Proceedings of the Tenth Pacific Conference on Earthquake Engineering
Building an Earthquake-Resilient Pacific
6-8 November 2015, Sydney, Australia

Mixed-Mode Hybrid Simulation of Large-Scale Structures through Multi-Axis Substructure Testing (MAST) System

M.J. Hashemi, R. Al-Mahaidi, J. Wilson, Y.K.F Al-Ogaidi & G. Burnett

Faculty of Science, Engineering and Technology, Swinburne University of Technology, Melbourne, Australia.

ABSTRACT: Hybrid simulation is an innovative cyber-physical testing technique that overcomes many limitations of shaking tables while using similar equipment used for quasi-static testing, making it a versatile and cost-effective experimental method. The primary objective of the present research is to expand the capabilities of large-scale hybrid testing to include three-dimensional responses of structures through the mixed load/deformation control of six degrees-of-freedom (6-DOF) boundary conditions. A state-of-the-art loading system, referred to as the Multi-Axis Substructure Testing (MAST) system, has been designed, assembled and validated at Swinburne University of Technology for the purpose of evaluating the performance of structural elements through quasi-static cyclic testing and hybrid simulation tests. This state-of-the-art facility is unique in Australasia and is capable to serve the research community or practice, nationally and internationally. The unique and versatile capabilities of the MAST system are discussed in this paper, which will greatly expand the capabilities of large-scale experimental testing. The results of two mixed-mode three-dimensional experiments performed to validate the system for quasi-static cyclic and hybrid simulation tests will also be presented.

1 INTRODUCTION

Hybrid simulation (also known as pseudo-dynamic testing) is a cost-effective experimental method for safe and economical dynamic testing of large-scale structural systems over the full range of the seismic response, from initial linear-elastic range to levels approaching collapse (Hakuno et al., 1969; Takanashi et al., 1975). Hybrid simulation combines the advantages of numerical simulation with those of conventional quasi-static testing and thus provides more accurate results than each individual method. During hybrid simulation, similar to pure numerical simulation, the dynamic equations of motion of the idealized structure are solved in the time-domain by numerical integration while some or all critical parts of the structure that are difficult to model or exhibit complex behaviour are physically modelled in the laboratory. The boundary force/deformations, worked out from the time-integration process are physically applied on the specimen by a set of actuators in a quasi-static manner. The restoring force/deformations are then measured and used in the numerical model to carry on the test with the next time-step. Slow loading of the structure is important so as not to excite its inertial and damping properties, which are already accounted for computationally (Mahin et al., 1989; Nakashima et al., 1992; Shing, 1996).

Despite all the benefits of hybrid simulation technique, there are also challenges in conducting such tests for a number of reasons: Firstly, actions on structures during extreme events such as earthquakes are generally multi-directional and continuously-varying due to the time-dependent nature of the input motion. For instance, variations of the axial loads during a seismic excitation may influence the response of the vertical structural components (e.g., bridge pier, building column, etc.) since the response of such elements when combined with flexural, shear, and torsional actions may differ from the cases when they are not subjected to the same axial load changes. Simulation of such highly-coupled multi-directional loading conditions using conventional structural testing methods can be expensive, time-consuming and difficult to achieve and consequently advanced and innovative experimental techniques and control strategies are under development by researchers (Nakata, 2007; Wang et al., 2012; Hashemi et al., 2014; Hashemi et al., 2014)

Secondly, the experiments should be conducted in large/full scale to accurately capture the local behavior of the elements. The local behavior may play a critical role in determining the performance of a structure given the fact that initial damage usually occurs on a local level. Certain types of behavior, especially local effects such as bond and shear in reinforced-concrete (RC) members, crack propagation, welding effects and local buckling in steel structures are well-known to have size-effects (Saouma et al., 2008). However, conducting the large-scale experiments may not be feasible often due to the limited resources available in many laboratories that include: the number and capability of available actuators, the dimensions and load capacity of the reaction systems and difficulties in actuator assemblies and testing configuration to reliably simulate the boundary conditions. Consequently, the specimen may be tested in small-scale or under uni/biaxial loading configurations, which do not necessarily represent the actual action or demand on the structural elements and correspondent nonlinear response of the prototype system.

Finally, conducting multi-directional loading including gravity load effects requires the mixed-mode control strategy. Application of gravity loads have been mainly considered by researchers through the combination of force-control actuators in vertical direction that are decoupled from displacement-control actuators in lateral direction of the specimen (Lynn et al., 1996; Pan et al., 2005; Del Carpio Ramos et al., 2015). In those tests, independent of lateral actuators, only the vertical force-control actuators apply the gravity forces. While under large deformations, lateral actuators will have a force component in the vertical direction that needs to be accounted for. Therefore, versatile and generally-applicable mixed-mode control algorithms are required to take into account instantaneous and spatial coupling in the control systems.

The primary objective of the present research is to expand the capabilities of large-scale experimental testing to include three-dimensional responses of structures and 6-DOF boundary conditions through the mixed load/deformation control strategy. A state-of-the-art loading system, referred to as the Multi-Axis Substructure Testing (MAST) system, has been designed, assembled and validated at Swinburne University of Technology for the purpose of evaluating the performance of structural elements through quasi-static cyclic testing and hybrid simulation tests. The results of a series of large-scale experiments conducted on a 5-by-5-bay 5-story concrete structure under bidirectional ground excitations are also presented to demonstrate the performance of the MAST system in mixed-mode control by simultaneously applying the axial load in force control while imposing lateral deformations in displacement control.

2 MULTI-AXIS SUBSTRUCTURE TESTING (MAST) SYSTEM

Multi-directional loading on structural components has been performed before in the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) facilities in U.S., including the Multi-Axial Sub-assemblage Testing Laboratory located at University of Minnesota, Minneapolis (French et al., 2004) that has been used in quasi-static tests and the Multi-Axial Full-Scale Sub-Structure Testing and Simulation facility at the University of Illinois at Urbana-Champaign (Mahmoud et al., 2013) that has been used in displacement control hybrid simulation experiments. These systems have the capacity for large-scale testing of structural components and the ability to control multiple DOFs. Building on the same concept, the Multi-Axis Substructure Testing (MAST) system at Swinburne University of Technology has been established to provide a state-of-the-art facility for mixed-mode large-scale quasi-static cyclic testing and local/geographically -distributed hybrid simulation experiments (See Fig. 1). The key components of the 6-DOF testing facility are:

1. Four ±1MN vertical hydraulic actuators as well as two pairs of ±500kN horizontal actuators in orthogonal directions. Auxiliary actuators are also available for additional loading configurations on the specimen (See Fig. 2 and Table 1).
2. An advanced servo-hydraulic control system capable of imposing simultaneous 6-DOF states of deformation and load in switched and mixed mode control.
3. A 9.5tonne steel crosshead that transfers the 6-DOF forces from the actuators to the specimen. The test area under the crosshead is approximately three meters cubed.
4. A reaction system composed of an L-shaped strong-wall (5m tall × 1m thick) and 1m thick strong-floor.

5. An advanced three-loop hybrid simulation architecture including: servo-control loop that contains the MTS FlexTest controller (inner-most loop), the Predictor-Corrector loop running on the xPC-Target real-time digital signal processor (middle-loop) and the Integrator loop running on the xPC-Host (the outer loop).
6. Additional high-precision draw-wire absolute encoders with the resolution of 25microns that can be directly fed back to the controller.

3 EXPERIMENTAL VALIDATION

In order to validate the performance of the MAST system for mixed-mode control, two pilot tests including a quasi-static cyclic test and a hybrid simulation were conducted on two identical large-scale RC columns. The test specimen is the first-story corner-column of a half-scale symmetrical five-story (h_1=2.5m, h_{typ}=2.0m) five-bay (b=4.2m) RC ordinary moment-resisting frame building, which was designed for Melbourne. The experimental setup and the results of two experiments are presented.

3.1 Mixed-Mode Quasi-Static Cyclic Test

The most common method to evaluate the response of large-scale structural elements in the laboratory is quasi-static (QS) test, which provides data on the hysteretic behavior and capacity of the specimen under cyclic loads. The first experiment conducted using the MAST system was a mixed-mode QS test with simultaneously applying the constant gravity load in force control while imposing biaxial lateral deformations in displacement control. Figure 3(a) shows the experimental setup where the specimen is attached to the strong floor from the base and to the crosshead from the top through the rigid concrete pedestals. The RC column is 2.5m high with a square 250mm×250mm cross-section and 30mm cover thickness. The compressive strength of the concrete is 35MPa and the specimen is reinforced with 4 longitudinal bars of N16 (reinforcement ratio = 1.28%) and tied with R6 stirrups spaced at 175mm.

With the aim of controlling the crosshead in mixed-mode, the load protocol consisted of a constant 189.3kN gravity load and lateral bidirectional deformation reversals following the orbital pattern suggested in FEMA 461 (Federal Emergency Management, 2007). The remaining DOF axes (Roll, Pitch and Yaw) were controlled in zero-angle to form a double-curvature deformation.

The sequence of loading in QS test started with applying the gravity load on the specimen in Z-axis. Then, the specimen was pushed to the initial uniaxial drift ratio towards Point-a, followed by the orbital pattern (a-b-c-d-e-f-a) depicted in Figure 3(b). The reversal from Point-a accompanies an orthogonal drift at Points b and c equal to one-half the maximum drift ratios at Points a and d. The entire loading cycle was then repeated at the same amplitude. Once the specimen was reached to Point-a for the second time, the amplitude value for the next two cycles was increased and the next two biaxial load cycles were applied on the specimen. The process continued until the failure of the specimen.

The results of the QS test including the hysteretic behavior of the concrete column in X and Y axes and the axial time history are presented in Figure 4. The controller was able to successfully apply the constant 189.3kN gravity load while pushing the specimen in the orbital pattern to maximum 7% and 3.5% drift ratio in Y and X axes, respectively. The force relaxations observed in the hysteresis are due to pausing the test in order to collect photogrammetry data at peak deformations in X-axis

3.2 Mixed-Mode Hybrid Simulation Test

Mixed-mode hybrid simulation (HS) allows to apply time-varying axial loads and therefore experimentally simulate: 1) the interactions of axial internal forces with bending moments and shears at the section level (P-M and P-V effects); 2) the influence of axial load on the stability of structural element and critical regions (P-δ effects); and 3) the influence of axial loads on the stability of entire structure by inducing additional overturning moments (P-Δ effects).

For hybrid simulation, the structure was partitioned into numerical and experimental substructures (See Fig. 5). The experimental substructure consisted of the first-story corner-column while the rest of the structural elements, inertia and damping forces, gravity and dynamic loads and second-order effects were modeled numerically in the computer. The frame's beams and columns were modeled using beam-with-hinges element, where the nonlinear behavior is demonstrated by using a distributed-plasticity concept that occurs in a finite-length near both ends. The plasticity model followed peak-ordinated hysteresis response based on the Modified Ibarra-Medina-Krawinkler (IMK) deterioration model for the flexural behavior (Ibarra et al., 2005). The IMK model parameters were calibrated using the results of quasi-static test and empirical equations provided by Haselton et al. (2008).

After developing the numerical model, the elastic fundamental period of vibration was obtained through eigenvalue analysis (T1=0.6sec). The biaxial ground motions used in hybrid simulation were two components of Imperial Valley 1979 El Centro station with peak ground acceleration of 0.15g. Figure 6 shows the acceleration and displacement response spectra of the ground motion components. 4 levels of ground motions were selected to cover the structure's response from initial linear-elastic range through collapse. The scale factors for the level of intensities obtained from incremental dynamic analysis are 0.6, 4.0, 8.0 and 9.0 that push the structure to 0.25%, 2.0%, 4% and 6% inter-story drift ratio, respectively.

Prior to conducting the actual hybrid simulations with the physical subassembly in the laboratory, a series of coupled numerical simulations were conducted to evaluate the integration scheme parameters for the actual experiments. This is due to the fact that special requirements need to be provided by the integration scheme that does not allow using the conventional integration schemes for hybrid simulation. Accordingly, Generalized Alpha-OS (Schellenberg et al., 2009) was used and the integration time-step was optimized to preserve the accuracy and stability of the simulation while allowing to complete the entire test during the regular operation time of the laboratory. 5% Rayleigh damping was specified to the first and third modes of vibration. Additional damping was also assigned to free vibration time intervals between the forced-vibrations in order to bring the structure to rest. OpenSees (McKenna, 2011) and OpenFresco (Schellenberg, Mahin and Fenves, 2009) were used for numerically-coupled simulation and the actual hybrid experiment.

The hybrid simulation started with applying the 221.26kN gravity load on the specimen followed by sequential ground motions. All the sequence of loading was performed and automated through OpenSees. Considering 117msec delay in the hydraulic system, 0.5sec was specified as the simulation time in xPC-Target Predictor-Corrector to provide sufficient time for integration computation, communication process, actuator motions and data acquisition. This scaled the 60 second of sequential ground motions in real time to 6 hours in laboratory time. Note that, slow loading of the structure is important so as not to excite its inertial and damping properties, which are already accounted for computationally. Figure 7 summarizes the hybrid simulation test results including the comparison of hysteresis in X and Y axes for quasi-static and hybrid simulation tests and axial force time history in Z-axis. It can be seen that controller were able to successfully apply instantaneous mixed force/deformations through continuous exchange of data between numerical and experimental substructures.

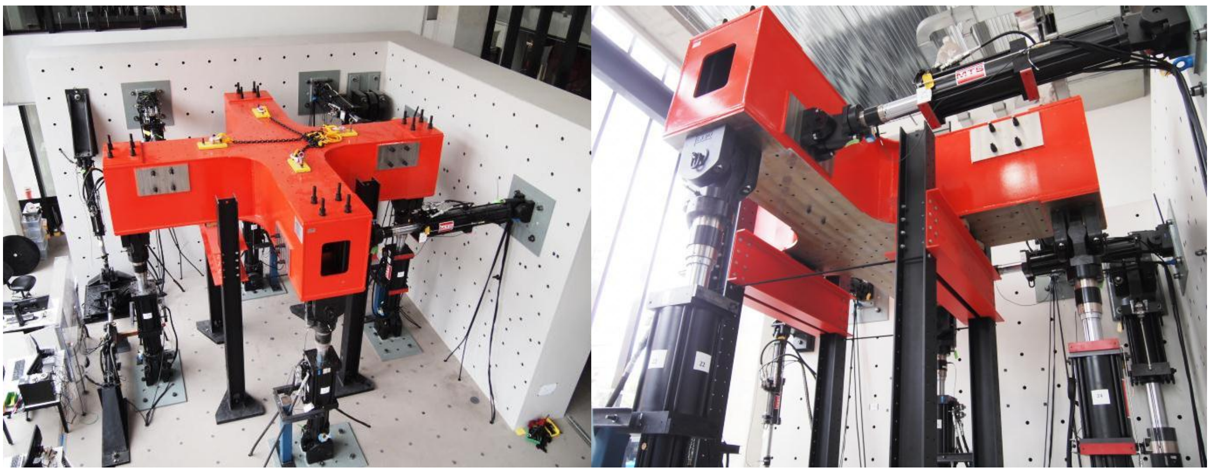
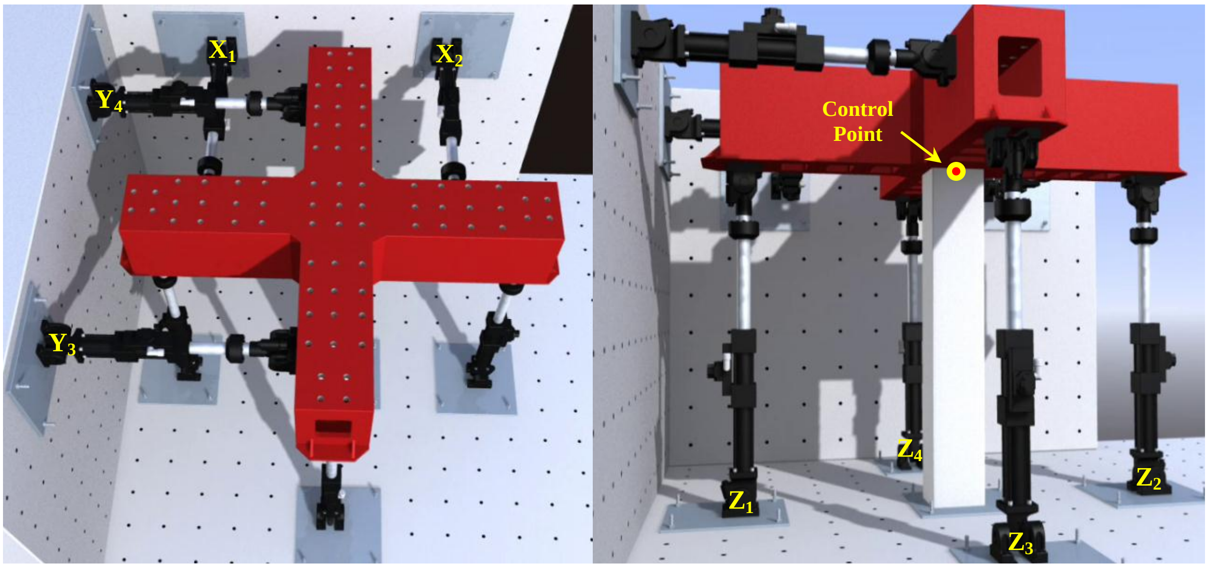


Figure 1. Multi-Axis Substructure Testing (MAST) system



a) Actuator assembly: plan-view b) Actuator assembly: side-view

Figure 2. Actuator assemblies in the MAST system.

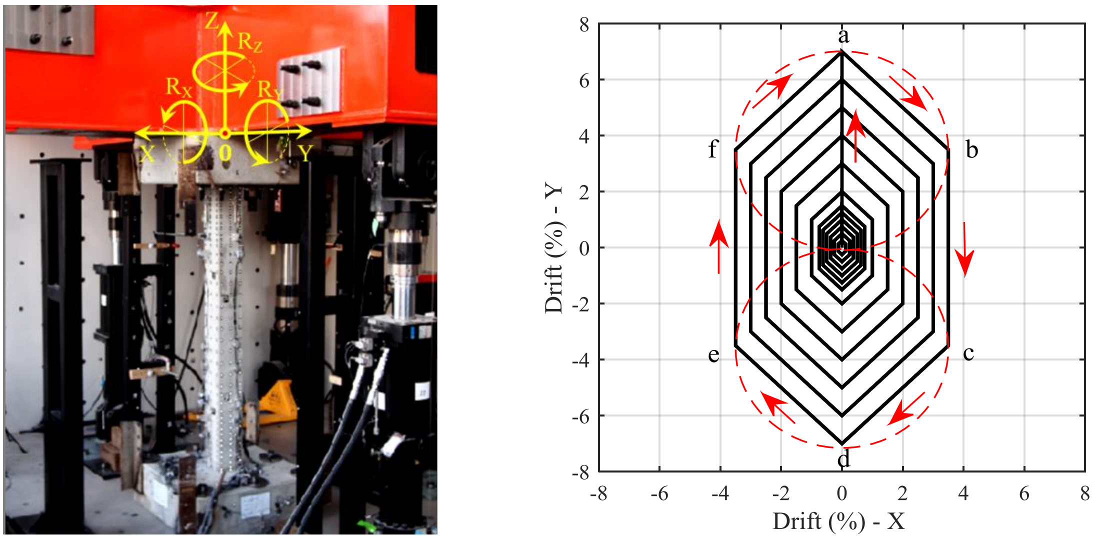
Table 1. Actuators and DOF specifications

MAST Actuators Capacity

Actuator	**Vertical**	**Horizontal**	**Auxiliary**	
Model	MTS 244.51	MTS 244.41	2 MN	(Qty. 1)
Quantity	4 (Z_1, Z_2, Z_3, Z_4)	4 (X_1, X_2, Y_3, Y_4)	250 kN	(Qty. 4)
Force Stall Capacity	± 1,000 kN	± 500 kN	100 kN	(Qty. 3)
Static	± 250 mm	± 250 mm	25 kN	(Qty. 3)
Dynamic	± 150 mm	± 150 mm	10 kN	(Qty. 1)
Servo-Controller		MTS FlexTest 100		

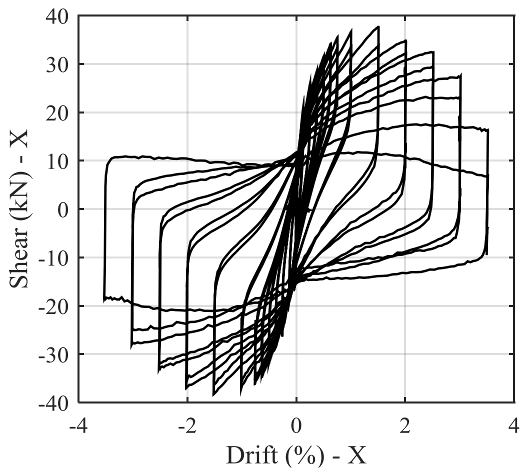
MAST DOFs Capacity (non-concurrent)

DOF	**Load**	**Deformation**	**Specimen Dimension**
X	1 MN	± 250 mm	3.00 m
Y	1 MN	± 250 mm	3.00 m
Z	4 MN	± 250 mm	3.25 m
Rx (Roll)	4.5 MN.m	± 7 degrees	
Ry (Pitch)	4.5 MN.m	± 7 degrees	
Rz (Yaw)	3.5 MN.m	± 7 degrees	

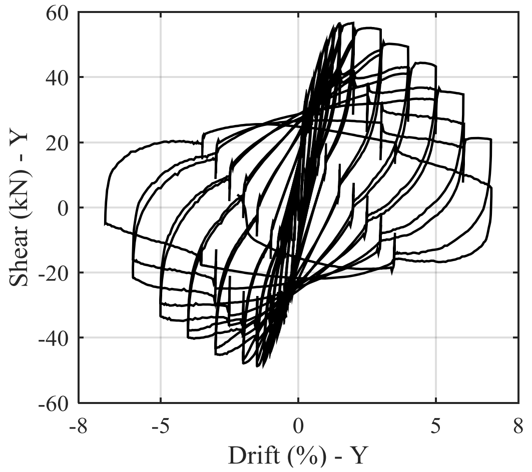


a) Experimental setup b) Orbital pattern load

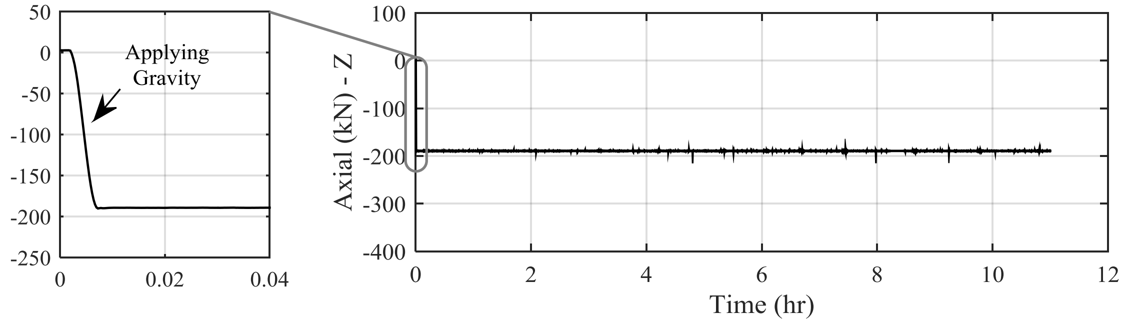
Figure 3. Experimental setup and load protocol for mixed-mode quasi-static cyclic test



a) Shear vs. drift ratio, X-axis

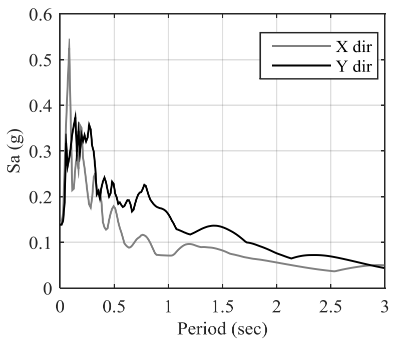


b) Shear vs. drift ratio, Y-axis

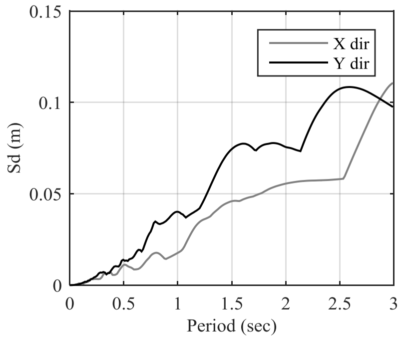


c) Axial load time history with a close-view of applying the gravity load, Z-axis

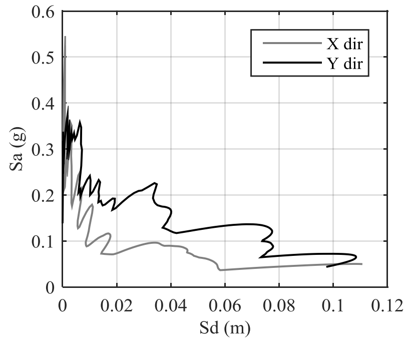
Figure 4. Results of mixed-mode quasi-static cyclic test



a) Acceleration response spectra



b) Displacement response spectra



c) ADRS

Figure 5. Response spectra for biaxial ground motions of Imperial Valley 1979 used in hybrid simulation

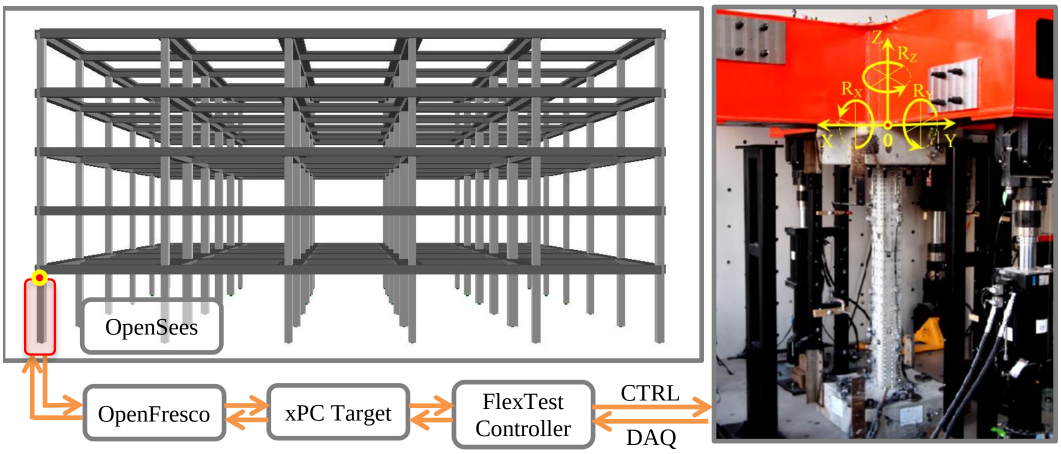
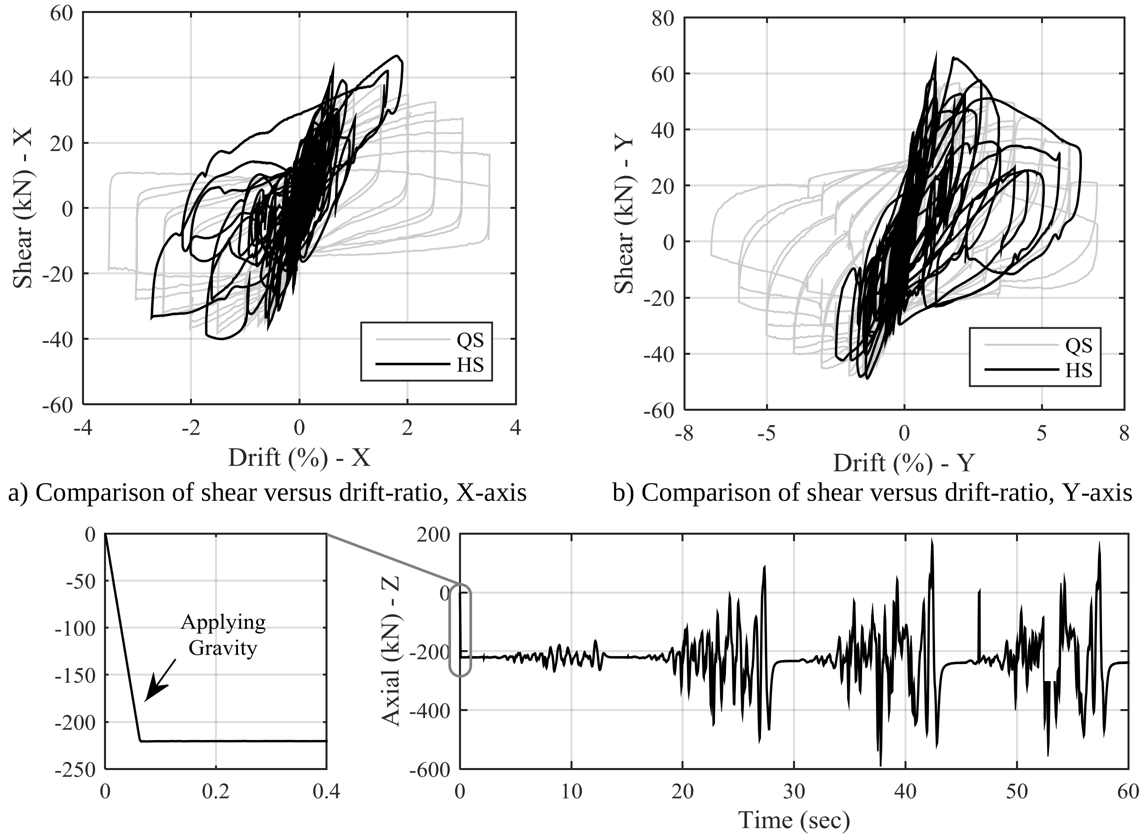


Figure 6. Hybrid simulation components including numerical and experimental substructures



a) Comparison of shear versus drift-ratio, X-axis

b) Comparison of shear versus drift-ratio, Y-axis

c) Axial load time history with a close-view of applying the gravity load, Z-axis

Figure 7. Hybrid simulation results for 4 sequential ground motions with increasing intensities

4 CONCLUSION

A state-of-the-art loading system, referred to as the Multi-Axis Substructure Testing (MAST) system, has been designed, assembled and validated at Swinburne University of Technology for the purpose of evaluating the performance of structural elements through quasi-static cyclic testing and hybrid simulation tests. The system facilitates the simulation of complex boundary effects by controlling all 6-DOF (vertical, lateral, longitudinal, pitch, roll and yaw) states of force or deformation, allowing the users to select force or displacement mode for each individual DOF. The performance of the MAST system was validated experimentally by conducting mixed-mode quasi-static and hybrid simulation experiments on a large-scale RC column by simultaneously applying the axial load in force control while imposing lateral deformations in displacement control. The results show confidence in using the MAST to simulate highly-coupled continuously-varying boundary force/deformations on large-scale structural components.

AKCNOWLEDGEMENT

The authors gratefully acknowledge the contribution of the Australian Research Council LIEF grant LE110100052 and 11 partner universities in assisting the establishment of the 6-DOF hybrid testing facility.

REFERENCES:

Del Carpio Ramos, M., Mosqueda, G. & Hashemi, M. J. 2015, Large-Scale Hybrid Simulation of a Steel Moment Frame Building Structure through Collapse, *Journal of Structural Engineering*, 04015086.

Federal Emergency Management, A. 2007, Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Nonstructural Components in (DHS), D. o. H. S. (ed.), Washington D.C., USA.

French, C. E., Schultz, A. E., Hajjar, J. F., Shield, C. K., Ernie, D. W., Dexter, R. J., Du, D. H.-C., Olson, S. A., Daugherty, D. J. & Wan, C. P. 2004, Multi-Axial Subassemblage Testing (Mast) System: Description and Capabilities 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada.

Hakuno, M., Shidawara, M. & Hara, T. 1969, Dynamic Destructive Test of a Cantilever Beam, Controlled by an Analog-Computer, *Transactions of the Japan Society of Civil Engineers*.

Haselton, C. B., Liel, A. B., Lange, S. T. & Deierlein, G. G. 2008, Beam-Column Element Model Calibrated for Predicting Flexural Response Leading to Global Collapse of Rc Frame Buildings, Pacific Earthquake Engineering Research Center.

Hashemi, M. J., Masroor, A. & Mosqueda, G. 2014, Implementation of Online Model Updating in Hybrid Simulation, *Earthquake Engineering & Structural Dynamics*, 43(3), 395-412.

Hashemi, M. J. & Mosqueda, G. 2014, Innovative Substructuring Technique for Hybrid Simulation of Multistory Buildings through Collapse, *Earthquake Engineering & Structural Dynamics*, 43(14), 2059-2074.

Lynn, A. C., Moehle, J. P., Mahin, S. A. & Holmes, W. T. 1996, Seismic Evaluation of Existing Reinforced Concrete Building Columns, *Earthquake Spectra*, 12(4), 715-739.

Mahin, S. A., Shing, P. S. B., Thewalt, C. R. & Hanson, R. D. 1989, Pseudodynamic Test Method - Current Status and Future-Directions, *Journal of Structural Engineering-Asce*, 115(8), 2113-2128.

Mahmoud, H. N., Elnashai, A. S., Spencer, B. F., Kwon, O. S. & Bennier, D. J. 2013, Hybrid Simulation for Earthquake Response of Semirigid Partial-Strength Steel Frames, *Journal of Structural Engineering*, 139(7), 1134-1148.

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

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.

Pan, P., Nakashima, M. & Tomofuji, H. 2005, Online Test Using Displacement-Force Mixed Control, *Earthquake Engineering & Structural Dynamics*, 34(8), 869-888.

Saouma, V. & Sivaselvan, M. V. 2008, Hybrid Simulation: Theory, Implementation and Applications, Taylor \\& Francis, Inc.

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.

Shing, P. B., Nakashima, M., Bursi, O. S. 1996, Application of Psuedodynamic Test Method to Structural Research, *Earthq. Spectra*, 12(1), 29-56.

Takanashi, K., Udagawa, K., Seki, M., Okada, T. & Tanaka, H. 1975, Nonlinear Earthquake Response Analysis of Structures by a Computer-Actuator on-Line System, *Bulletin of Earthquake Resistant Structure Research Centre*.

Wang, T., Mosqueda, G., Jacobsen, A. & Cortes-Delgado, M. 2012, Performance Evaluation of a Distributed Hybrid Test Framework to Reproduce the Collapse Behavior of a Structure, *Earthquake Engineering & Structural Dynamics*, 41(2), 295-313.