State-of-the-Art System for Hybrid Simulation at Swinburne

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Abstract

Complex civil structures are being evolved to serve the needs of future generations and this leads to the design, construction and maintenance of more robust and resilient structural systems under an extremely wide range of operating conditions and hazards. Therefore, assessing the effectiveness of new design methods, utilizing new materials and elements that have the capability of reducing the impact of extreme loading events and improving retrofitting strategies are of utmost importance in structural engineering. Seismic evaluation of structural systems has traditionally been explored using either experimental methods or analytical models. However, the development and use of advanced cyber-physical systems has paved the way for structural and earthquake engineers and provided the opportunity to enhance the existing experimental methods of examining the performance of novel smart structures in a suitable and cost-effective manner. Hybrid simulation is a cyber-physical testing technique that overcomes many of the limitations of shaking tables while using similar equipment used for quasi-static testing, making it a versatile and cost-effective experimental method to evaluate the dynamic performance of large-scale structures. Hybrid simulation system including Multi-Axis Substructure Testing (MAST) system in the Smart Structures Laboratory (SSL) at Swinburne University of Technology provides a powerful tool for investigating the dynamic effects of earthquakes, hurricanes, and other extreme loading events through local or distributed hybrid simulation of large or full scale structural components. The MAST system is unique in Australasia and is capable to serve the research community or practice, nationally and internationally. The unique and versatile capabilities of the hybrid simulation system at Swinburne are discussed in this paper, which will greatly expand the capabilities of large-scale experimental testing.

Keywords: experimental testing, hybrid simulation, large-scale structures

1. INTRODUCTION

Natural hazards, such as earthquakes and strong winds are the largest potential source of casualties for inhabited areas. Damages to structures cause not only loss of human lives and disruption of lifelines, but also long-term impact on the local, regional, and sometimes national and international economies.

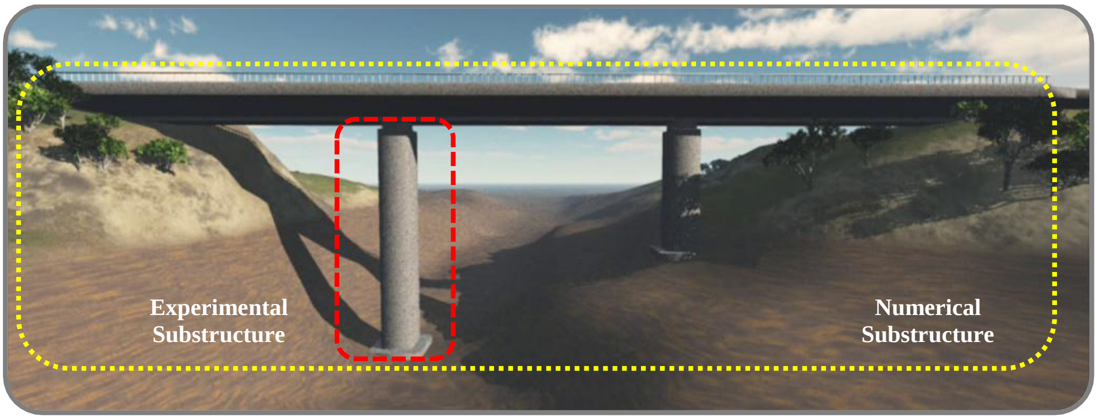
One of the main goals of structural and earthquake engineering is to improve the understanding of earthquakes and their effects on the structural systems and non-structural components. Accordingly, in order to develop new smart materials, new devices and technologies and new smart structural systems for extreme dynamic load-resistant structures, the priorities lies on gaining an understanding of the behavior of various classes of structures under different dynamic load types from elastic range through failure and developing collapse mechanisms. However, reliable assessment and prediction of nonlinear structural behavior and their failure mechanism has proven to be an extremely difficult task.

Nowadays, dynamic analysis of complex structures can be efficiently computed utilizing different available software. However, earthquake engineers still rely on experimental testing methods since the seismic response of structural systems is extremely complex. This is, firstly, due to the uncertainty associated with the occurrence of the earthquake that does not allow the exact evaluation of the seismic demands on the structures and secondly, the needs for the knowledge of nonlinear dynamic response of the materials and elements over the full range of the seismic response, from linear elastic range to levels approaching collapse. Therefore, laboratory testing still has significant importance for the research community for verification and further development of numerical models and their calibrations.

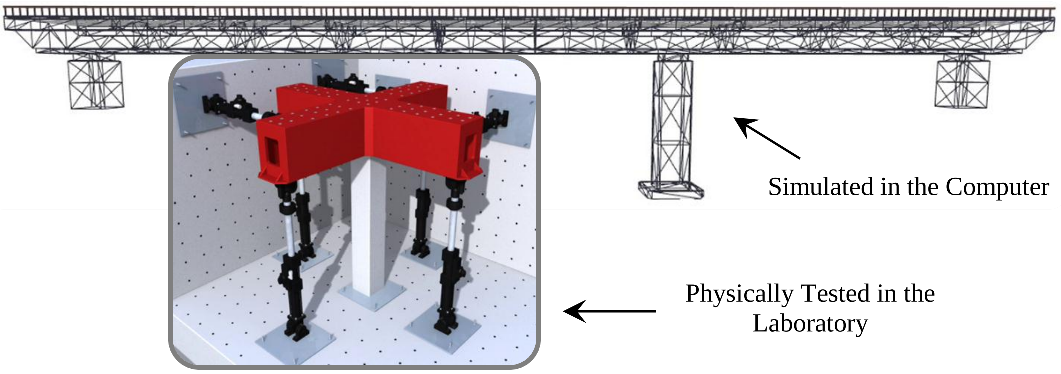
Currently, there are three types of experimental testing procedures used to evaluate structural behaviour subjected to dynamic loadings: shake table testing, quasi-static testing, and hybrid simulation (Filiatrault et al., 2013). In shake table testing, realistic test conditions can be produced to evaluate the dynamic behaviour of civil structures. In this method, some critical issues such as collapse mechanisms, component failures, acceleration amplifications, residual displacements and post-earthquake capacities can be investigated. Nevertheless, very few shake tables in the world are capable of testing full-scale large civil structures. Therefore, shake table testing is excessively expensive, limited to the load-bearing capacity of the testing platform and the interaction between the specimen and the shake table. Quasi-static testing is another technique used to evaluate the dynamic performance of civil structures. Commonly, this technique is applied to study the hysteretic and cyclic behaviour of structural components subjected to seismic loading. Even though quasi-static testing can be implemented on large civil structures, it has two major drawbacks. Firstly, it requires a pre-defined displacement history, which is generally inadequate for resembling the structural behaviour as the load distribution continuously changes during an actual seismic event. Secondly, the effect of the specimen's nonlinear behaviour on the overall response cannot be studied since there is no interaction between the specimen response and the pre-determined loading sequence. Evolved from pseudo-dynamic testing (Nakashima et al., 1992), hybrid simulation is a versatile and economically viable experimental technique to evaluate the dynamic performance of large civil structures (Nakashima, 2001). According to a report developed by the US earthquake engineering community in 2010, hybrid simulation capabilities are a major emphasis of the next generation of earthquake engineering research (Dyke, 2010).

Hybrid testing provides an attractive alternative for safe and economical dynamic testing of structural systems over the full range of the seismic response, from linear-elastic range to levels approaching collapse. It facilitates the study of the structures by experimentally evaluating only the critical portion of the structure while the rest of the structure, inertia and damping forces, gravity and dynamic loading and second order effects are modelled numerically in the computer. During the simulation, the physical portion of the overall hybrid model is tested in one or more laboratories using computer-controlled actuators, while the numerical portion is analysed on one or more computers (Schellenberg et al., 2009). Since dynamic aspects of the simulation are handled numerically, such tests can be viewed as an advanced form of quasi-static tests, where the loading history is determined as the simulation progress for the structure of interest subjected to a specific ground motion. The governing equation of the motion is solved similar to pure numerical simulations using a time-stepping integration. The displacement demands are then applied to the physical specimen and the resisting forces are measured and fed back to the computation solver to calculate the displacements corresponding to the next time step.

To illustrate this process for the various types of substructures in hybrid simulation, an example is presented for a bridge structure with two piers (Fig.1a). Utilizing the hybrid simulation technique, one of the bridge piers can be constructed and physically tested in the lab and the remaining parts of the bridge, mass, viscous and friction damping, gravity and dynamic loads and also the second order effects can reliably be modelled in the computer (Fig.1b).



a) Prototype structure



b) Hybrid Model

Figure 1. Hybrid simulation technique

2. STATE-OF-THE-ART SYSTEM FOR HYBRID SIMULATION AT SWINBURNE

The hybrid simulation system in Smart Structures Lab (SSL) at Swinburne consists of several components including software and hardware that allow for hybrid testing in various configurations. Currently, the experimental hybrid procedures include scaled-time hybrid testing (pseudo-dynamic) with substructuring but can be extended to real-time hybrid simulation and effective force testing.

An advanced hardware configuration has been set up to ensure a strong coupling and a very high-speed data communication between the servo-controllers and the main computer solving the equation of motion. Hybrid simulation frameworks include:

1- Multi-Axis Substructure Testing (MAST) system for three-dimensional large-scale structural systems and components (Suitable for Users).
2- 1MN universal testing machine that is suitable for SDOF tests (Suitable for Developers).
3- Generic actuator configuration system for substructure hybrid tests (Suitable for both Developers and Users).

The MAST system in the Smart Structures Laboratory at Swinburne (Fig.2) advances the current state of technology by allowing the experimental simulation of complex boundary effects through its multi-axial capabilities. The unique and versatile capabilities of the MAST system will greatly expand the experimental testing of large-scale structural components such as beam-column frame systems, walls, bridge piers, etc. Using MAST system, the developments of new materials and structural components, and the effectiveness of new retrofit strategies for seismically damaged structural elements can be reliably evaluated through three-dimensional (3D) large-scale hybrid simulation, which provides significant insight into the effects of extreme loading events on civil structures. The capabilities and specification of MAST system is discussed next.

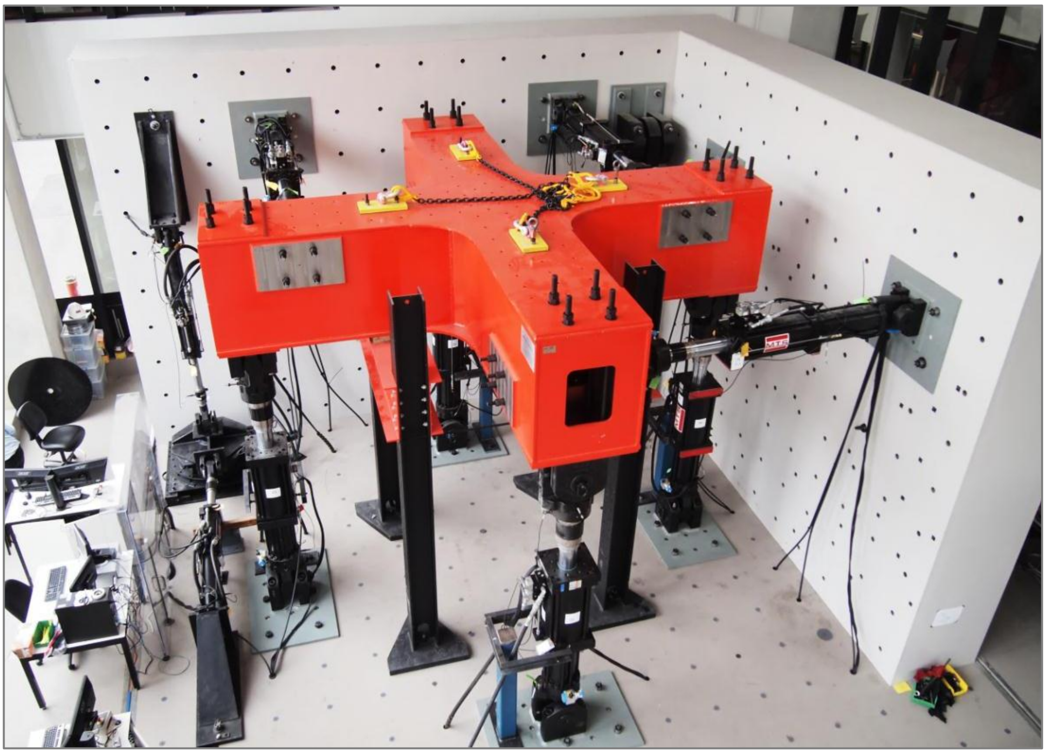


Figure 2. MAST System in Smart Structures Laboratory at Swinburne

2.1. MAST System in Smart Structures Laboratory at Swinburne

Multi-Axis Substructure Testing system in the Smart Structures Laboratory at Swinburne provides a powerful tool for investigating the effects of earthquakes, hurricanes, and other extreme loading events on large structural components using hybrid simulation testing. A sophisticated 6-DOF control system is used utilizing eight high-capacity hydraulic actuators that enable application of complex multi-directional deformation or loading schemes to structural components. The MAST system has the capability to accommodate test specimens with up to 3m×3m in-plan and approximately 3m height.

2.1.1. MAST Laboratory

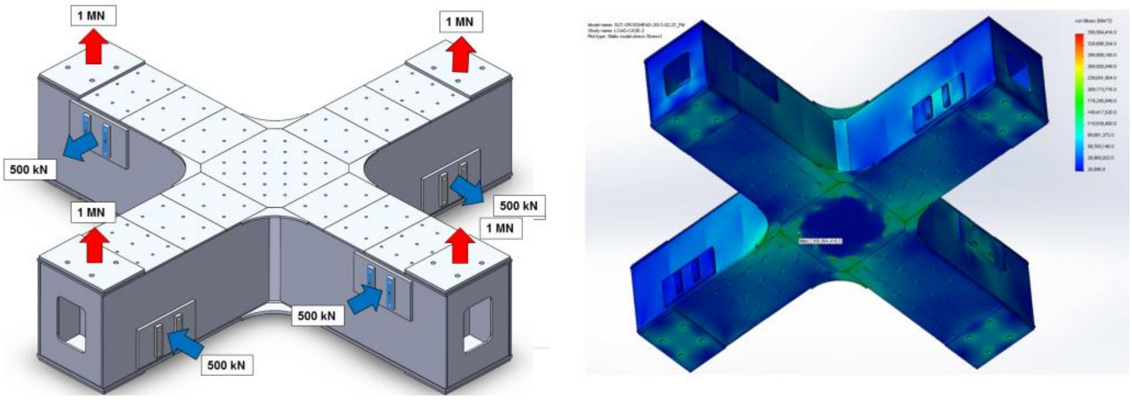
The MAST system is located in the Smart Structures Laboratory at Swinburne University of Technology. The $15 million laboratory is a major 3D testing facility developed for large-scale testing of civil, mechanical, aerospace and mining engineering components and systems and the only one of its type available in Australia. The 1.0m thick strong floor measures 20m×8m in plan with two 5m tall reaction walls meeting at one corner. The 3D strong cell contains a grid of tie down points 0.5m apart to secure the test specimens in place, in addition to a suite of hydraulic actuators and universal testing machines varying in capacity from 10tonnes to 500tonnes. The laboratory is serviced by adjacent workshops and a hydraulic pump system located in the basement. The facility is housed in a large architecturally designed test hall about 8m tall.

2.1.2. MAST Reaction System

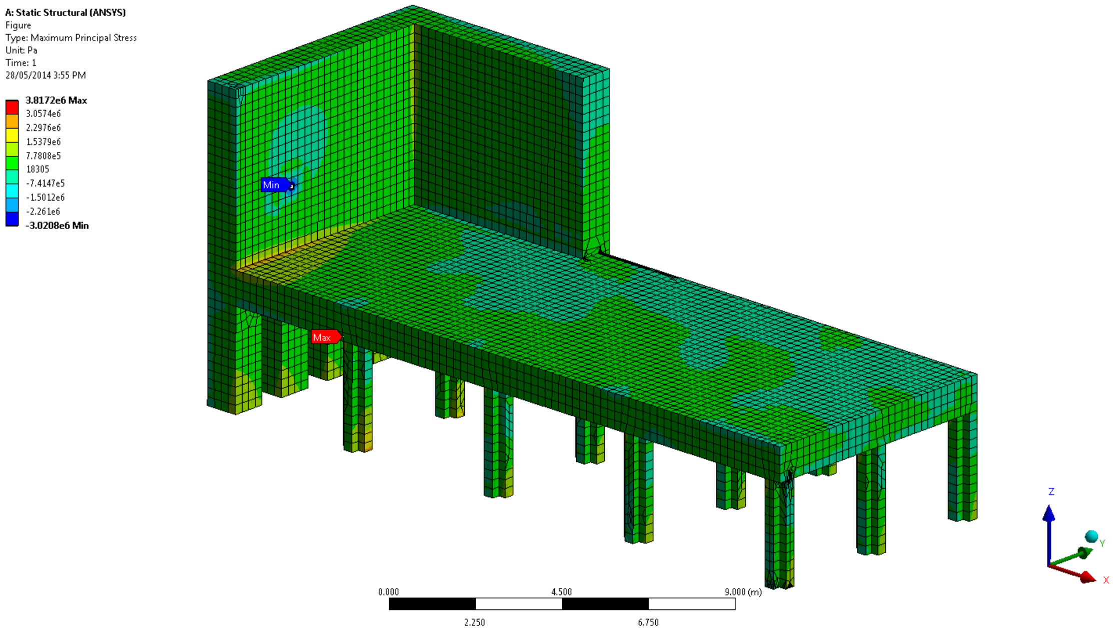
The MAST system utilizes a highly stiff steel crosshead in the form of cruciform attached to eight hydraulic actuators (i.e., four vertical and two in each of the horizontal orthogonal directions) connected to an L-shaped strong-wall strong-floor system that enables testing of large-scale structural components. The rigid steel crosshead is used to apply tri-axial control, roll, pitch and yaw to the test structure.

The design of the crosshead in the form of a cruciform was undertaken independently by Swinburne University in collaboration with Hofmann Engineering Pty. Ltd. (Hofmann, 2013). Nonlinear finite element simulations were performed to optimize the design of the MAST steel cruciform. The model included all relevant details such as: holes for base plate connections and stiffener plates. Zones of weakness at weld connections were considered by modelling local elements of lower strength/stiffness in the vicinity of welds. Four load cases were considered to induce the highest possible flexure, shear and torsion within the structure (Fig.3a).

The design of the strong floor was undertaken independently by Waterman International Consulting (Waterman, 2010) engineers in collaboration with Swinburne University. The 3D strong-cell contains a grid of tie down points 0.5m apart to secure the test specimens in place. The 6-DOF hybrid testing facility introduces an array of possible loading conditions to both the strong floor and reaction wall. 3D solid models were constructed to assess the maximum load that may be applied to the reaction wall in any given configuration without exceeding the tensile strength of the concrete. Over 100 load configurations were constructed to determine maximum allowable wall loading in any given scenario (Fig.3b).



a) FE Model of Crosshead



b) FE Model of Strong Wall/Floor

Figure 3. Finite Element Analysis (FEA) for MAST Reaction Systems

2.1.3. MAST Actuators

Two sets of actuator pairs with strokes of ±230mm provide lateral loads up to ±500 kN in the orthogonal directions. These actuator pairs are secured to the L-shaped strong-wall. Four ±1 MN vertical actuators, capable of applying a total force of ±4 MN with strokes of ±230 mm, connect the crosshead and the strong floor. Auxiliary actuators are also available to be used for additional loading configurations on the specimen. The actuator system specifications are presented in .

Table 1. Actuator Specifications

Actuators Position	Vertical	Horizontal	Auxiliary
Model	MTS 244.51	MTS 244.41	MTS 244.41 × 1 MTS 244.31 × 2 MTS 244.22 × 2
Quantity	4	4	5
Force Stall Capacity	± 1,000 kN	± 500 kN	± 500, 250, 100 kN
Static	± 230 mm	± 230 mm	± 230 mm
Dynamic	± 150 mm	± 150 mm	± 150 mm
Servo-Controller	MTS FlexTest 60	MTS FlexTest 60	MTS FlexTest 60

2.1.4. MAST Control System

The movement of the MAST crosshead is governed by the collective movement of four vertical and four horizontal actuators. To create a desired crosshead movement, actuators are time synchronized using a DOF control concept (Thoen, 2013). This concept allows the user to control system motion in a coordinate domain most natural to the test. With multiple actuators positioning the crosshead, it is impractical to control the system by individually controlling each actuator. Therefore, the MTS controller (MTS, 2014) has been programmed to simultaneously control the 6-DOF movement of the crosshead at its datum point, where it is attached to the specimen. In DOF control, the feedbacks for each loop are determined by summing together all individual feedbacks that contribute to that specific DOF, and each actuator drive-signal is determined by summing together all individual DOF error signals that are affected by that actuator.

In addition, the MAST system features mixed-mode control, allowing users to specify the displacement or force required for the desired direction of loading to test large-scale structural components. In the mixed-mode control, the DOF displacement commands for the force-controlled axes are estimated based on the approximation of the stiffness Jacobian. Once DOF commands are all specified in the displacement, they will be decomposed into each actuator command displacement using geometric transformation. Then, all of the actuator commands are simultaneously executed. Following the convergence of the actuator displacements, the measured actuator displacements and force obtained from the LVDT and load cell, respectively, are converted into the DOF measured displacement and force. At the end of each step, the measured mixed forces and displacements are compared with the target mixed loads and displacements in the DOF system. Depending on the acceptable tolerance in all the axes, the process iterates or goes to the next step. Therefore, in the mixed-mode control all actuator servo-loops are displacement control regardless of the force-controlled axes in the DOF system. This makes the system more robust compared to the traditional approach, where force-control actuators are used (Nakata, 2007).

Also, since the MAST system has eight actuators operating to control 6 DOFs, it is over-constraint. Therefore, in order to manage this redundancy in the actuation system, the controller uses force balance compensation. Since the crosshead is designed to have a very high stiffness, tiny offsets in actuator position can generate large distortion forces. The force imbalances can seriously limit the performance of the system when applying large forces to the specimen. Force wasted in distorting the crosshead, with actuators working against each other, is the force not available to apply to the test specimen. Force balance compensation corrects for this by ensuring that the force is distributed equally among all driving actuators.

Further, in order to improve the displacement control resolution in the hybrid simulation of stiff and strong physical specimens, in addition to the actuator’s LVDT, the system uses additional high precision string potentiometers (SICK, 2014) with 25micrometers precision for displacement feedback. Conduct of hybrid simulation of stiff MDOF structures without precise control of the displacement will lead to the appearance of spurious higher-mode response. This comes from the fact that very small errors in imposed displacements can translate to high restoring-force deviations. The experimental errors, which are introduced into the numerical computations through restoring-force feedback, impose the most significant problems in implementation of hybrid simulation.

2.2. Hybrid Simulation Architecture

The hybrid simulation control system at Swinburne uses xPC-Target and consists of a three-loop architecture, which is depicted in Figure 4. The innermost servo-control loop contains the MTS FlexTest controller that sends displacement/force commands to the actuators while reading back measured displacements/forces. The displacements are measured from both the actuator LVDTs and high-precision string potentiometers. The middle loop runs the Predictor-Corrector actuator command generator on the xPC-Target (Mathworks., 2009) real-time digital signal processor (DSP) and delivers the displacement/force commands to the FlexTest controller in real-time through the shared memory SCRAMNet (Systran, 2004). Finally, the outer integrator loop runs on the xPC-Host and includes OpenSees (McKenna, 2011), MATLAB (Mathworks., 2009) and OpenFresco (Schellenberg, Mahin and Fenves, 2009) that can communicate with the xPC-Target through TCP/IP network.

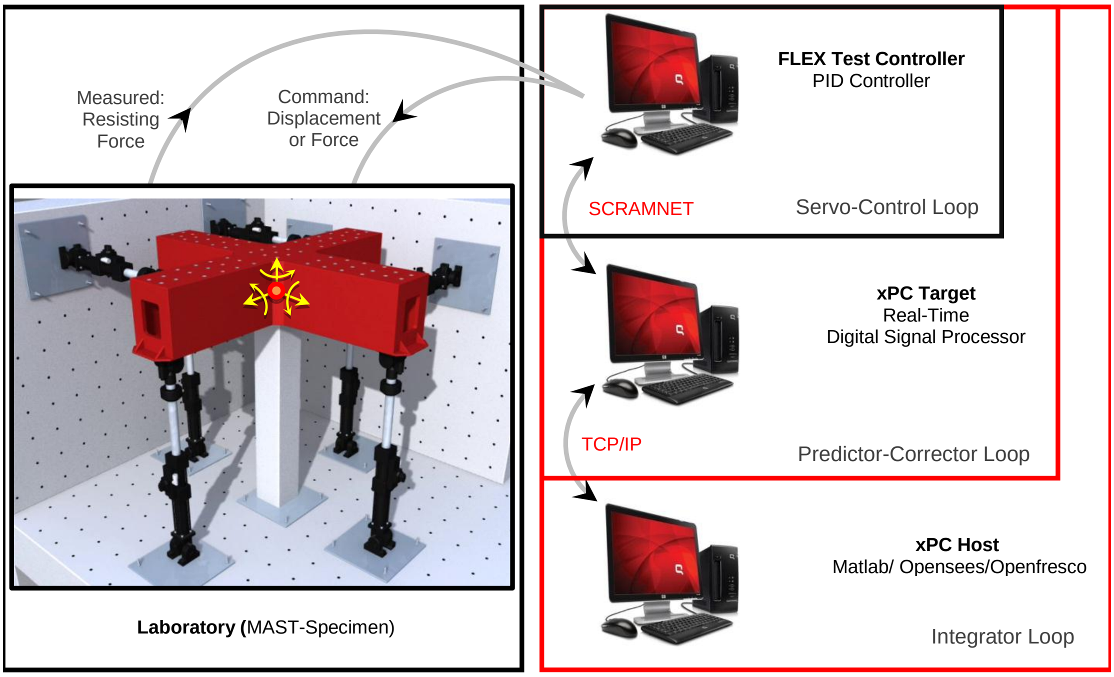


Figure 4. Hybrid Simulation Architecture at Swinburne

3. CONCLUSION

Large-scale testing of structural components can deliver significant benefits to structural and earthquake engineers. The behaviour of structural elements can be studied by replicating extreme loading conditions that currently cannot be produced by other means. The Multi-Axis Substructure Testing system at Swinburne enables the evaluation of existing systems, retrofitted systems, and new systems and materials to develop durable and economical structural systems capable of resisting seismic, wind, and other types of loading. Key features of the MAST system include but are not limited to: 1) It allows to control 6-DOF (vertical, lateral, longitudinal, pitch, roll and yaw) utilizing a rigid cruciform and therefore reliably simulates the complex boundary effects. 2) It accommodates the testing specimen up to 3meters cubed that is suitable for large-scale substructures. 3) Four 1MN vertical actuators and four 500kN horizontal actuators serve to impose displacements up to ±250mm in vertical, lateral or longitudinal directions and ±7degrees in pitch, roll or yaw. 4) The system uses additional high precision string potentiometers (25micrometers precision) for displacement feedback in hybrid simulation.

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REFERENCES

Dyke, S. J., Stojadinovic, B., Arduino, P., Garlock, M., Luco, N., Ramirez, J. A., Yim, S. . (2010), 2020 Vision for Earthquake Engineering Research: Report on an Openspace Technology Workshop on the Future of Earthquake Engineering.

Filiatrault, A., Tremblay, R., Christopoulos, C., Folz, B. & Pettinga, D. (2013), Elements of Earthquake Engineering and Structural Dynamics 3rd Edition.

Hofmann. (2013), Hofmann Engineering Pty. Ltd., Perth, Australia.

Mathworks. (2009), Matlab, the Language of Technical Computing.

McKenna, F. (2011), Opensees: A Framework for Earthquake Engineering Simulation, Computing in Science & Engineering, 13(4), 58-66.

MTS. (2014), Mts Systems Corporation, Minneapolis, USA.

Nakashima, M. (2001), Development, Potential, and Limitations of Real-Time Online (Pseudo-Dynamic) Testing, Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences, 359(1786), 1851-1867.

Nakashima, M., Kato, H. & Takaoka, E. (1992), Development of Real-Time Pseudo Dynamic Testing, Earthquake Engineering & Structural Dynamics, 21(1), 79-92.

Nakata, N. (2007), Multi-Dimensional Mixed-Mode Hybrid Simulation, Control and Applications, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign.

Schellenberg, A. H., Mahin, S. A. & Fenves, G. L. (2009), Advanced Implementation of Hybrid Simulation, University of California, Berkeley, California, Pacific Earthquake Engineering Research Center.

SICK. (2014), Sick Ag, Industrial Sensors, Waldkirch, Germany.

Systran, C. (2004), The Scramnet+ Network (Shared Common Ram Network).

Thoen, B. (2013), Generic Kinematic Transforms Package, MTS Systems Corporation, MA, USA.

Waterman. (2010), Waterman Group Plc, Melbourne, Australia.