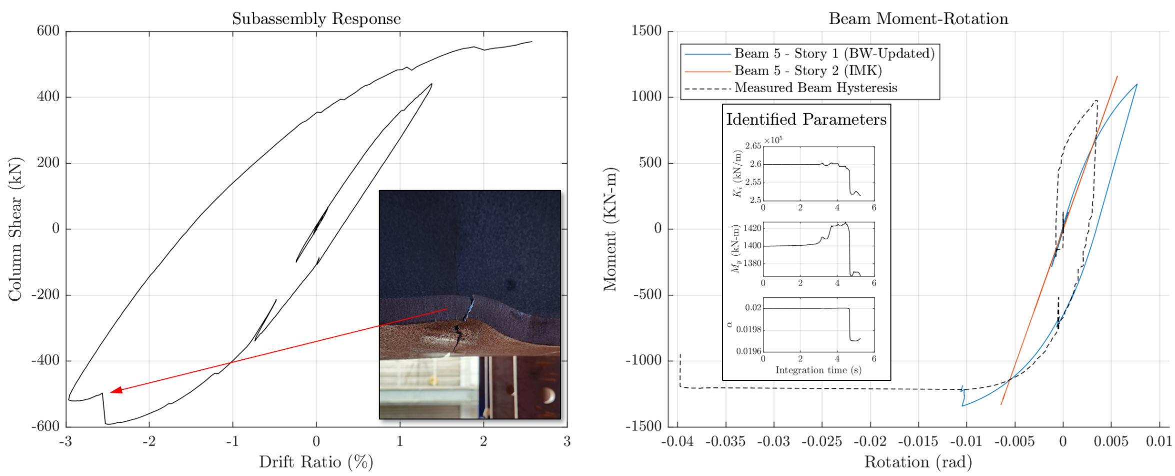
Performing a hybrid simulation using conventional displacement-control mode can be challenging for highly rigid DOFs because small displacement increments result in large variations in the applied force. Also, since the expected displacement increments are small, they can be even smaller than the resolution of the actuator (Pan et al., 2005). In this case, hybrid simulation with actuators in force-control can overcome this issue imposing a commanded force and sending back displacement feedback (Wu et al., 2007) to the numerical substructure. However, a specialized integration algorithm is needed because traditional finite element platforms are displacement based, sending displacements and receiving forces from each element. Past applications of hybrid simulations have utilized force control for stiff DOFs but neglected displacement compatibility (Del Carpio et al.,2015). In this test, a new closed-loop-based mixed displacement/force control approach is used to overcome issues with rigid DOFs while capturing column shortening (Sepulveda et al. 2022). The method is formulated for application in a traditional finite element platform like OpenSees, sending displacements for each element and receiving forces. For stiff DOFs, the command is converted to an equivalent force to be applied by the actuators in force control and the feedback is the measured displacements converted into equivalent forces. A recent test of a mixed displacement and force control including feedback forces assumed linear vertical stiffness for the columns and led to small errors in vertical displacement compatibility (Wang et al., 2022). To correct for nonlinearities in the numerical model, the equivalent force is calculated here using a closed-loop proportional-integral (PI) controller. For the closed-loop controller, the target is the feedback displacement being measured in the test u_{exp}, while the current displacement in the numerical substructure u_{num} is the observed variable. The PI controller uses the error (u_{exp} - u_{num}) to calculate the change in equivalent force F_{eq} in the numerical substructure. For every time integration step, the equivalent force is calculated based on the error and imposed in the numerical substructure as an external force.

For this hybrid simulation, the axial force command for the hydraulic jacks applying the axial load on top of the specimen is the internal axial force of one of the second story columns at the overlapped zone boundary of the numerical substructure. The vertical displacement is then measured at the top end of the first story column in the physical substructure. The feedback displacement is sent back to the numerical model and converted into the equivalent force to apply displacement compatibility between both substructures. With this method, the axial force can be imposed in the specimen and the measured displacement can be fed back into the numerical model, allowing to simulate the system behavior of the structure when column axial shortening occurs in the specimen.

RESULTS FROM HYBRID SIMULATION

A hybrid simulation was carried out using a specimen previously tested under a quasistatic protocol. The ground motion recorded during the M_w 6.9 Loma Prieta Earthquake was scaled by a factor of 1.86 to target MCE level. The axial load on the column is equivalent to 10% of the yield load. The objective of these tests was to verify the hybrid simulation algorithms including the features described previously. Additional tests are planned on undamaged specimens.

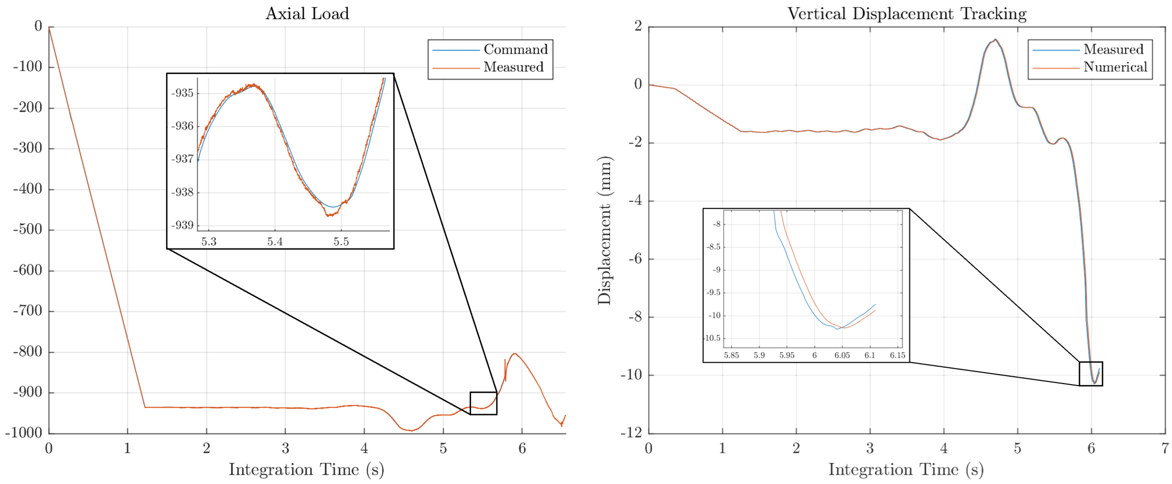
Figure 6(a) shows the column shear versus drift ratio of the specimen. The sudden drop in the resisting force is evident due to a fracture of one of the beam flanges near -3% drift ratio. Figure 6(b) shows the hysteresis for the measured response of a beam plastic hinge, the numerical hinge model at the 1st story with parameters updated from the measured response, and a numerical hinge model from the 2nd story. The fracture of the south beam produced a sudden measured rotation increment at the north beam, which was used for model updating. Because of this, the parameters started to adapt to the measured behavior and then the test was stopped.



(a) (b)

Figure 6. Force response of experimental column in horizontal direction and beam hysteresis

The performance of the closed-loop mixed-control model is verified by the equilibrium and compatibility between the experimental and numerical model in the vertical direction. Figure 7(a) shows the commanded axial load generated from the numerical substructure, and the axial load measured during the test. The initial axial load applied is 935 kN with the zoom plot showing noise on the order of 0.1 kN that is within the expected precision for using hydraulic jacks. More importantly, the axial load begins to drop as shortening increases demonstrating that the hybrid model captures this interaction. Figure 7(b) shows the measured vertical displacement due to the applied axial load including shortening and the displacement in the numerical substructure imposed through the equivalent force F_{eq} using the closed-loop approach. It can be observed that there is a small delay in the displacement imposed in the numerical substructure. This was expected because the PI controller used to estimate F_{eq} was tuned for stability instead of a faster response that could be excited by the high frequency noise in the displacement measurement. Overall, this approach can capture the coupling between the numerical and experimental substructures in the vertical direction.



(a) (b)

Figure 7. Examination of the vertical response in the numerical and experimental substructures

CONCLUSIONS

A hybrid simulation framework was developed and applied to study the complex behavior of deep slender columns under seismic loads and their interaction with the frame system. The substructuring method simplify the experimental setup to work within the limitations of the experimental facility. To improve the numerical models for beam plastic hinges, an online model updating algorithm is used to update the model parameters according to the measured data. The algorithm was tested using a virtual hybrid simulation and will be fully tested to future hybrid test. A closed-loop-based algorithm is proposed to implement a mixed displacement/force control mode to apply displacements in the numerical model compatible with the measured axial shortening in the experiment. Tests results showed that the axial behavior of the system can be simulated successfully using the proposed method. The complete framework will be implemented to simulate the nonlinear response of the system subjected to several high intensity ground motions in planned tests.

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