VI International Conference on Computational Methods for Coupled Problems in Science and Engineering
COUPLED PROBLEMS 2015
B. Schrefler, E. Oñate and M. Papadrakakis (Eds)

DESIGN AND DEVELOPMENT OF TEN-ELEMENT HYBRID SIMULATOR AND GENERALIZED SUBSTRUCTURE ELEMENT FOR COUPLED PROBLEMS

SAEID MOJIRI, XU HUANG, OH-SUNG KWON, CONSTANTIN CHRISTOPOULOS

Department of Civil Engineering, University of Toronto
35 St. George St., Toronto, ON, Canada
E-mail: saeid.mojiri@mail.utoronto.ca, xu.huang@mail.uotoronto.ca,
os.kwon@utoronto.ca and c.christopoulos@utoronto.ca

Key words: Multi-platform Analysis, Coupled systems, Substructuring, Hybrid simulation, Pseudo-dynamic testing, Dynamic testing.

Abstract. The University of Toronto's ongoing work towards the improvement and further development of multi-platform simulation methods is presented in this paper. These developments include a ten-element hybrid simulator and a generalized OpenSees substructure element. Hybrid simulation which encompasses development of new integration algorithms, simulation frameworks, and applications has been an active research area in the past decade. Yet, unless the physically tested element significantly contributes to the overall lateral response of the structure in terms of stiffness, strength and energy dissipation, the improvement in the accuracy of results from the use of hybrid simulation may only be marginal. In most cases, the number of physically tested elements in the hybrid simulation is limited by the availability of experimental resources such as actuators, controllers, and laboratory space. As a step towards overcoming this limitation, a novel experimental apparatus, the UT10 Hybrid Simulator, is being developed at the University of Toronto. The UT10 is being developed to allow up to ten elements, such as braces and hysteretic dampers, to be concurrently tested and integrated into a hybrid simulation. The system can test up to ten physical specimens with peak force capacity ranging between 800 kN or 1,600 kN per specimen depending on the total number of tested specimens. The main design requirements, current development status, and potential applications of the UT10 Hybrid Simulator are presented in this paper. To integrate the potential numerical or physical substructures into distributed multi-platform simulations such as hybrid simulations, a generalized substructure element is being developed for OpenSees. The main research focus in this development is to standardize the data exchange format and communication protocol such that any other potential experimental and numerical substructure modules can be readily integrated into the simulation. The data exchange format is defined such that the number of degrees of freedom, data type, and error checks can be communicated in a seamless manner between modules. Designing a versatile data exchange format and a communication protocol is expected to facilitate simulation of coupled systems including diverse substructure modules and other loading scenarios such as thermal loading. The data exchange format and example implementations will be made available to the research community in the near future. To illustrate the current developments, an example of multi-platform simulation with a numerical substructure is presented in this paper.

1. INTRODUCTION

The inelastic dynamic response of structures under earthquake loads is a complex problem, which involves complicated mechanical response of structural elements and their materials. In addition, the recent development of performance based seismic design methods require performance assessment of a structure against multiple seismic hazard levels. Thus, the research community recognizes the need for more accurate and reliable seismic response prediction tools for complex structures subjected to seismic loading.

Although there have been considerable advances in the capabilities of numerical simulation platforms, most of the time a single platform is unable to handle all types of material behavior, loading conditions, and boundary configurations and therefore specialized software is required if a further detailed response is required for particular structural elements. Furthermore, since solving for the response of a complex and large structure with a similar level of model complexity for all elements is computationally expensive and even sometimes impossible, it may be preferred to use sophisticated models only for critical parts of the structure. Despite the advances in computational power and numerical techniques, physical testing, arguably the most realistic source of data, is still essential for validation and calibration of numerical elements. Therefore, structural analysis methods that can combine different numerical platforms and experimental components and benefit from advantages of each during the analysis are invaluable for more realistic response prediction of structures under earthquake loads. One approach to achieve this goal is by dividing a large structure into smaller substructures and model each substructure by the most suitable numerical or experimental platform with the desired level of model complexity. In these multi-platform simulation methods, the responses of different substructures are coupled during the analysis [1,2].

Numerical-experimental hybrid simulation, also known as pseudo-dynamic (PsD) or online testing, is a laboratory dynamic test method which incorporates realistic experimental behaviour of the critical structural components into the numerical model of a structural system, thereby enhancing the accuracy in the response predictions of the system under earthquake loads. In this method some structural components, mainly the most critical ones, can be tested as physical substructures, while the rest of the structure is modeled in a computer as a numerical substructure. The numerical substructure contains dynamic properties of the system like damping and mass. The analysis of the model involves stepwise time integration loops. In each time step, the displacements of the physical substructures due to earthquake loads are numerically predicted in the computer model and are applied quasi-statically on the physical substructures using hydraulic actuators in the laboratory. The forces and displacements from the physical substructures are then measured and sent back to the numerical model and are used to correct the predicted displacements. This process is repeated in each time step. Because the displacements on the physical substructures are applied with an expanded time scale, the PsD test is mainly suitable for physical substructures with rate independent mechanical behaviour [3].

Since its early development in 1969 [4] and 1980s [5,6], numerical-experimental hybrid simulation has evolved considerably in different aspects such as integration algorithms, simulation frameworks, actuator delay compensation methods, and applications. The hybrid simulation method has been successfully implemented in many applied research projects for testing a variety of structural components [7,8,9,10]. However, in cases where the global response of the structure is of interest, this improvement is not necessarily considerable, unless the behaviour of the physical substructures dominates the global response of the structure. Furthermore, if there are many structural components considerably affecting the response of the structure, a sufficient number of these structural components should be tested as physical substructures. In most cases however, the number of physically tested components in hybrid simulations is limited by the availability of experimental resources in the laboratory such as actuators, controllers, and laboratory space. To overcome this limitation, a new experimental platform, *UT10 Hybrid Simulator,* is being developed for hybrid simulation in the Structural Testing Facilities at the University of Toronto. This simulator is capable of performing hybrid simulations with up to 10 large-scale uniaxial physical substructures such as braces and hysteretic dampers. Development of this facility can significantly affect the accuracy of the hybrid simulation by making it possible to include significantly more physical substructures into the simulations and therefore incorporate more realistic experimental data into the model. Based on the authors's knowledge, this facility will be the first of its kind when considering the number of physical substructures.

In order to facilitate multi-platform simulations using substructuring techniques, a new element named *SubStructure* is being developed for the finite element analysis software, OpenSees [11]. This element is developed for general purpose such that it can be used to represent either experimental or numerical substructures regardless of the number of nodes and degrees of freedoms. The *SubStructure* element is based on the *GenericClient* element which has been implemented in OpenSees to enable the data exchange between the numerical module and the physical substructure modules through the interface program OpenFresco [12]. The original *GenericClient* element is compatible with only four types of experimental elements in OpenFresco namely the Truss, Beam-Column, Two-Node Link, and Inverted-V Brace elements. In addition, it is difficult to use the *GenericClient* element for other substructure modules and different loading scenarios. For instance, in order to include thermal loads in a hybrid simulation, the data exchange format and the communication protocol need to be modified accordingly. To make substructure hybrid simulation methods more approachable, a standardized data exchange format and a communication protocol are being developed for the generic *SubStrucutre* element. The implementation of this versatile data exchange format can not only facilitate maintenance and extension of the hybrid simulation framework for developers but also help users with similar configuration inputs for diverse substructure modules.

Numerical-experimental hybrid simulation requires the implementation of two main modules: 1) The experimental module which is comprised of the physical substructures and the experimental platform including actuators to apply command displacements calculated by the numerical module on the physical substructures, control and communication platform to communicate between the numerical module and the actuators, and required frames to support and hold the specimens in place and 2) the numerical module which is the numerical substructure modeled in a software platform. The UT10 Hybrid Simulator is an experimental platform enabling hybrid simulations on uniaxial physical substructures. Different components of the UT10 Hybrid Simulator and the challenges involved for design and development of each component are described in the next section. The details of the development of the *SubStructure* element used in the numerical module are discussed in

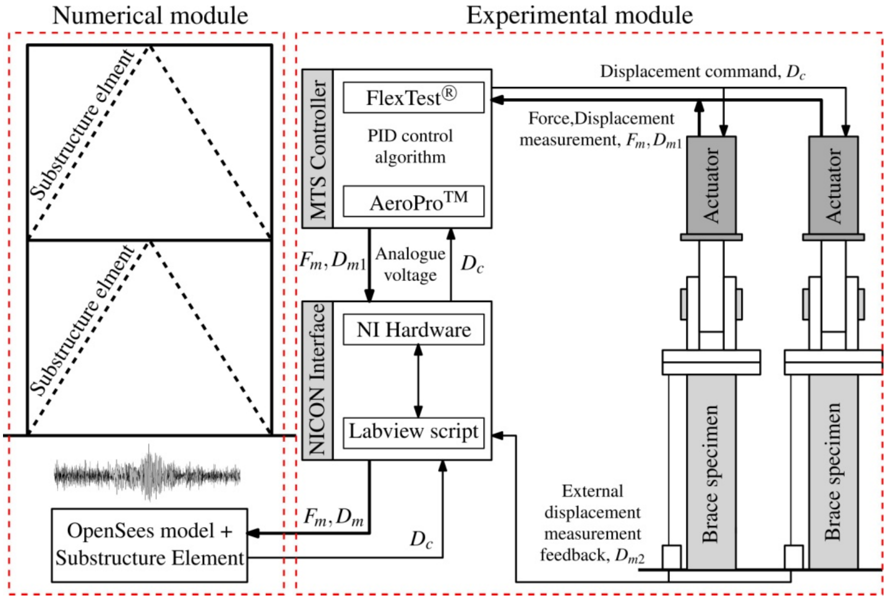

Figure 1: Flow of communication between components of hybrid simulation.

section three. A schematic showing both modules and the communication flow between their components is given in Figure 1.

2. DEVELOPMENT OF UT10 HYBRID SIMULATOR

2.1 Specimens

The UT10 Hybrid Simulator is designed for performing hybrid simulations with up to 10 large-scale uniaxial physical substructures with rate independent hysteretic properties hereafter referred to as specimens. These specimens can be simple steel braces, Buckling Restrained Braces (BRBs), friction dampers, Self Centering (SC) braces, etc. The specimens will be pinned at both ends and will be loaded in their axial direction. The hybrid simulator provides space and axial loading capacity for testing up to 10, 800 kN and 5, 1600 kN large scale specimens with a maximum length of 1,660 mm, simultaneously.

2.2 Actuators and specimen support frame

UT10 Hybrid Simulator uses the existing Shell Element Tester (SET) located in Structures Testing Facility at the University of Toronto. The SET was originally developed to study the behaviour of large scale reinforced concrete (RC) shell elements under various loading configurations. The SET is equipped with 40, 1000 kN in-plane and 20, 500 kN out-of-plane actuators. Figure 2.a shows the SET with a RC shell specimen.

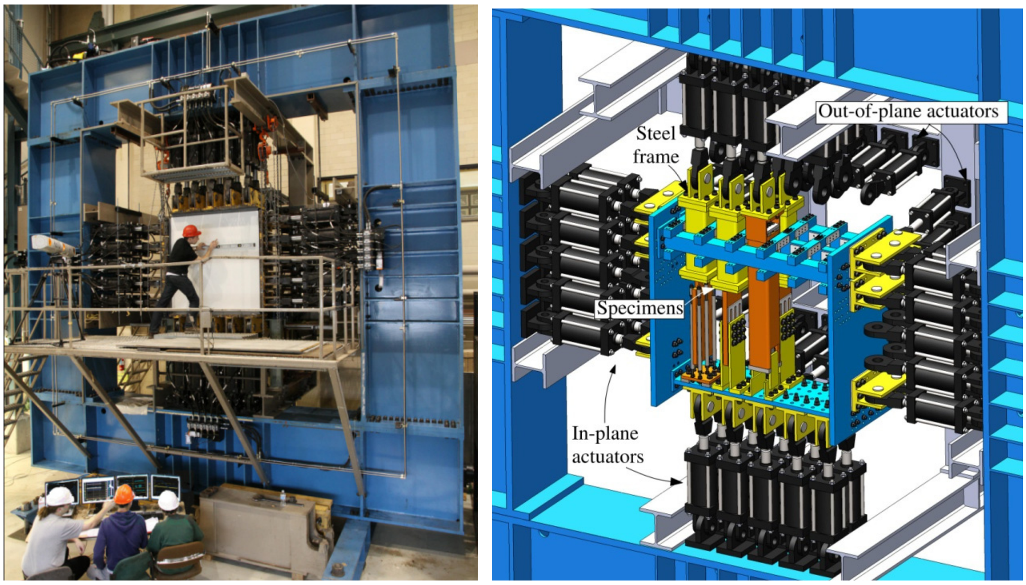

Figure 2: a) The Shell Element Tester (SET) with RC shell specimen in the lab, b) 3D illustration of the UT10 Hybrid Simulator steel frame with 4 specimens inside SET

For the purpose of hybrid simulations, uncoupled axial displacements are applied on 10 separate specimens, and hence, only ten in-plane vertical actuators at the top of the SET are used to control the specimens as shown in Figure 2.b. The other ten actuators at the bottom are used as fixed supports. Because both the top and bottom actuators are pinned at their both ends, the whole system develops a mechanism with four hinges and becomes unstable. To prevent this, the specimens are supported laterally in both the in-plane and out-of-plane directions while allowed to move freely in the vertical (axial) direction. A steel frame was designed and fabricated for the purpose of enabling the connection between the specimens and the in-plane vertical actuators for loading in the axial direction. The frame also provides lateral support to the specimens and connects to the horizontal in-plane and out-of-plane actuators to stabilize the system. Figure 2.b shows the 3D illustration of the steel frame with 4 specimens, installed in the SET. Figure 3 shows a 3D illustration of different components of the steel frame. As can be seen from Figure 3 each specimen is laterally supported by adjustable lateral support beams through a loading shaft which can be also part of the specimen. In order to reduce the amount of friction between the lateral support beams in the steel frame and the loading shaft when the specimen is moving in the axial direction, low friction PTFE sheets are used at the interface of the lateral support beams and the exterior of the loading shafts.

The axial deformations in UT10 Hybrid Simulator are applied by top vertical in-plane actuators that are pinned to the loading yokes which are connected to the loading shafts. The specimens are axially supported at their base by a base plate. The whole system is supported in all directions by in-plane and out-of-plane actuators that are pinned to the yokes which are in turn connected to the side plates and the base plate (see Figure 3). The loading shafts can be rectangular or square hollow structural sections (HSS) and the design of the steel frame is flexible to accommodate different sizes of loading shafts. The maximum size of the shaft that can be accommodated is 508 mmx254 mm.

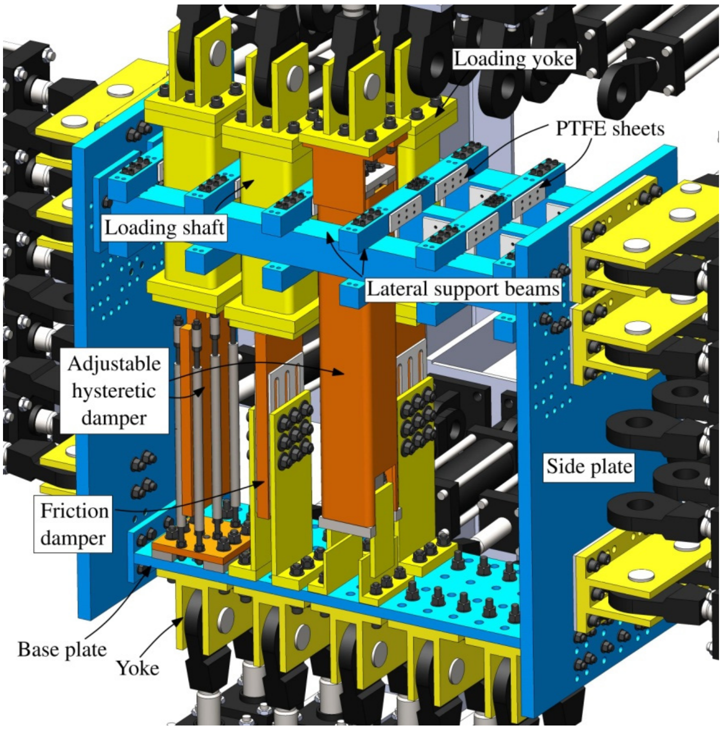

Figure 3: 3D illustration of different component of the steel frame with friction damper and adjustable hysteretic specimens

2.3 Control and communication platform

All 60 actuators in the SET are controlled simultaneously with an MTS FlexTest® controller and AeroPro™ control software with both force and displacement control capabilities. Additional analogue to digital input and digital to analogue output cards are installed on the existing MTS controller in order to provide external communication with the controller through analogue voltages.

An interface program called Network Interface for Controllers (NICON) has been developed at the University of Toronto to facilitate communication between the numerical module and the MTS controller for hybrid simulations [13]. NICON uses National Instruments (NI) hardware and a LabVIEW script to receive displacement commands from the numerical module, communicate them to the MTS controller, and receive and send the feedback force and displacements from the controller to the numerical module. NICON has some added features like displacement and force limit checks, noise filtering, ramp generation, and coordinate transformation. The initial version of NICON can only handle problems with one independent degree of freedom. An updated version of NICON which is able to handle problems with several independent single degrees of freedom (SDOF) (which is needed for the UT10 Hybrid Simulator) and also for problems with multiple coupled degrees of freedom is being developed and is planned to be used in the UT10 Hybrid Simulator [14]. The communication between the controller and NICON is achieved with analogue voltages. Data flow between different components of the UT10 Hybrid Simulator is shown in Figure 1.

It is predicted that the amount of axial movement of the actuators can be different from the real axial displacements transmitted to the specimens and this is one of the major challenges for the control of the actuators in the UT10 Hybrid Simulator. These differences are mainly due to the elastic deformations of the actuator reaction frames and their connections and also the slackness present in the pin connections between the actuators and loading yokes. One solution to correct for these differences and to ensure that the command displacements are imposed on the specimens with acceptable accuracy is that the actual movement of the specimens be measured externally (D_{m2} in figure 1) and fed back to NICON where they are compared to the actuator displacement feedbacks from the MTS controller (D_{m1} in figure 1) based on which the command displacements to the actuators (D_c) can be corrected. The implementation of this error correction scheme is still in progress.

3. DEVELOPMENT OF SUBSTRUCTURE ELEMENT

3.1 Implementation and characteristics

A generic *SubStructure* element is being built upon an object-oriented, open source software framework, OpenSees. A key feature of OpenSees is the ability to allow user-defined elements to be integrated into the application without the need to change the existing code. Therefore, the development and maintenance of the *SubStructure* element is independent from the main OpenSees software. The *SubStructure* element has the following characteristics:

- It does not have geometry and material descriptions and is only defined by the connected nodes and the number of degrees of freedom.
- It allows for the integration of any number of nodes and degrees of freedom for the substructure.
- All degrees of freedom are defined in the global coordinate systems and hence no coordinate transformation is required in OpenSees. Coordinate transformation for the substructure modules connected through the element is automatically handled,
- The represented substructure can have several structural elements.

The main contribution in development of the *SubStructure* element is the implementation of a standardized data exchange format and a communication protocol. The data exchange format defines a structure of data to be transmitted through network between the integration module which performs the analysis and the numerical and/or physical substructure. It should cover all information needed for various simulation purposes and have flexibility for further extensions. Figure 4 shows the proposed data exchange format which is under development. The data format includes a message header as shaded in the figure and actual data to be sent or received within this communication. Specifically, the *Version* parameter indicates the version of the data exchange format for the purpose of maintenance. The *Command* parameter indicates the communication action which can be sending target displacement to the substructures or asking restoring forces from them. *Test type* parameter indicates whether the simulation is Pseudo-dynamic or real-time. *Substructure type* describes the type of the substructure used in the simulation which can be either numerical or experimental. *Precision* parameter defines the precision of data appended to the message header. *Data type* indicates the type of the appended data which can be displacement, force, velocity, acceleration, and temperature, or any combination of them. The size of the header is fixed to be 16 bytes while the size of the attached data depends on the parameters defined in the message header. For example, if an experimental truss element is represented by a *SubStructure* element and the parameters of the message header for the communication have been initialized with the *Number of DOFs* parameter of 4 (the total number of DOFs of the substructure), the *Command* parameter of 3 (sending target displacements to the substructure), and the *Precision* parameter of 2 (double precision), then the size of the data appended to the message header will be set to be 32 bytes (4 DOFs×8 bytes) for target displacements. An example using the proposed data exchange format and the communication protocol in a multi-platform simulation with numerical substructure is shown in the following section. More details on the data exchange format will be released to the research community in upcoming publications.

The *SubStructure* element is planned to be used with UT10 Hybrid Simulator for running numerical-experimental hybrid simulations. For this purpose, this element will be used to represent uniaxial physical substructures in the numerical module providing the connection and communication with the experimental modules.

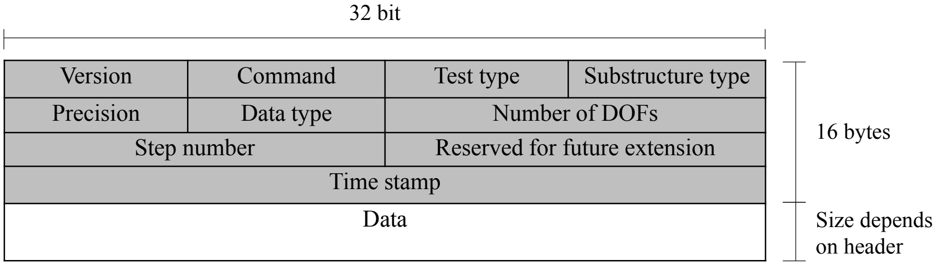

Figure 4: Standardized data exchange format

3.2 Test example

In order to verify the functionality of the new OpenSees *SubStructure* element, a 6 story simple steel frame equipped with Buckling Restrained Braces (BRBs) in concentric chevron configuration was modeled in OpenSees and its response under a ground motion was evaluated using nonlinear time history analysis. The ground motion was the scaled (SF = 1.89) 1994 Northridge earthquake recorded at Canoga Park-Topanga Can station with scaled peak ground acceleration of 0.68g. The record was selected from PEER NGA strong motion database [15]. The frame constitutes the main lateral load resisting system in one direction for a 6 story building located in Los Angeles where the earthquake loads are expected to govern the design of the structure for lateral loads. This building is designed and studied by Choi et al. [16].

For the analysis of the structure, it is divided into two parts as indicated in Figure 5. The 10 BRBs in the first 5 stories are modeled as a single numerical substructure in a separate OpenSees platform while the rest of the structural elements are modeled in the main OpenSees platform. The numerical substructure is represented by the *SubStructure* element that was developed in the main OpenSees platform. The frame is analyzed once using one OpenSees platform without substructuring (whole structure model) and once with two OpenSees platforms with one numerical substructure as explained above. Figure 6 shows the first 30 seconds of history of the first floor interstory drift ratio for both analyses. As can be seen from this figure, the results completely match for both analyses showing that the *Substructrue* element is working properly.

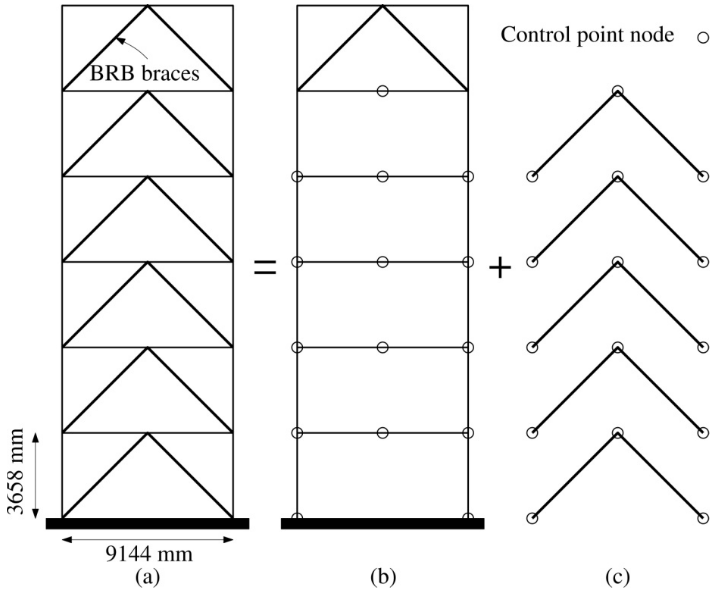

Figure 5: Six story frame model. a) Full frame with BRB braces, b) Main OpenSees model, c) Numerical substructure model

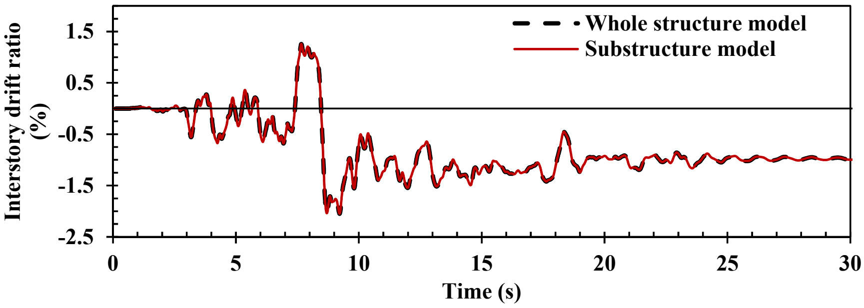

Figure 6: History of first floor interstory drift ratio for the 6 story frame

4. FIRST PLANNED RESEARCH PROJECT APPLICATIONS

4.1 Investigation of response of structures with hysteretic damper braces

Hysteretic energy dissipating braces are one of a number of effective devices for enhancing the seismic performance of structures [17]. The application of these devices is steadily increasing in North America. Several research projects have recently been completed at the University of Toronto on the development and deployment of novel hysteretic energy dissipation devices for use in high seismic performance steel structures [18,19]. Hybrid simulations are planned using the UT10 Hybrid Simulator to investigate the effect of the real properties of various hysteretic damper systems on the accuracy of commonly used numerical models to predict the seismic performance of these structures. For this purpose and as a first step, the seismic performance of a 6-story steel structure equipped with BRBs will be evaluated using the UT10 Hybrid Simulator. In this study large scale BRB specimens will be used as specimens. In the second step, reusable specimens with adjustable hysteretic behaviour will be designed, fabricated, and used as the physical substructures in hybrid simulations. These specimens will be reusable and their important hysteretic parameters, like the post yield stiffness and self-centering capabilities, will be adjustable making it possible to perform experimental parametric studies. These specimens will be used to represent different types of hysteretic damper braces in the hybrid simulations. This experimental parametric study will not only help in verification of performance predictions inherent in existing design procedures, but will also provide a more realistic understanding from the behaviour of structures equipped with hysteretic damper braces.

4.2 Selection strategy for physical substructures

There are many cases in hybrid simulations where the number of critical structural elements that can be considered as physical substructure is more than what can be experimentally tested in the laboratory. In these cases, a strategy is required for the most efficient selection of physical substructures (number and location) which has the maximum effect on the response prediction of the structure. Preliminary studies of this kind have been completed at University of Toronto [13] and it was observed through experimental investigations on braced frames that the system-level response prediction of the structure can be significantly changed by changing the location of the brace (first story brace, second story brace, etc) that is represented by the physical substructures. A preliminary selection strategy for shear type buildings is also presented. More comprehensive studies of this kind using UT10 Hybrid Simulator with several specimens are planned.

5. CONCLUSIONS

The University of Toronto's ongoing projects for development and improvement of multi-platform simulation methods was presented in this paper. These developments include a novel experimental platform called the UT10 Hybrid Simulator which is capable of performing hybrid simulations on up to 10 uniaxial structural elements simultaneously. This facility uses the existing Shell Element Tester (SET) facility in the structural laboratory for applying the required loads on the specimens. An improved version of the NICON interface is developed to facilitate communication of the numerical models with the existing MTS FlexTest actuator controller. A new OpenSees element called *SubStructure* was also developed which represents the numerical or experimental substructures in the multi-platform simulations. This generic element provides a newly developed standardized data exchange format and a communication protocol for communication between the integrating numerical module and other numerical and/or physical substructures. The functionality of this element was verified by a multi-platform simulation with a numerical substructure. The developments are still ongoing and future experimental-numerical hybrid simulations are planned in the near future using the new developed systems.

REFERENCES

[1] Kwon, O., and Elnashai, A. Seismic analysis of Meloland road overcrossing using multiplatform simulation software including SSI. *Journal of Structural Engineering* (2008) 134, No. 4: 651-660.

[2] Kwon, O., Elnashai, A., and Spencer, B. F. A framework for distributed analytical and hybrid simulations. *Structural Engineering and Mechanics* (2008) 30, No. 3: 331-350.

[3] Saouma, V., and Sivaselvan, M. *Hybrid simulation: Theory, implementation and applications*. Taylor and Francis Group, London, UK, (2008).

[4] Hakuno M., Shidawara M., and Hara T. Dynamic destructive test of a cantilever beam controlled by an analog-computer. *Proceedings of the Japan Society of Civil Engineers* (1969) 171: 1–9.

[5] Takanashi, K., and Nakashima, M. Japanese activities on on-line testing. *Journal of Engineering Mechanics* (1987) 113, No. 7: 1014-1032.

[6] Mahin, S. A., and Shing, P. B. Pseudodynamic method for seismic testing. *Journal of Structural Engineering* (1985) 111, No. 7: 1482-1503.

[7] Negro, P., Mola, E., Molina, F. J., and Magonette, G. E. Full-scale PSD testing of a torsionally unbalanced three-storey non-seismic RC frame. In *Proceeding of 13th World Conference on Earthquake Engineering*, Vancouver, BC, Canada, (2004), No. 968.

[8] Yang, T. Y., Stojadinovic, B., and Moehle J. Hybrid simulation of a zipper-braced steel frame under earthquake excitation. *Earthquake Engineering & Structural Dynamics* (2009) 38, No. 1: 95-113.

[9] Elnashai, A., Spencer, B., Kim, S. J., Holub, C., and Kwon, O. Hybrid distributed simulation of a bridge-foundation-soil interacting system. In *4th International Conference on Bridge Maintenance, Safety, and Management,* Seoul, Korea. (2008).

[10] Kammula, V., Erochko, J., Kwon, O., and Christopoulos, C. Application of hybrid-simulation to fragility assessment of the telescoping self-centering energy dissipative bracing system. *Earthquake Engineering & Structural Dynamics* (2014) 43, No. 6: 811-830.

[11] Mazzoni, S., McKenna, F., Scott, M. H., and Fenves, G. L. OpenSees command language manual. *Pacific Earthquake Engineering Research (PEER) Center* (2006).

[12] Takahashi, Y., and Fenves, G. L. Software framework for distributed experimental–computational simulation of structural systems. *Earthquake engineering & structural dynamics* (2006) 35, No. 3: 267-291.

[13] Kammula, V. Application of hybrid simulation to fragility assessment of self-centering energy dissipative (SCED) bracing system. MASc dissertation, Civil Engineering Department, University of Toronto, Toronto, Canada, (2013).

[14] Zhan, H. Development of a generic controller interface program NICON for multi-degrees of freedom PSD hybrid simulation. MASc dissertation, Civil Engineering Department, University of Toronto, Toronto, Canada, (2014).

[15] Pacific Earthquake Engineering Research Center: NGA Database. (Accessed December, 2013). http://peer.berkeley.edu/peer_ground_motion_database.

[16] Choi, H., Erochko, J., Christopoulos, C., and Tremblay, R. Comparison of the seismic response of steel buildings incorporating self-centering energy-dissipative dampers, buckling restrained braces and moment resisting frames. Rep. No. 05-2008, Dept. of Civil Engineering, University of Toronto, Toronto, Ontario, (2008).

[17] Christopoulos, C., Filiatrault, A. *Principles of passive supplemental damping and seismic isolation*. IUSS Press, Milan, Italy, (2006).

[18] Gray, M. G., Christopoulos, C., and Packer J. A. Cast steel yielding brace system for concentrically braced frames: concept development and experimental validations. *Journal of Structural Engineering* (2013) 140, No. 4.

[19] Erochko, J., Christopoulos, C., and Tremblay, R. Design, testing, and detailed component modeling of a high-capacity self-centering energy-dissipative brace. *Journal of Structural Engineering* 10.1061/(ASCE)ST.1943-541X.0001166 (2014).