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# ONLINE P-DELTA CORRECTION FOR MULTI-DEGREE-OF-FREEDOM HYBRID SIMULATION TESTING

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## Abstract

Hybrid Simulation (HS) is a fast-growing computational/physical testing technique that can replace shaking table tests using an online computational substructure to update the input signal based on the feedback from the physical substructure. This paper presents the development and validation of a new Hybrid Simulation System (HSS) and communication scheme with online P-delta correction capabilities. The developed HSS utilizes readily available laboratory data acquisition (DAQ) systems along with inexpensive TCP/IP-Ethernet protocols to establish multi-degree-of-freedom communication between the physical and computational substructures. An approximate method for accounting for the P-delta effect from both of the gravity load and the vertical earthquake excitations was devised for application to bridge systems. The P-delta correction arithmetic operation is performed using a Digital Signal Processor (DSP) subroutine and relies on adjusting the lateral force feedback before it is sent back to the HS computational model to solve for the next displacement input step. The developed HSS comprises a novel hybrid computational model where part of the computations is performed using a finite element platform while another part is performed using a DSP subroutine. To verify the new system communication loop, several single and double free actuators, i.e. not attached to specimens, were used. Moreover, a repaired reinforced concrete bridge column-bent cap-box girder subassemblage was used to conduct a large-scale bidirectional HS trial tests using the developed system for further verification. Another similar bridge subassemblage specimen was used to conduct HS tests with and without including the P-delta correction to investigate and verify the correction method. The verification tests are discussed herein where the new communication scheme and the entire HSS were shown to be accurate.

*Keywords: MDOF Hybrid Simulation; P-Delta Effect; Reinforced Concrete Bridges*

# 1. Introduction

Hybrid Simulation (HS) was first introduced by Takanashi et al. [1], who referred to the method as "online test". The essence of HS is to use an online computational substructure to update the earthquake input signal at each time step based on the force feedback from the physical substructure. In the last three decades, there were significant development efforts in different HS areas that included, but not limited to, development of suitable integration methods (e.g. Nakashima and Masaoka [2]; Magonette [3]), study of the effect of experimental errors (e.g. Mosqueda [4]; Elkhoraibi and Mosalam [5]), and real-time HS (e.g. Mosalam and Günay [6]). Large portion of the previous studies that involved HS focused more on the development side and robustness of the testing method. However, several studies utilized HS directly in different applications (e.g. Mosalam et al. [7]; Terzic and Stojadinovic [8]).

The main objective of this paper is to present upgrading a recently developed Hybrid Simulation System (HSS) at the University of California, Berkeley [9] with an online P-delta correction scheme. A brief discussion of the HSS development and verification along with P-delta implementation and effect on response of large-scale bridge subassemblage is presented. The developed practical HSS utilizes readily available laboratory data acquisition (DAQ) systems along with inexpensive TCP/IP-Ethernet connections to establish the communication between the physical and computational substructures. The HSS was primarily developed to test a ¼-scale retrofitted bridge subassemblage (designated as SP2) and compare its behavior to an as-built identical specimen tested under cyclic loading (designated as SP1) [10]. However, the first specimen SP1 that was tested under cyclic loading only was repaired and used in a HS trial test to verify the developed HSS before using it for testing SP2. The HSS was then upgraded with an approximate online P-delta correction scheme. The second specimen SP2 was used to conduct preliminary tests to investigate the effect of incorporating the P-delta correction.

The main development of the HSS presented here is the Pacific Instruments (PI) DAQ interface to communicate with OpenFresco [11] from the computational side and a Digital Signal Processing (DSP) card from the experimental side. The PI interface communicates with OpenFresco through an inexpensive Ethernet connection to replace expensive shared memory communication cards such as SCRAMNet while controlling the laboratory hardware and receiving the physical substructure feedback via the DSP card. Moreover, the devised P-delta correction involves simple arithmetic operations that take place at the DSP card to adjust the measured lateral force while feeding it back to the loop. One last development is a new test setup component in OpenFresco to perform geometric transformations between the computational model global degrees-of-freedom (DOFs) and the actuators local DOFs for the command displacements and force feedbacks. More details of each of the aforementioned developments, system verification, and large-scale bridge system tests results are presented in the following sections.

# 2. Hybrid Simulation System and developments

To perform a HS test, several key components of software and hardware are necessary. The components of the specific HSS utilized in this study and the new developments in the system are discussed in this section.

## 2.1 HS Components

Four main components comprise a typical HSS. The first is a discrete model of the structure to be computationally analyzed under any static and the dynamic loading. The finite element (FE) method is used to discretize the problem spatially and a time-stepping integration algorithm is used for the solution of the equations of motion with time discretization. The second required component is a transfer system consisting of a controller and static or dynamic actuators, so that the incremental response (generally the displacements) determined by the time-stepping integration algorithm can be applied to the physical substructures. For slow tests such as the ones conducted in this study, quasi-static testing equipment can be used. The third major component of the HSS is the physical specimen that is being tested in the laboratory and a support system (e.g. reaction wall or frame and a strong floor) against which the actuators of the transfer system can react. The fourth component is a DAQ system including displacement transducers and load cells. This data acquisition system in this study is responsible for measuring the response of the test specimen and returning the resisting forces to the time-stepping integration algorithm to advance the solution to the next analysis step. A vital feature of HS is to connect the above-mentioned four components together to achieve reliable two-way communication for sending the displacement input and receiving the force feedback. The major components and their connectivity of the utilized HSS at the Structures Laboratory of the University of California, Berkeley are shown in Fig.1. The main components identified in this figure are: (a) A computational platform where the numerical integration of the governing equations of motion is performed (OpenSees [12] was used in this case), (b) OpenFresco [11] generic middleware that communicates with the computational platform, (c) New interface software developed within the PI DAQ that communicates, in turn, with OpenFresco through TCP/IP connection, (d) DSP card that further complements the communication loop with the laboratory hardware and performs the P-delta correction operations, and (e) digital controllers that command the hydraulic actuators in displacement control.

Two multi-DOF computational models were considered in this study. The first model was a generic one with many DOFs that was used only for the verification tests that used the free actuators without any attached specimen. A multi-story multi-bay frame was used in this computational model where one of the first story columns was replaced by the experimental element. A simulation experimental element, available in OpenFresco and based on input material and geometric properties, was used instead of an actual experimental physical substructure. In this case, a multiplier (assumed stiffness) of the displacement of the free actuators in the HS verification tests was used as a virtual force feedback to the hybrid system to check the communication loop against the pure simulation results. The second computational model was used in the bridge subassemblage HS tests and consisted of multi-DOF column with lumped mass at the top and defined damping ratio. The lumped mass was calibrated to reflect a representative segment of the prototype bridge used in the study [10]. Damping was modeled as Rayleigh damping with coefficients determined using 5% damping ratio for periods corresponding to the transverse and longitudinal modes of vibration. The physical substructure used with the second computational model was a ¼-scale reinforced concrete (RC) column-bent cap-box girder bridge subassemblage. Moreover, the HSS verification tests used different ground motions with more cycles and harmonic nature, such as the El Centro record, and pulse-like nature, such as the Rinaldi record.

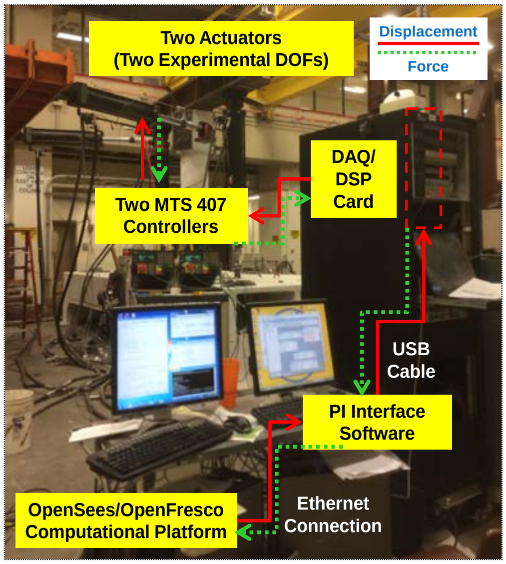



Fig. 1 – Overview of the main components and connectivity of the developed HSS.

OpenSees [12] was used as the FE software to analyze the computational substructure and solve the dynamic equation of motion for the displacement at each time step. Moreover, OpenSees was used along with the middleware OpenFresco [11] to connect the FE model with the control and data acquisition software. OpenFresco is designed in an object-oriented structure that is similar to OpenSees and shares common classes, e.g. for element types and numerical integration methods. Therefore, OpenFresco is most conveniently used with

OpenSees as the FE platform and a single OpenSees/OpenFresco input file (prepared using the Tool Command Language, TCL) to define the computational model and the communication settings.

To properly connect all the HSS components, a robust communication loop is indispensable. In general, the readily available OpenFresco software comprised the main part of the necessary middleware needed for connecting the FE software and the experimental control and DAQ systems. However, OpenFresco lacked the needed experimental setup to perform the specific geometric transformations between the global DOF and the local DOF of the lateral actuators per the required setup for the bridge subassemblage test [10]. Thus, implementing a new experimental setup object in OpenFresco was the first development to achieve the sought HSS. On the other hand, to avoid using expensive shared-memory network cards, such as SCRAMNet, to communicate with the controllers, a practical use of the inexpensive TCP/IP Ethernet connection was another objective sough in this HSS. Although a generic TCP control is available in OpenFresco, an interface that utilizes such TCP connection to communicate the commands to the controllers was required. The PI DAQ software was modified to encompass a new module that can integrate the networking capabilities of the DAQ console along with the programmable DSP card to achieve the desired PI interface as the second development achieved in this study. The third development was the P-delta correction scheme which involves simple arithmetic operations and was implemented using a DSP subroutine. More details about these three developments are presented in the following subsections.

## 2.2 Development I: OpenFresco New Experimental Setup

The *ExperimentalSetup* is one of four main classes in OpenFresco. The transformation of the prescribed boundary conditions from the local or basic element DOF of the experimental elements into the actuator DOF of the transfer system is the first core task of the *ExperimentalSetup* class. Similarly, the transformation of the work conjugates measured by transducers and load cells back to the experimental element DOF is the second core task of the *ExperimentalSetup* class [11]. For the HS tests considered in this study, the two horizontal actuators used for applying the lateral load were arranged in a planer triangular configuration. A new *ExperimentalSetup* object was required in OpenFresco to perform the geometric transformation between the two model (global) DOFs, designated as *x* and *y*, and the two actuators (local) DOFs, designated as 1 and 2, as shown in Fig. 2. The sough transformation is applied to the computed displacements such that displacement command readily in each actuator DOF is delivered to the corresponding controller. Similarly, the received force feedback in each actuator DOF is transformed to the *x* and *y* DOFs before passing it to the FE software to proceed with the next time step calculations. The “TriangularActatuors” object was successfully developed and implemented in an updated version of OpenFresco. The TCL syntax input for the new experimental setup is as follows:

expSetup TriangularActuators *$tag* -control *$ExpControltag $A1 $A2 $B1 $B2 $C1 $C2*

where *$ExpControltag* is the defined tag for the used experimental control object, which is the GenericTCP in this case, and *$A1*, *$A2*, *$B1*, *$B2*, *$C1*, and *$C2* are geometric input parameters that describe the relative locations of the two actuators as identified in Fig. 2.

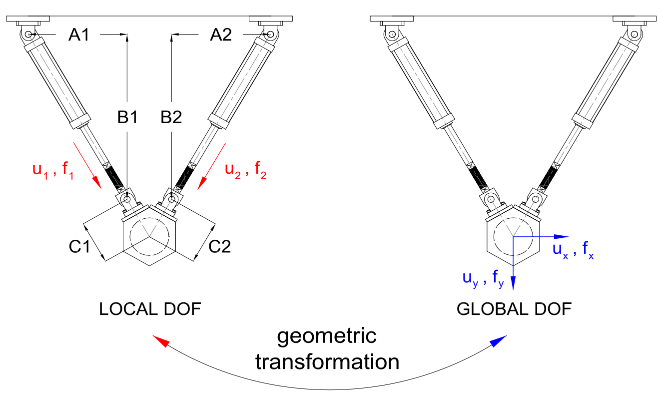
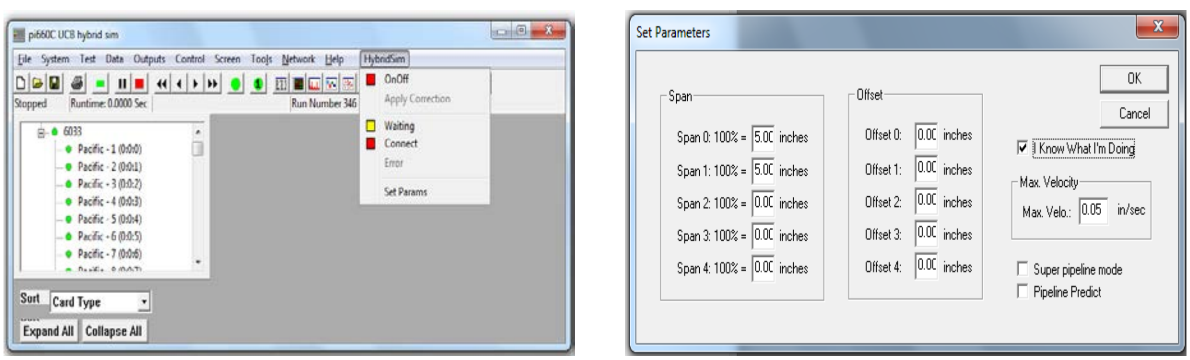



Fig. 2 – Input displacement and measured force feedback geometric transformation between the model global DOFs and the actuators local DOFs.

### 2.3 Development II: New PI Interface

An important development achieved in this study is a practical interface between OpenFresco and the controllers. This interface is built into the PI DAQ system. The final interface consists of two parts: (1) Microsoft Windows application customized from the PI DAQ software, and (2) PI test file containing specific PI6042 DSP routines.

***Microsoft Windows Custom Application:*** The application *PI660C UCB HybridSim* interface is a heavily modified version of the original *PI660C DAQ* program. The modifications include the addition of a TCP communications interface, an OpenFresco command interpreter, and a raw data format handler and translator. The main purpose of this PI interface is to exchange displacement and force vectors up to 5 DOFs with OpenFresco over an Ethernet TCP/IP connection. Thus, this application is responsible of receiving the displacement vector from OpenFresco and passing it through the DSP routines to the controllers. In addition, it receives the force feedbacks from allocated memory locations and send them back to OpenFresco. All the operations performed through this part of the interface utilize data in the actuators DOF. The geometric transformation to the global DOFs to solve the equations of motion takes place in OpenFresco through the new *ExperimentalSetup* class, as previously discussed. A screen shot of the *PI660C UCB HybridSim* Microsoft Windows application is shown in Fig. 3a. The figure shows the implemented module that handles the HS mode and sets its parameters. A set of parameters that can be assigned beforehand are shown in Fig. 3b. All the parameters are considered input for the DSP routines that are called through the PI application. Because the interface can exchange data from up to 5 DOFs, a span definition is required for each of these 5 DOFs for control purposes. The rate of loading, defined in terms of the maximum velocity, is one of the parameters input shown in Fig. 3b. A maximum velocity is defined instead of a constant one because based on the number of controlled DOFs, one actuator might have to slow its velocity to match other actuators motion. The reader is referred to [9, 13] for more details are available.




(a) (b)

Fig. 3 – Screen shots of the new PI interface with: (a) HybridSim module; and (b) HS parameters.

***PI6042 DSP routines:*** The DSP routines are responsible for the low-level, high-priority, and time-sensitive tasks. The main purpose of these routines is the motion interpolation and data generation tasks. They are also responsible for data acquisition hardware handling, e.g. sending and receiving analog signals via the USB data link interface to and from the computer where the new PI interface is running. The DSP program is uploaded via a USB link from the control computer to the PI6042 DSP cards residing in the PI6000 chassis and executed once per data acquisition scan. The PI6042 DSP routines were coded in a Reversed Polish Notation (RPN), close variant to the Assembly Language. The RPN routines are executed once per data acquisition scan cycle at the requested sampling rate. For proper operation, the sampling rate required to define the actuators path velocity was set to 10 msec for the HS trials and tests conducted in this study. The RPN routines, called by the *PI660C UCB HybridSim* interface, are executed on the PI6042 DSP card sequentially at every data acquisition scan. One of the main functions of these routines is to interpolate the final end-displacement at a given time step, as received from OpenFresco via the new PI interface, and deliver the interpolated calculated signal to the MTS 407 controllers. The physical connection for the interpolated signal transfer to the controllers is a standard BNC to BNC cable where one end is connected to the DSP card in the PI chassis, and the other end is connected to the controller.

## 2.4 Development III: P-Delta Correction

In structural analysis, P-delta refers to the abrupt changes in a sufficiently tall structural component base shear and bending moment when it is subjected to lateral displacement. The P-delta effect can be interpreted as a destabilizing secondary moment that results from a vertical gravity force multiplied by the lateral displacement as schematically represented in Fig. 4a. Accordingly, in case of progressing lateral displacements, the destabilizing secondary moment increases and can cause instability or complete collapse. The P-delta effect is more dramatic in buildings, especially tall buildings, more than bridges because of the elevated gravity load levels at the lower floors columns. The vertical ground excitations can additionally increase the axial load levels, which can accelerate the collapse. In bridges, the gravity loads are not typically high as in the case of buildings, yet at large lateral displacement, the P-delta effect might be pronounced. Moreover, the developed HSS and P-delta correction scheme are generic and can be used for any other applications.

In this study, an approximate method for accounting for the P-delta effect from both of the gravity load and the vertical excitations was devised for HS testing. That is through correcting the lateral force feedback before it is sent back to the computational model to solve for the next displacement input step. Given the known lateral displacement at a time step, the acting gravity load along with the additional axial load resulting from the solution of the computational model under the vertical excitation were utilized to calculate the P-delta secondary moment, and accordingly, correct the lateral force feedback. Fig. 4a shows schematically how the corrected force is achieved when the P-delta effect is incorporated. The simple arithmetic operation to correct the force feedback is performed using a DSP subroutine that is performed within the PI6042 DSP routines discussed above, and is similarly coded using RPN. The split computations provide additional flexibility for future development where the conventional DAQ system can be used to accommodate a hybrid computational model, i.e. part of the computations is performed using the FE platform while another part is performed using DSP subroutines.

The P-delta correction involved the applied gravity load during a HS test as well as the corresponding axial force resulting from the vertical excitation calculated using the model featured in Fig. 4b. This model assumes that the vertical response is decoupled from the lateral response, which is one limitation of the devised correction scheme. This limitation, however, can be acceptable for the inverted bridge subassemblage application considered in this study. A different P-delta correction force is calculated at each time step to accommodate the fluctuating total axial load from the gravity and the vertical excitation. The solution in the vertical direction for the bridge subassemblage model assumed a bi-linear force-deformation of the interacting column-bent cap-box girder system as shown in Fig. 4b. This approximation aimed at capping the resulting vertical force at a certain limit based on extensive 3D FE bridge model vertical pushover and triaxial time history analyses [13].

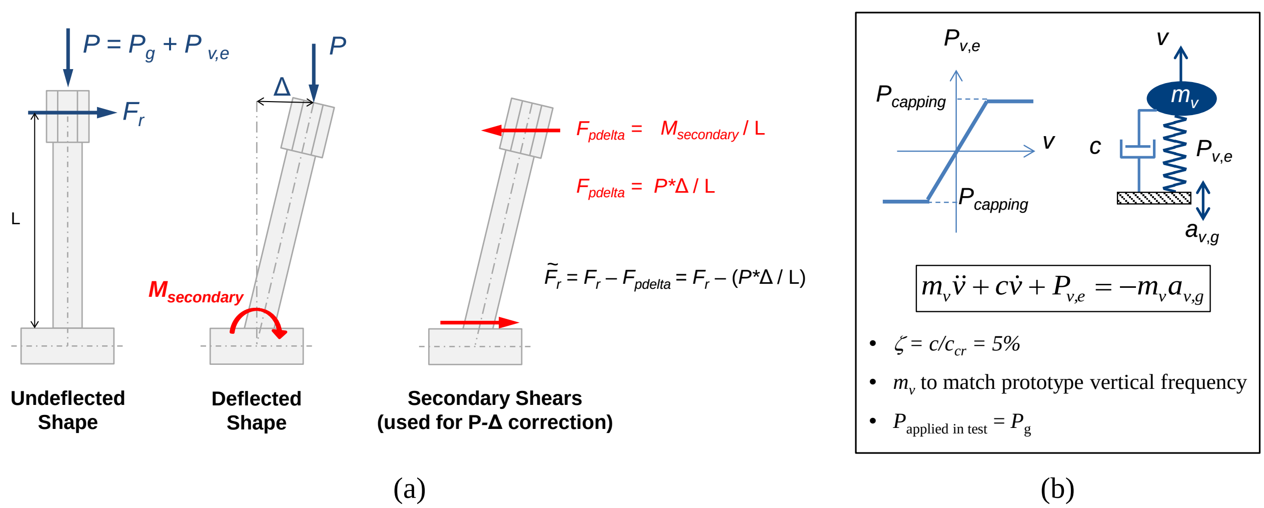



Fig. 4 – (a) Schematic representation of the P-delta (P-Δ) correction; (b) Computational model used for including vertical excitation in the P-delta correction.

## 3. HSS Verifications

To confirm the performance of the implemented developments and validate the HSS for testing, several trials and verification tests were conducted. The verification tests started with network protocol analysis, then utilized single and double free actuators, i.e. not attached to any physical specimens, as presented in this section.

### 3.1 TCP/IP Network Stack

Numerous performance and characterization tests were performed on the TCP/IP performance between the OpenFresco/OpenSees platform and the new *PI660C UCB HybridSim* interface. These characterization tests were performed directly using the Wireshark network protocol analyzer program [14], which attaches directly to the network software stack and records all the Ethernet packets traversing the Ethernet interface, commonly referred to as “sniffing”. By looking at the timestamps and decoding the packet payloads, the traffic flow and timing were understood. A screenshot of the Wireshark sniffing of an established Ethernet TCP/IP connection in the developed HSS is shown in Fig. 5. The Ethernet TCP/IP network transactions flowing through a preliminary established connection between the OpenFresco platform and the new PI interface was analyzed. The timing data from the Ethernet transactions first indicated a latency of approximately 216 msec. In order to reduce latency, the transmit buffer of OpenFresco was resized to be an integer multiple of the payload size of the Ethernet frame, i.e. the OpenFresco variable *OF_Network_dataSize* was modified from 256 to 365 such that on every network transaction, two totally filled Ethernet frames were utilized. Adjusting the OpenFresco packet size reduced the latency to 70 msec. Due to the slow loading rate of the test in this study, 70 msec latency was insignificant to alter the HS communication.

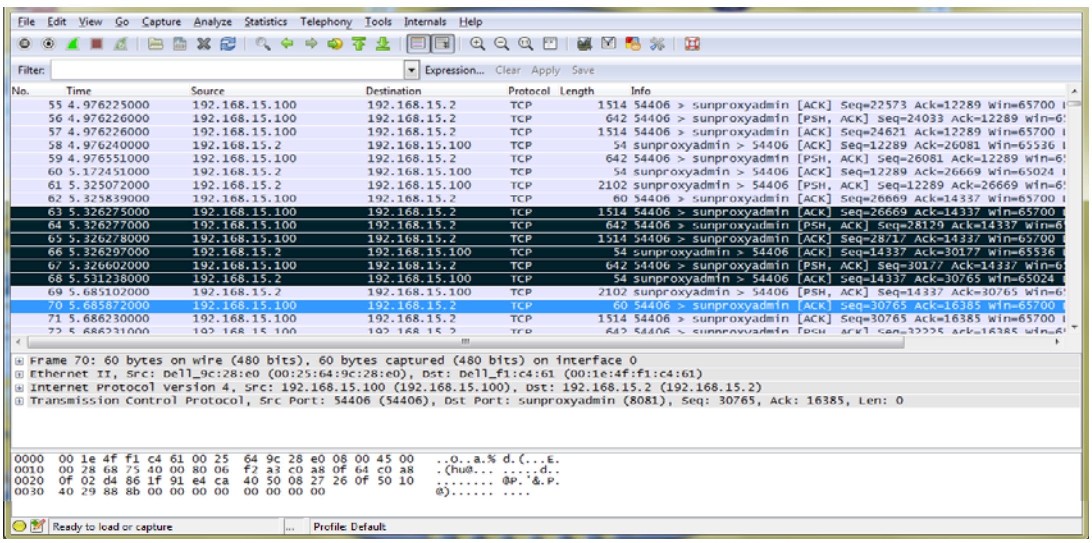


Fig. 5 – Screenshot of the Ethernet TCP/IP network packet analysis using Wireshark [14].

### 3.2 Standalone Actuator Tests

Single and double free actuators, i.e. not attached to any physical specimens, were used to conduct numerous verification tests for one or more components of the developed HSS including the P-delta correction scheme. The single actuator tests considered a large multi-DOF computational model to test the communication loop between all components of the HSS. Two-way communication is necessary in HS; one way is for sending the displacement command and the other is for receiving the force feedback. A free actuator that is not attached to any specimen will report zero force feedback or only the load cell noise. Thus, for the free actuator trials, a multiplier (stiffness) of the displacement command was fed back to the DSP and DAQ as a virtual force feedback. The constant multiplier reflected the stiffness of a hypothetical linear force-displacement relationship. The advantage of this virtual feedback is to compare with pure simulation results where an elastic element with a constant stiffness replaces the actuator displacement/force feedback virtual experimental element. A multiplier of 2 was chosen for the displacement feedback to the DSP to reflect a hypothetical elastic element with 2 kip/in. stiffness, which was comparable to other columns in the hybrid model to compare with the pure simulation case.

The obtained displacement and force histories from the pure simulation were compared to those from the HS recorded data at both OpenSees and the PI DAQ in Fig. 6. OpenSees recorded the displacements obtained from the solution of the equation of motion at each time step along with the discrete force feedback at solution time steps only when received through the new PI interface. Meanwhile, the PI DAQ recorded the actual command data, i.e. actuator motion, and its multiplier when received at the DSP card. The comparison shows the perfect match between the simulation and the HS tests. Despite the perfect match in the displacement amplitudes, the progression with time was different from the actual actuator motion and the OpenSees command, or pure simulation case. This is expected and attributed to the constant velocity or rate of loading used for commanding the actuator. The DSP routines were used to interpolate the received displacement command and apply it smoothly to the controller to pass it to the actuator with a constant velocity. The linear actuator displacements shown in Fig. 6 reflect a constant slope, i.e. constant actuator velocity as required. Therefore, the good comparison between the HS tests that used a hypothetical feedback of a constant multiplier applied to the actual command, and the pure simulation provided confidence on the accuracy of the communication loop among the different HSS components.

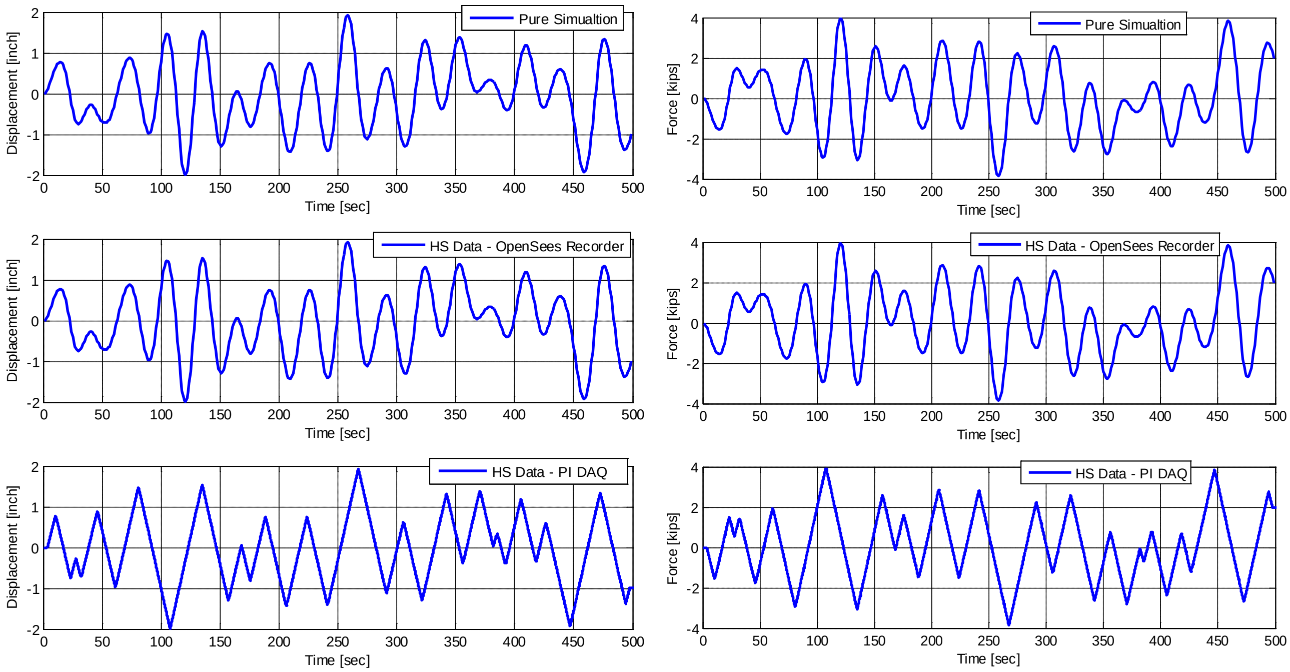
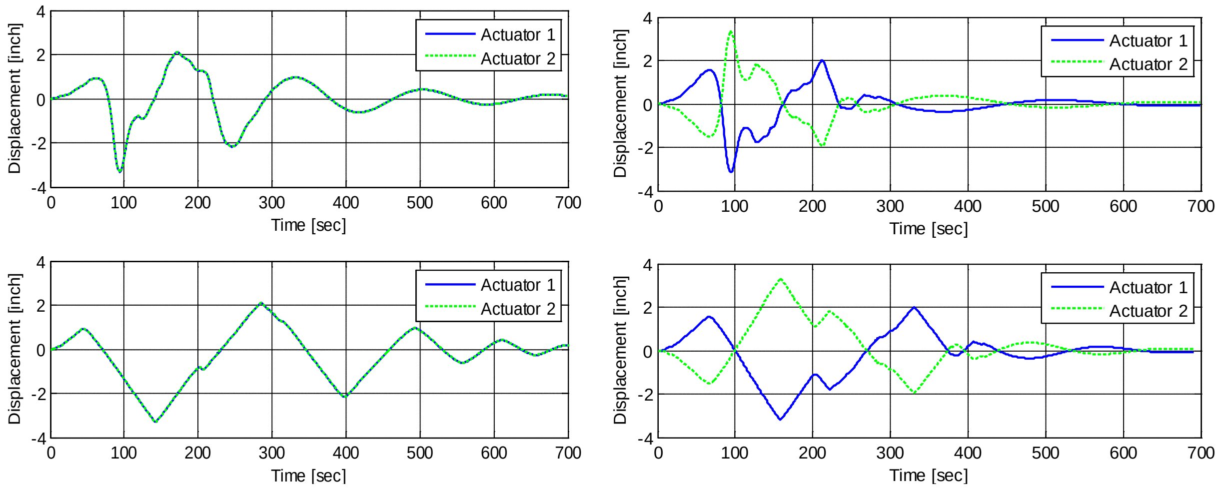


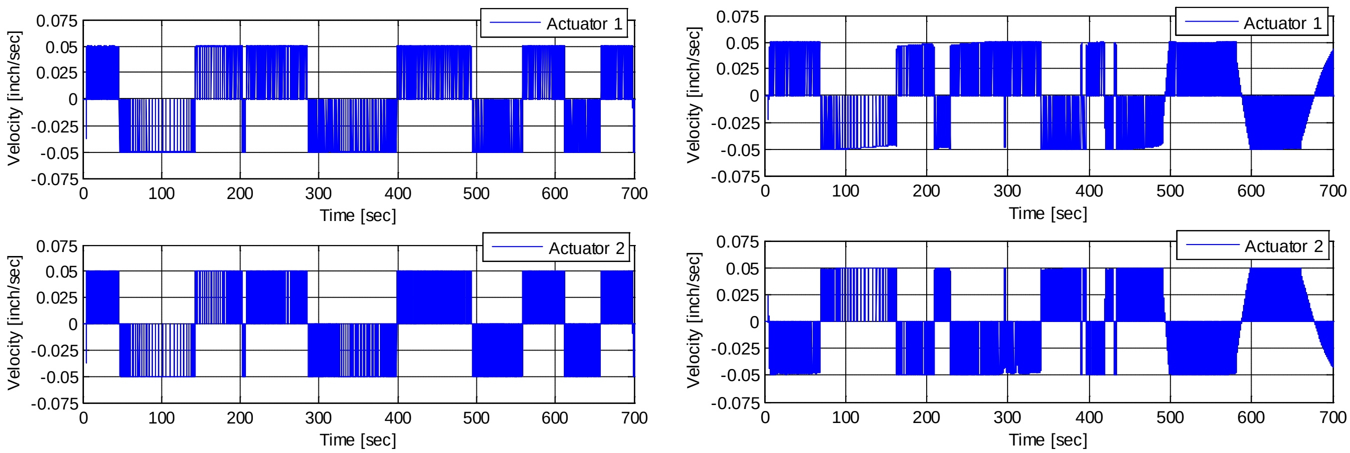

Fig. 6 – Comparison of the displacement (left) and force (right) history obtained from the pure simulation, the computed OpenSees command for HS, and the actual actuators motion from the single free actuator tests

Similar trial tests were conducted using two free actuators setup with the actual computational model for the bridge subassemblage test specimen, i.e. utilizing the newly implemented geometric transformation setup (the *TriangularActuators ExperimentalSetup* class) in the OpenFresco/OpenSees input file. The same concept of feeding back a hypothetical force that is 2 times the actual displacement command was used in these trials. These tests aimed at verifying the correctness of the newly implemented geometric transformation and the DSP routines in interpolating the displacement command for two actuators simultaneously. To verify the geometric transformation, the input of the OpenFresco "*TriangularActuator*" command was set up in a way that rendered each of the actuators inclined with a 45$^{o}$ angle, e.g. *A1* and *B1* identified in Fig. 2 were set to similar values. In this geometry, if a global transverse-only motion ($u_x$ in Fig. 2) is required, the two actuators should have identical input along the local DOFs. On the other hand, if a longitudinal-only motion ($u_y$ in Fig. 2) is required, the two actuators should have same magnitude but opposite direction local DOFs input. This anticipated geometric transformation was accurately verified from the two actuators displacement history shown in Fig. 7 for the transverse-only and longitudinal-only motions. Fig. 7a shows an identical linear actuator displacement motion of the two actuators in the transverse-only case, which indicates a constant velocity and verifies the capability of the DSP routines to interpolate the command for two actuators simultaneously. Fig. 7b shows that the two actuators had similar input along the local DOFs but with opposite direction (sign). This implies that the two components of the actuators motion in the transverse direction cancelled the effect of each other and forced the actuators along a longitudinal path as intended. Moreover, Fig. 7 compares the OpenSees displacement command for the two actuators with the actual PI DAQ recorded data. The comparable peak values confirm that the computed displacements form OpenSees were successfully achieved by the actuators. To further verify the capability of the DSP routines to interpolate the command for two actuators simultaneously, the actual actuator velocities were obtained as plotted in Fig. 8. In the case of transverse-only motion (Fig. 8a), both actuators moved with the input constant velocity of 0.05 inch/sec. in the same direction (similar velocities sign). However, a constant velocity but with opposite signs was observed in case of the longitudinal-only motion (Fig. 8b).




(a) transverse-only (b) longitudinal-only

Fig. 7 – Actuators displacement history from the HS computed OpenSees signal (top) and actuators feedback from the DAQ (bottom).




(a) (b)

Fig. 8 – Actuators velocity as calculated from the obtained feedbacks from the DAQ data for: (a) transverse-only; and (b) longitudinal-only double actuator tests.

The double free actuators were also used to check the P-delta correction DSP subroutine. Using the Elcentro ground motion and bridge subassemblage computational model, a HS test was conducted with and without applying the P-delta correction. The adjusted force feedback as received in OpenSees to use for next step displacement calculations is shown in Fig. 9 for both transverse ($F_x$) and longitudinal ($F_y$) with and without applying the P-delta correction. It can be seen from the figure that applying the P-delta correction slightly reduces the force feedback, i.e. reflecting a more flexible system, which demonstrates the destabilizing secondary moment effects under compression axial loading. The comparison shown in Fig. 9 suggests that the P-delta correction scheme and DSP subroutine is working as anticipated and further verifies the system. More verification configurations and tests were conducted and reader is referred to [13] for full details.

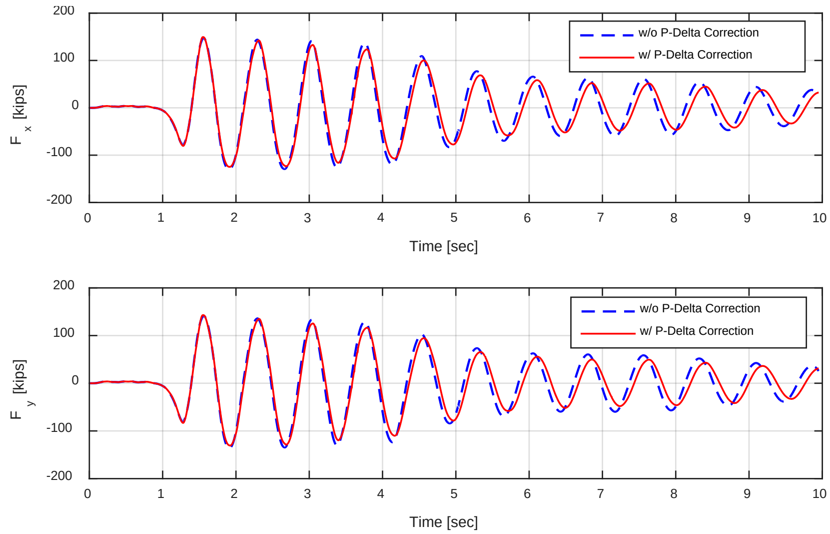



Fig. 9 – Adjusted force feedback in both transverse and longitudinal directions as received in OpenSees from double free actuators HS test with and without applying the P-delta correction.

## 4. Large-Scale Bridge Subassembly HS Tests

Sample brief results from a full HS trial test that utilized the repaired bridge subassemblage SP1 to validate the whole HSS and SP2 HS tests with and without incorporating the P-delta correction are presented in this section.

### 4.1 Repaired Specimen SP1

To complete the validation of the integrated HSS and its new developments, a full specimen HS test was conducted using a repaired bridge subassemblage that was tested under quasi-static cyclic loads in another study [10]. The benefit of the full specimen HS tests was to validate the whole system using a true specimen with inelastic nonlinear behavior. The test setup and physical specimen (substructure) are shown in Fig. 10. Several HS trials with and without gravity load, and using different ground motion scales and components were conducted. Only sample results from an 80% bidirectional test that used Rinaldi ground motion and a gravity load of 10% of the column axial capacity is shown in Fig. 11. This is the overall force-displacement relationships from OpenSees versus that where the global force calculated from the local load cell measurements along with the actual displacements from the wirepots for both transverse and longitudinal directions. The good match of the nonlinear hysteretic behavior in the global DOFs of the calculated and actual measured response validated the developed HSS in terms of the communication loop and geometric transformation.

Fig. 10 – MDOF HS test setup using the repaired SP1 bridge subassemblage

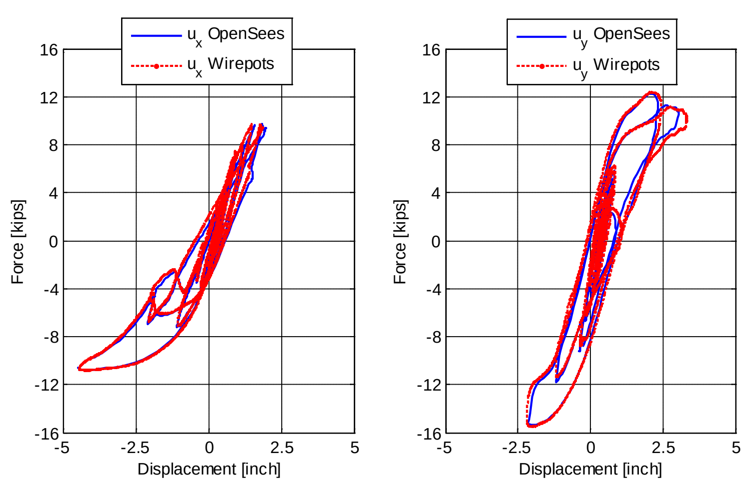



Fig. 11 – Force-displacement relationship in transverse (left) and longitudinal (right) directions from OpenSees and DAQ data

## 4.2 Retrofitted Specimen SP2

The objective of SP2 HS test was mainly to investigate the behavior of integral bent cap beams and box-girder contributions to bent cap effective width and stiffness under realistic earthquake loading [10,13]. The HSS presented here is generic for MDOF HS testing, but was initially developed for SP2 HS tests. The devised P-delta correction was meant to be an upgrade to the HSS to enhance its future capabilities rather than using it for SP2 tests. Thus, only few HS tests at lower ground motions scales were applied with the P-delta correction for SP2 only to preliminarily investigate the effect of incorporating the P-delta corrections, while the large ground motions runs applied until the system failed did not incorporate the P-delta correction [13]. Accordingly, the P-delta corrections were applied for tests that used Rinaldi ground motion at 25%, 50%, and 75% bidirectional, and the 100% scale test with ground motion applied only in the transverse direction. The bridge column started going in tension at the 100% scale due to the effect of the vertical excitation included through the P-delta correction. Thus, it was preferred not to include the P-delta correction at higher intensity tests to avoid the influence of any factors that are not fully understood such as the effect of the column subjected to tension on the overall subassemblage behavior. Sample results from the 100% scale test in the transverse direction only are presented here. The test was repeated twice with and without incorporating the P-delta correction to see how this affects the behavior. The recorded force feedback history and the force-displacement relationships are shown in Figs. 12 and 13, respectively, for both cases with and without P-delta correction. It can be seen from Fig. 12 that the P-delta correction overall reduced the feedback force expect at earlier instance that corresponded to the peak response. This can be attributed to the vertical force used in the P-delta correction being tension at some instances which caused the secondary moments and shears to work against the lateral load effect, which in turns stiffens the system rather than softening it. This observation can be interpreted from Fig. 13b where a sudden increase in the force-displacement slope (i.e. stiffness) corresponds to the observed increase in the force feedback when p-delta correction is included.

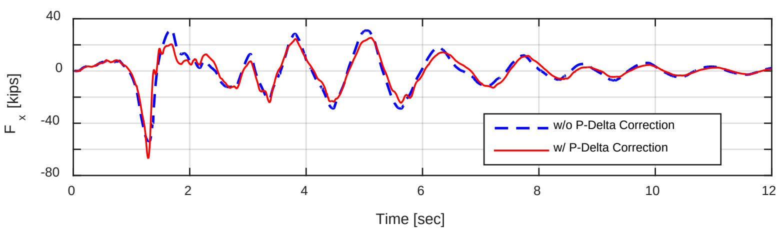



Fig. 12 – Force feedback history for SP2 HS test (100% scale Rinaldi applied in transverse direction only) with and without including the developed online P-delta correction scheme.

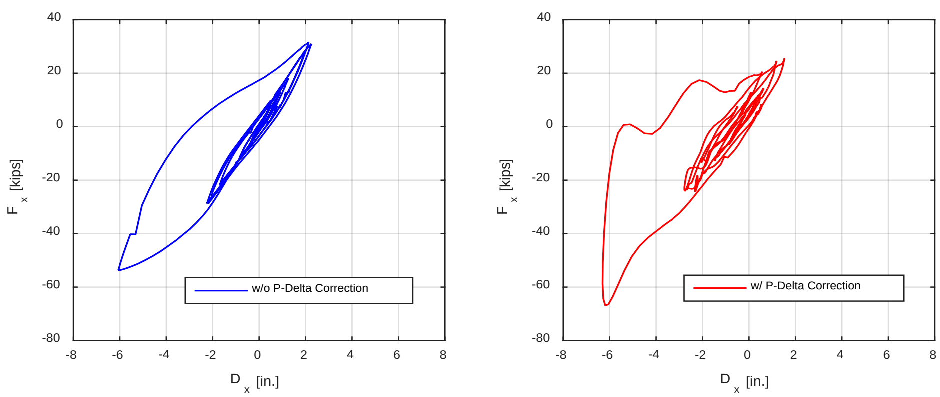



Fig. 13 – Comparison of force-displacement relationship in transverse direction for SP2 HS test (100% scale Rinaldi) with and without including the developed online P-delta correction scheme.

## 5. Conclusions

Based on the verification tests from the free actuators and the repaired SP1 HS test, it was concluded that the sought HSS for testing is reliable and performs as expected. In particular, the new *PI660C UCB HybridSim* application (interface) successfully communicates the displacement and force feedback vectors between

OpenFresco and the experimental hardware. The associated DSP routines developed within the *PI660C UCB HybridSim* successfully interpolated the commands for multi-actuators simultaneously, and communicated the DAQ actuators load cell measurements back to the PI interface. The devised online P-delta correction scheme was successfully implemented using an integrated DSP subroutine. The newly implemented OpenFresco experimental setup object correctly performs displacement and force geometric transformation between the global DOFs and the two actuators in a triangular arrangement local DOFs. The online P-delta correction was considered for some of SP2 HS tests conducted at relatively low ground motion scales. The verification and large-scale bridge system tests preliminarily showed that including the P-delta correction reduces the force feedback in a general sense. However, further investigation might be needed to fully understand the P-delta effect when vertical excitations are included.

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