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TIME STEP OPTIMIZATION FOR DISTRIBUTED HYBRID SIMULATION BETWEEN UNIVERSITY OF CALIFORNIA – BERKELEY AND UNIVERSITY OF AUCKLAND

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ABSTRACT

A new real-time hybrid simulation laboratory at the University of Auckland has facilitated the first distributed hybrid tests from New Zealand. Hybrid simulation is an emerging dynamic testing technique, capable of linking finite element and physical substructures, geographically distributed at laboratories worldwide, to create a structural representation unachievable by a single laboratory alone. Structural seismic response is investigated through a simultaneous and linked regime over the internet, using numerical solutions to the equations of motion. In these first-of-a-kind distributed tests, the University of Auckland hosted a finite element model of a one-story, one-bay frame linked with the University of California-Berkeley's micro-NEES experimental column. A long simulation time step was chosen for the initial tests, where parameters investigated included both linear and nonlinear behavior and varying packet size to optimize network performance. Following this first successful distributed test series, faster simulations were performed to find an optimal simulation time step without compromising the test results. These first distributed tests performed mark an important milestone for a new mode of international collaborations between the US NEES and New Zealand.

Introduction

Hybrid simulation offers key advantages over conventional testing methods including quasi-static and shake table testing. Quasi-static testing employs actuators to apply pre-defined load or displacement histories to a specimen, designed to represent the expected loading experienced by the prototype during an earthquake. Large or even full scale specimens can be used to overcome the effects of scale and size, but the pre-determined test histories often fall short in reproducing multi-directional action expected in the prototype. In addition, the traditionally slow quasi-static tests do not reflect the dynamic response of the prototype. Although shake table testing applies a ground motion input to a structure and better captures the

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dynamic properties of the specimen, the size and weight capacity of all but the biggest shaking tables usually restrict the size and scale of the models. This leads to cumbersome similitude compensations such as added mass to compensate for the reduced volume of the specimen, and is likely to introduce errors when replicating construction details in small scale. Hybrid simulation takes advantage of the benefits of the two previous testing techniques by combining a physical quasi-static test with a computer model to simulate dynamic loading. The equation of motion for the hybrid model is discretized in time and written as

$$M\ddot{u}_i + C\dot{u}_i + r_i = f_i \tag{1}$$

where M is the mass hybrid model matrix, C is the viscous damping hybrid model matrix, r is the nodal restoring forces vector, assembled from the restoring forces from the physical and the computer portions of the hybrid model, and f is the nodal driving force vector at time step i. A displacement control scheme is employed, and a numerical integration technique is used to solve the equation of motion for the displacements at the next time step. These displacements are applied to the physical specimen, the nodal restoring forces are recorded and entered into the governing equation, and then the equation of motion is resolved at the next time step. This process repeats throughout the duration of the ground motion as the system response is recorded.

A key advantage of hybrid simulation is the ability to substructure. The well-understood portions of the structure can be represented in the finite element model, while the portions whose behavior is highly nonlinear or otherwise not well understood can be modelled physically. This physical portion can be large or full scale as the whole structure need not be modelled.

A second advantage of hybrid simulation is the ability to safely test structures to collapse, which is the focus of many recent research efforts. Since gravity loads are contained in the numerical model, there is no physical danger of falling objects and the physical specimen just needs to accommodate large displacements. At University of California-Berkeley, the micro-NEES columns were used to test a portal frame model to collapse (Schellenberg 2006).

A third advantage of hybrid testing is collaboration and sharing of work-load through distributed testing and software development. There have been very few worldwide distributed tests thus far. One such test was performed between University of California-Berkeley and Kyoto University in 2006. The prototype structure was a single-column bridge pier with two seismic isolation bearings. The finite element model was located at Berkeley and a physical isolation bearing was tested at Kyoto (Takahashi 2007). Another international hybrid test used a two-pier bridge system, with one pier physically tested at the NCREE laboratory in Taiwan, and the other pier physically tested at the National Taiwan University laboratory. The finite element model of the remainder of the bridge was located at Stanford University (Wang 2007). Taiwan also performed a four-pier bridge hybrid simulation. Three piers were physically tested simultaneously at NCREE, the National Taiwan University, and Carleton University in Ottawa, Canada (Tsai 2007). With each laboratory contributing a component of the structure, the final result is a test assembly unachievable by a single laboratory alone. Additionally, laboratories with specialty equipment can assist other institutions without access to the same resources.

The software used for the hybrid simulation performed at the University of Auckland included finite element software, Open System for Earthquake Engineering Simulation (OpenSees 2009), and hybrid simulation framework, Open-source Framework for Experimental Setup and Control (OpenFresco 2009), both developed at Berkeley. OpenFresco uses a client-server architecture, and it facilitates the communication between the client and server in either a local or distributed configuration. A client is typically defined as the finite element model of the structure and the server as the control system in the laboratory driving the physical specimen. In a distributed hybrid simulation, the client is located at one laboratory and the server at another. OpenFresco is a flexible framework, suitable for incorporating various finite element software and laboratory hardware (Schellenberg 2006).

Distributed testing performed between the University of California – Berkeley and the University of Auckland used a physical specimen located at Berkeley, under xPC-target experimental control. This control scheme implements a predictor-corrector algorithm developed in Simulink (Mathworks 2009) on a real time data processor to facilitate communications between the finite element software and the servo-hydraulic control system in the laboratory. The finite element model produces a target displacement when the time integration algorithm has converged. This event occurs at relatively long time intervals, whose length is unpredictable due to the unpredictable number of iterations that may be needed for convergence. Meanwhile, the servo-hydraulic control system requires a command at 1/1024 s intervals, selected by the manufacturer to ensure stability and good response of the servo-hydraulic control loop and the actuators. The predictor-corrector algorithm extrapolates past target displacement data points to generate predicted displacements at the required rate needed by the servo-hydraulic control system until the finite element model can provide the next displacement value (Mosqueda 2005). Then the algorithm generates new displacements to correct the previously predicted displacements to the target value. The predictor corrector must receive the next target displacement before 60% of the simulation time step elapses to leave sufficient time for correction. If the next target displacement is too slow, the actuator driving the physical specimen slows down. In distributed testing, the simulation time step interval must be longer than in a local test to accommodate network delay time.

Hybrid Model

The geometry of a one-story one-bay frame model is shown in Fig. 1, measuring 100 in (2.54 m) by 54 in (1.37 m). The bases of the two columns are fixed.

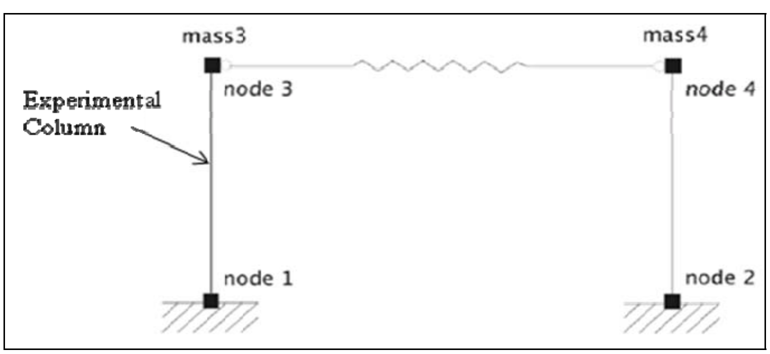

Figure 1. One Bay Frame Model Geometry.

The model was subjected to the 1940 El Centro North-South ground motion, recorded at a time step of 0.02 s. It is loaded with 15.5 kips (68.9 kN) and 7.75 kips (34.45 kN) vertical loads, applied to nodes 3 and 4, respectively, to represent the gravity effects. The right column and connecting spring were simulated in OpenSees. In the distributed test, the left column was represented using a physical specimen located at the UC Berkeley NEES Equipment Site micro-NEES laboratory, shown in Fig. 2a. This S4X7.7 cantilever column is outfitted with an idealized plastic hinge clevis connection and two coupons (Rodgers 2003). When the clevis connection is pushed well into the nonlinear range of its response, the coupons yield and buckle, as shown in Fig. 2b. The coupons are designed to be easily replaceable for the next test.

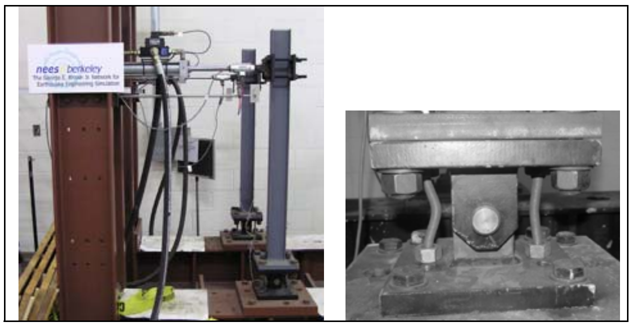

Figure 2. (a) UCB micro-NEES (Schellenberg 2008) (b) Yielded coupons (Mosqueda 2003).

The other column and beam of the one bay frame were modelled analytically in OpenSees at the University of Auckland laboratory in New Zealand. The time history integration to compute the structural response was done using a Newmark explicit method. Linear response of the hybrid model was investigated using the 1940 El Centro ground motion record scaled to 15% of its original intensity. The same ground motion scaled to 130% of its intensity was used to investigate the nonlinear response of the hybrid model.

Test Cases

The first distributed tests between Berkeley and Auckland using the micro-NEES specimen were performed successfully using a similar model to the one used in this study. A one-story, one-bay portal frame was subjected to the 1978 Tabas earthquake ground motion, recorded at a time step of 0.01 s. The structural response was solved using an implicit method with a fixed 5 iteration substeps per step (Whyte 2009). This insured that one step would not proceed after one iteration while the next step might take ten iterations. In these first distributed tests, the simulation time step was conservatively selected to be 0.5 s, meaning that OpenFresco would command the actuator to complete the target displacement in 0.5 s on a wall clock. With the earthquake record time step of 0.01 s/step and 5 iterations per step, this means that every 0.5 s simulation time step solves for 0.002 s of the earthquake record. This equates to a test performed at 0.5/0.002 = 250 times slower than real time. In practical terms, it takes approximately one hour to process the first 15 seconds of the earthquake record. The success of the simulation was determined by the cumulative displacement error between commanded displacements from OpenSees to the micro-NEES test setup and the measured displacements. The other criterion was how many times the actuator had to slow down and wait for the next displacement command from OpenSees. As mentioned above, this slow down occurs if the next displacement command has not arrived by the time 60% of the simulation time step has elapsed. For the distributed tests using a simulation time step of 0.5 s, there was minimal cumulative displacement error. There were no actuator slowdowns in the linear test case (0.15 x earthquake ground motion) and just 3 actuator slowdowns in the nonlinear test case (1.3 x earthquake ground motion).

After successfully implementing these initial distributed tests, the focus turned to understanding the optimal conditions for distributed hybrid testing over large geographic distances. First, the data packet size sent over the network was varied to maximize transmission speed. Once the appropriate packet size was selected, the round trip packet time between Berkeley and Auckland was monitored every 30 minutes over the course of a week.

Then using the one bay frame model shown above in Fig. 2, a series of linear tests were performed both locally at Berkeley and distributed between Berkeley and Auckland, using simulation time steps between 0.1 s and 0.7 s. This resulted in an optimal simulation time step for this particular hybrid model and integration procedure. A smaller number of nonlinear distributed simulations were then performed to confirm the chosen simulation time step.

Results

Network Performance Tests

The data packet size sent between Berkeley and Auckland was varied to maximize network speed. OpenSees logs the time per iteration over the course of a test. Using the portal frame model, the average value for each test was recorded for each data packet size in Fig. 3. Since the default packet size of 256 64-bit doubles had the fastest time of 0.311 s/iteration, this packet size was selected for all remaining distributed tests. Additionally, the round trip packet time between Berkeley and Auckland was recorded every 30 minutes over the course of a week, shown in Fig. 4. This was very consistent at 163 ms with approximately two outliers per day. Such stable network performance is beneficial for repeatability of distributed test results.

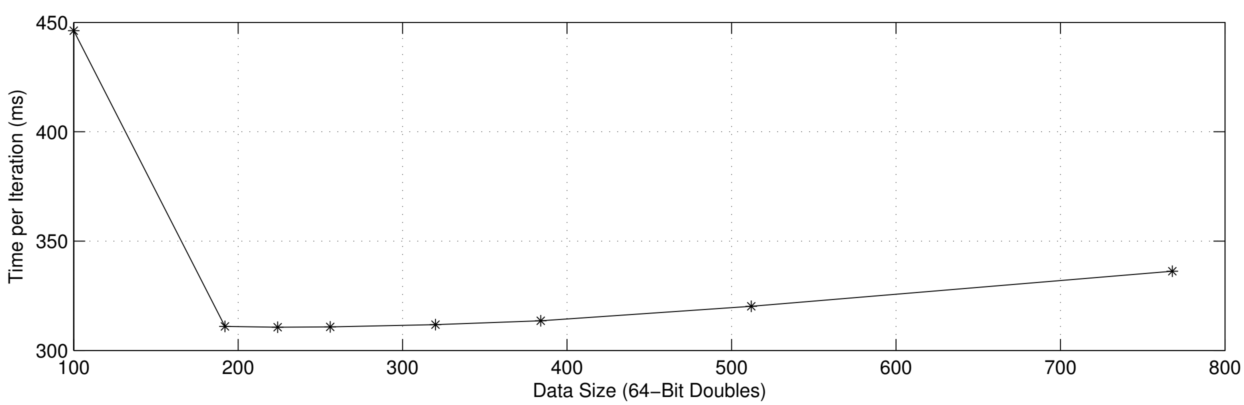

Figure 3. Network packet transmission time.

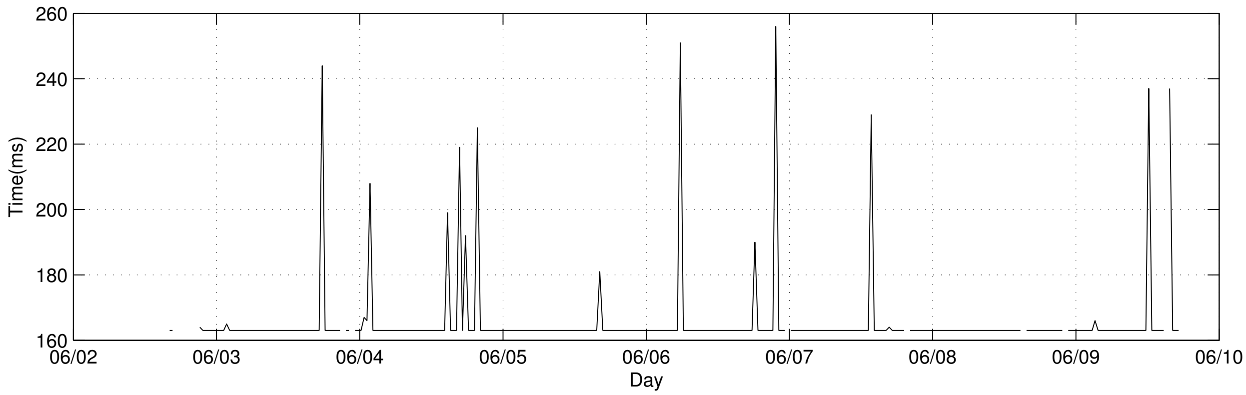

Figure 4. Round trip packet time between Berkeley and Auckland.

Distributed Hybrid Tests

Using the one story one bay frame model, linear distributed hybrid tests were performed with simulation time steps varying from 0.1 s to 0.7 s. Linear structural behavior was achieved by applying the 1940 El Centro earthquake ground motion at 15% of its recorded intensity. Corresponding local implementations of the same tests (with all hybrid model components located at the UC Berkeley NEES Equipment site and connected on a local fiber-optic network) were also performed for the same range of simulation time steps and for the real time case with a simulation time step of 0.02 s, equal to the time step of the ground motion record. The cumulative error between target displacements sent to the physical specimen and measured displacements from the physical specimen was calculated for each simulation time step. Additionally, the percentage of steps that the actuator slowed down was calculated for each simulation time step. Based on these results, an optimal time step was selected for the distributed tests. To confirm this selection, distributed tests exhibiting nonlinear behavior were also performed. This was achieved by applying the 1940 El Centro ground motion scaled to 130% of its recorded intensity. These results are displayed in Fig. 5.

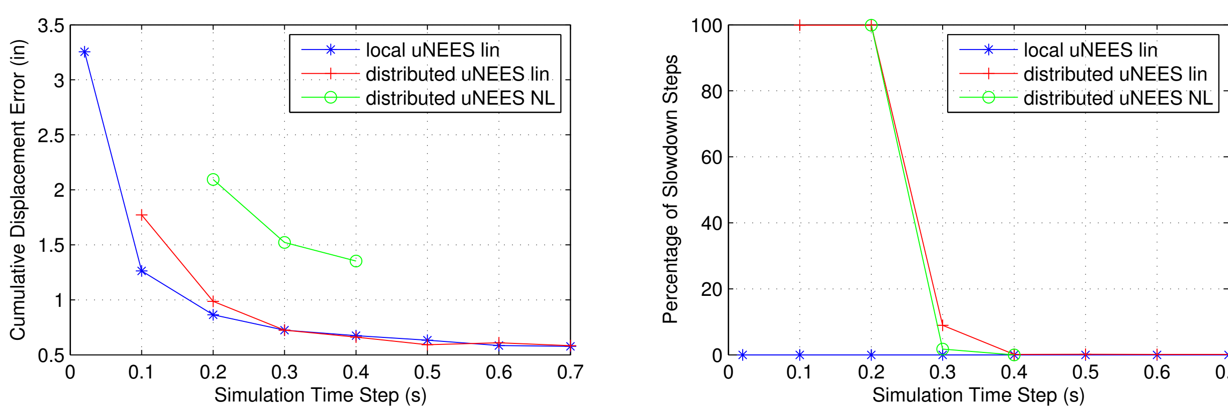

Figure 5. (a) Cumulative displacement error (b) Percentage of actuator slowdown steps.

From the cumulative displacement error plot, the linear local (local uNEES lin) and linear distributed tests (distributed uNEES lin) were compared. For the faster simulation time steps of 0.1 s and 0.2 s, the distributed case showed more errors than the local case. Additionally, practically all of the time steps were slowed down in both distributed tests. Once the simulation time step was increased to 0.3 s, the distributed linear test performs as well as the local test with 0.73 in (1.85 cm) cumulative displacement error. The actuator slowed down during 8.9% of the steps, but this is accepted considering it does not introduce any extra displacement error. Thus, a simulation time step of 0.3 s was chosen to be appropriate for this test. This is 15 times slower than real time ($dt_{sim}/dt_{int}=0.3/0.02=15$). After selecting a simulation time step of 0.3 s as optimal for this model, distributed nonlinear tests (distributed uNEES NL) were performed with simulation time steps of 0.2, 0.3, and 0.4 s. In the cumulative displacement error plot, the nonlinear distributed tests follow the same trend as the linear distributed tests except with approximately 2 in more cumulative displacement error for each simulation time step. At a simulation time step of 0.3 s, the nonlinear distributed test had 1.52 in (3.86 in) cumulative displacement error. 1.75% of the steps had actuator slowdown. This is slightly less than in the linear distributed case and is due to some variability in the communication network.

Figure 6a displays the error between the measured displacements in the local and distributed tests for a simulation time step of 0.3 s. Figure 6b shows the FFT of the error. In the frequency domain, the peak is located at 0.1042 Hz. This corresponds to a vibration period of 9.594 s. Since the test is 15 times slower than real time, the non-real-time vibration period of 9.594 s corresponds to a real-time vibration period of the hybrid model equal to 0.64 s. This closely matches the actual period of the hybrid model of 0.62 s.

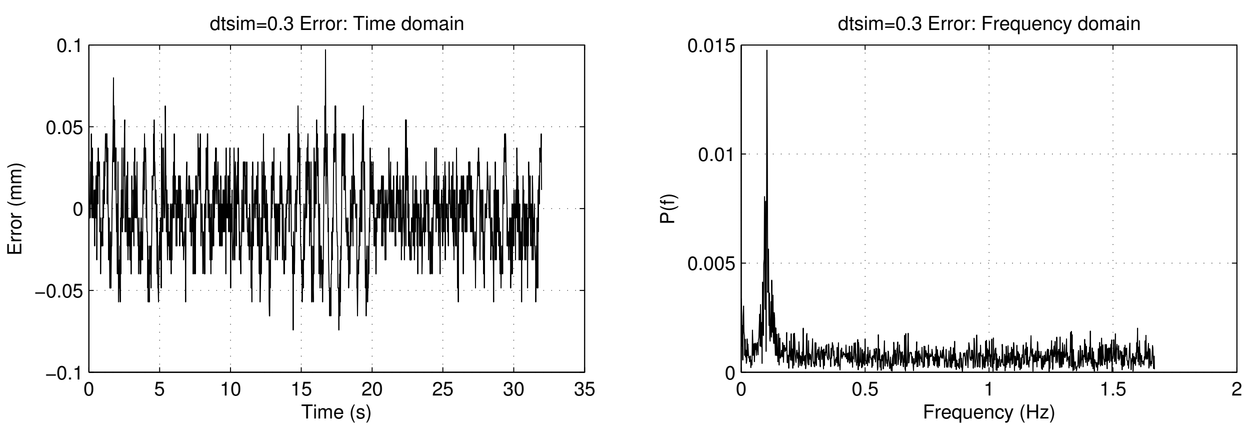

Figure 6. (a) Error between local and distributed tests (b) FFT of error.

Fig. 7 below shows a tracking indicator, developed by Mercan (Mercan, 2007). The indicator measures the accumulation of area enclosed in the hysteresis loops of measured displacement plotted against target displacement for the experimental specimen. Since the indicator is decreasing, the displacement response is lagging and energy dissipation is negative. The 0.3 s simulation time step achieves the same tracking indicator value in both the local and the distributed simulation cases, shown in Figures 7a and 7b, respectively. Longer simulation time steps are also consistent in the local and distributed cases, and result in less cumulative error. Nevertheless, the 0.3 s simulation time step length was selected as it represents a good compromise between the induced error and the speed (and ultimately the duration) of the test.

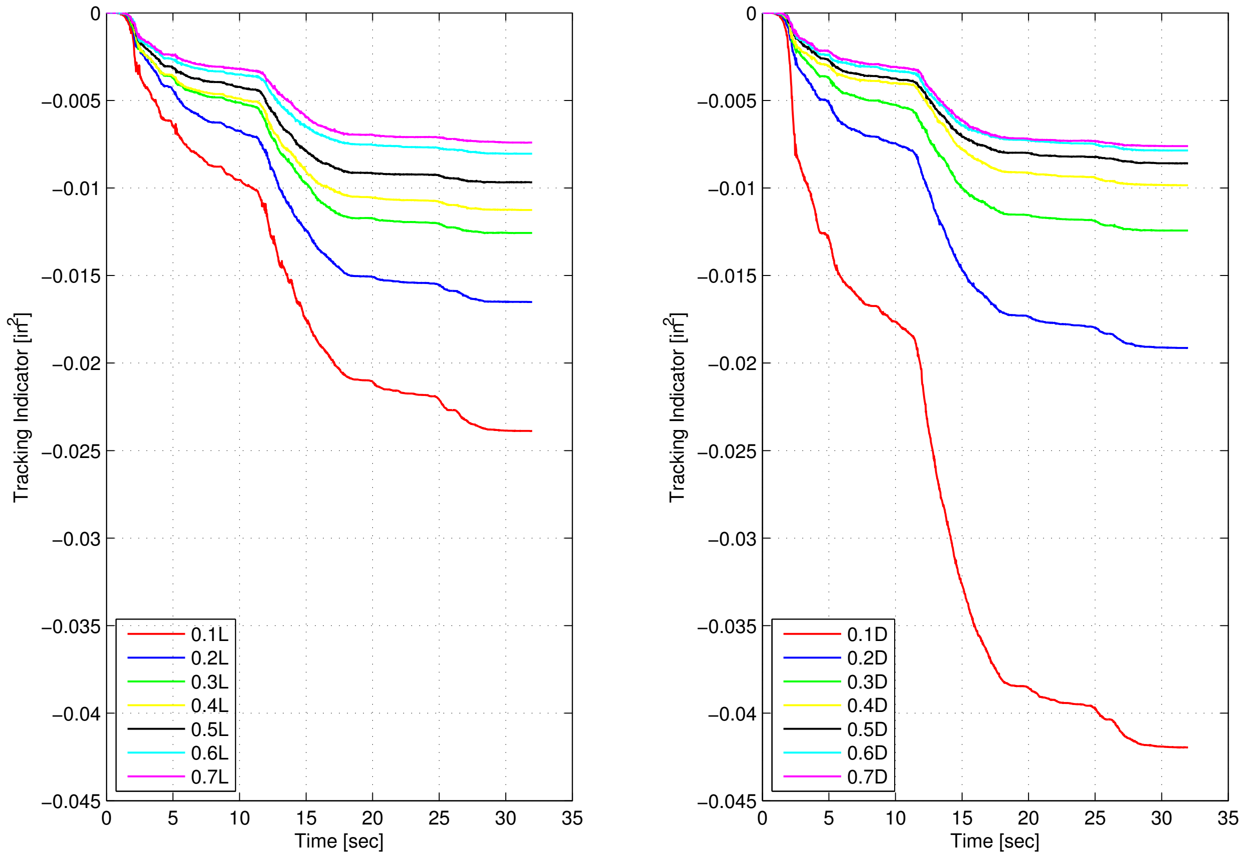

Figure 7. Mercan tracking indicator for (a) local linear simulations and (b) distributed linear simulations.

Concluding Remarks

Distributed hybrid simulations have been successfully performed between the University of California-Berkeley and the University of Auckland. The time for packet transmission between the two universities was monitored over the course of a week to aid in finding an appropriate simulation time step for the distributed simulation. This type of network performance information would be valuable between NEES sites. Considering cumulative displacement error and the percentage of steps that the actuator slowed down to wait for the next displacement command, a simulation time step of 0.3 s was chosen as optimal. For the case of linear structural behavior, the distributed test gave the same cumulative displacement error as the local test. Nonlinear structural behavior was also tested and the chosen simulation time step was still appropriate. Thus, the distributed test can be completed 15 times slower than real time.

The University of Auckland is building a specimen in their new hybrid testing laboratory, which will be included in future distributed testing. The successful testing of this one story, one bay frame hybrid model has helped to establish a method for selecting an appropriate time step for distributed tests of more complex structures. Future collaborative tests between the UC Berkeley NEES Equipment Site and the University of Auckland hybrid simulation laboratory will focus on the sensitivity of time step duration on the complexity of the hybrid model both with respect to the number of experimental sub-structures and the nonlinearity of the model response, as well as the sensitivity of the test speed to the chosen integration algorithm. These studies will ultimately provide guidance for design of distributed hybrid model simulations that explicitly account for the performance of the network and the performance of the computational and controller hardware involved in the test.

Acknowledgments

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