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Application of hybrid simulation for the evaluation of the buckling response of steel braced frame columns

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ABSTRACT

Hybrid simulation is an economical structural testing technique in which the critical part of the structure expected to respond in the inelastic range is tested physically whereas the rest of the structure is modelled numerically using a finite element analysis program. This paper describes the application of hybrid simulation for steel I-shaped columns in Multi-Tiered Braced Frame (MT-BFs) structures. A full-scale W250x101 column part of a two-tiered concentrically braced frame was physically tested while the rest of the frame was numerically analysed using the *OpenSees* finite element program. The development and main challenges of the hybrid simulation are first described and the main findings of the hybrid simulation are then presented. The test results show that the testing technique is an effective experimental tool to generate reliable data on column stability limit states. Furthermore, the results from the hybrid simulation confirmed the findings of previous numerical simulations to assess the seismic response of columns in steel braced frames.

Keywords: large-scale testing, multi-tiered braced frame, column buckling, pseudo dynamic hybrid testing.

1 INTRODUCTION

Hybrid simulations combines experimental testing and numerical modelling in order to examine the seismic response of structures under actions from extreme events such as earthquake actions. In hybrid simulation, a critical component of the structure expected to respond in the inelastic range or fail is tested experimentally whereas the rest of the structure is modelled numerically using a finite element analysis program. This testing method offers a cost-effective solution for large-scale testing of various structural components such as steel columns and bracing members, reinforced concrete walls, and bridge piers. Two types of hybrid simulation are commonly used in the seismic evaluation of structures: 1) pseudo-dynamic hybrid simulation; and 2) real-time hybrid simulation. In this paper, application of the pseudo-dynamic hybrid simulation method will be discussed.
The concept of pseudo-dynamic hybrid simulation was first proposed nearly 50 years ago [1] and have since been implemented and improved by several researchers [e.g. 2, 3]. Key improvements include the development of robust numerical integration techniques [4] and effective delay compensation approaches [5], the implementation of geographically distributed hybrid simulations [6, 7], and the development of force based control methods [8]. Past studies focused on the accuracy, stability and reliability of the hybrid method and only a few tests examined the response of structures in which hybrid simulation is used as a seismic test method. Hybrid simulation was used for a half-scale three-storey steel concentrically braced frame in which the bottom-storey was tested in the laboratory whereas the remainder of the structure was numerically analysed [9]. A series of large-scale hybrid simulations were performed to investigate the seismic performance of self-centering rocking steel frames with the main objective of verifying the ability of the rocking system to self-centre buildings [10, 11]. The fragility assessment of structures built with self-

centring energy dissipative bracing system was studied using pseudo-dynamic hybrid simulations [12]. In that case, the physical substructure consisted of the braced frame of the first storey and the upper stories were included in the numerical substructure. Multi-axial pseudo-dynamic hybrid simulations was conducted to evaluate the behaviour of steel bridge piers under multi-directional seismic loading [13, 14].

Multi-tiered braced frames (MT-BFs) consist of multiple bracing panels stacked over the height of a storey. This braced frame configuration is prone to column instability as well as brace fracture due to uneven distribution of the inelastic frame deformations [15]. Column buckling is made more critical because the columns are not supported about their strong axis, which may lead to column instability along the full frame height. In the last decade, extensive numerical simulations were performed to better understand the seismic response of MT-BFs [16] and develop seismic design provisions for the system in Canada [17] and the U.S. [18]. The numerical studies showed that inelastic brace response tends to concentrate in one tier over the frame height, which imposes bending moments on the columns that may lead to column failure by instability. This article presents a hybrid simulation program that was recently undertaken at the Structural Engineering Laboratory of Polytechnique Montreal to validate the findings of the numerical simulations with focus on the stability of the MT-BF columns. The development and main challenges of the hybrid simulation are first described and the results of one pseudo-dynamic hybrid simulation of a two-tiered braced frame are presented. In that simulation, a full-scale W250x101 column part of the braced frame was physically tested using an advanced multi-directional structural testing facility, while the rest of the frame was modelled in the *OpenSees* environment [19].

2 MULTI-DIRECTIONAL HYBRID TESTING SYSTEM (MDHTS)

Hybrid simulation of the MT-BF structure was performed in the Multi-Directional Hybrid Testing System (MDHTS), a structural testing system that can perform multi-axis static, quasi-static cyclic, pseudo-dynamic, and/or hybrid tests on large-scale specimens such as columns, walls and bridge piers. The system has been designed to impose any combination of forces and displacements along 6 degrees of freedom (DOFs) to test specimens using a sophisticated control system.

2.1 System capacities

The MDHTS with an I-shaped steel column specimen is shown in *Fig. 1*. The system includes a rectangular upper platen with 2.5 m x 3.5 m x 0.625 m dimensions. The platen is a stiff multi-cellular steel construction that can be displaced along 6 DOFs using a total of eight actuators: four 1.8 MN vertical actuators placed at the four corners and four 1.0 MN horizontal actuators (two in each horizontal direction). A lower platen with the same dimensions is anchored to the laboratory's strong floor. The specimens are placed between the two platens. The four vertical actuators are connected to the upper platen and the lower platen/strong floor assembly and their length can be adjusted to achieve test heights varying from 4.0 m to 8.0 m. The four horizontal actuators are placed between the upper platen and the laboratory L-shaped reaction wall.

In the system, axial displacements and forces in each actuator are monitored and transformed into displacements or forces along three translational and three rotational DOFs at a control point located at the centre of the bottom surface of the upper platen (see *Fig. 1*), which is being the centre of the top end of the specimen. This transformation is performed by a dedicated routine implemented in the MTS FlexTest 793 controller. Since the individual controlling of each actuator is not practical, the MTS controller provides simultaneous control of the 6-DOF movements of the upper platen with respect to the control point. The controller is also designed to function using net relative displacements measured between the top and bottom ends of the specimens, thus eliminating displacements induced by deformations in the platen, actuators and the laboratory strong floor and reaction wall. This local control displacement feedback is obtained using eight high-precision digital transducers mounted on rigid frames attached to the specimen ends (see *Fig. 1*). The control mode can be in either load- or displacement-controlled, or any combination of the two. Typically, the test specimens are rigidly connected to the platens at their both ends. Relative forces and/or displacements are then applied at the specimen top end by the upper platen. The top end condition can be pinned (moments are set to zero), fixed (displacements are set to zero), or semi-rigid (by specifying the relationship between end moment and rotation in the control system).

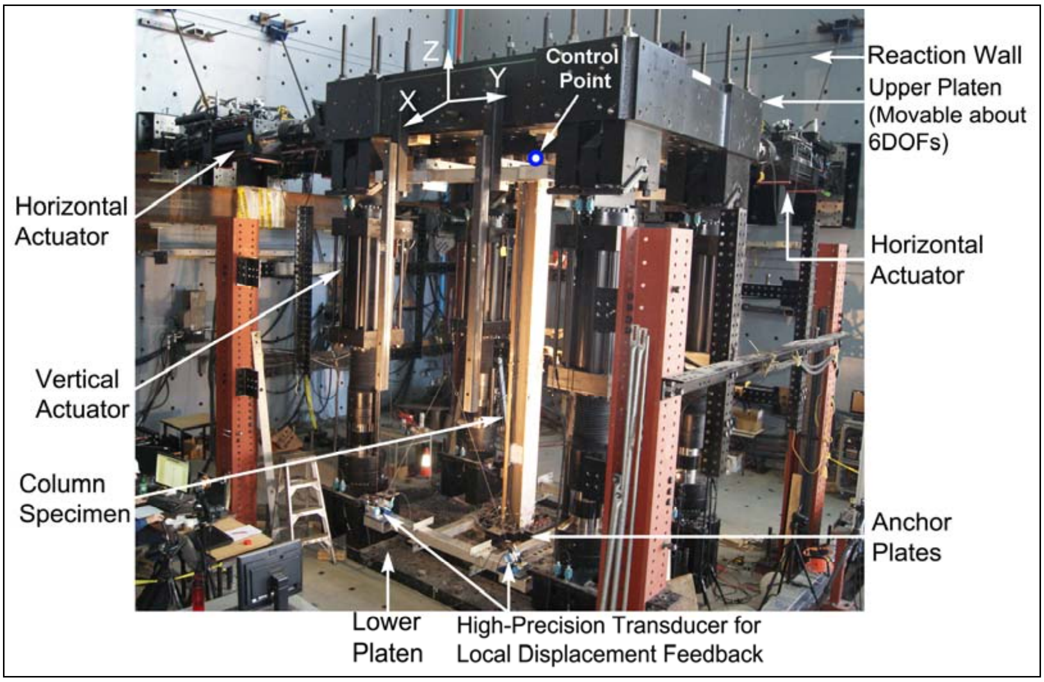

Fig. 1. I-shaped column specimen in the Multi-Directional Hybrid Testing System.

The vertical and horizontal actuators are placed on a 2 m by 3 m horizontal grid. As shown in *Fig. 1*, the X and Y axes correspond to the horizontal directions parallel to the 2 m and 3 m dimensions, respectively. The Z axis represents the vertical direction. The total force, moment, displacement and rotation capacities of the system in each DOF are given in *Table 1*. Note that the moment capacities were calculated assuming that the specimen is centered in the test setup and no axial load is applied.

Table 1. Translational and rotational capacities of the MDHTS (at control point).

Translational Capacities			Rotational Capacities			
Plane Axis	Vertical Z	Horizontal X & Y	Plane Axis	Vertical About X	Vertical About Y	Horizontal About Z
Force (kN)	± 7200	± 2000	Moment (MN-m)	± 10.8[1]	± 7.2[1]	± 5.0
Displacement (mm)	± 300	± 375	Rotation (rad.)	± 0.122	± 0.122	± 0.122[2]

[1]From vertical actuators only, with no concomitant axial load.
[2]Without concomitant translations.

2.2 Hybrid simulation capabilities

Schematic of the hybrid simulation loop used for the pseudo-dynamic hybrid simulation of the MT-BF structure is shown in *Fig. 2*. It includes two main portions: the computational driver, or the finite element model, and the physical test portion that includes the FlexTest controller and experimental equipment. The first portion consists of the well-understood components of the structure and is referred to as the numerical substructure. The second portion includes the critical structure element that is expected to develop complex inelastic response, strength deterioration or instability. This element forms the experimental substructure of the hybrid model. In addition to these components, the hybrid simulation requires a middleware which provides the communications between the finite element model and the testing system. In this study, the *OpenFresco* program [20] was used as the middleware because of its robust, flexible and easily extensible environment. Additionally, it supports a large variety of computational drivers such as the *OpenSees* program used in past numerical simulations of MT-BFs. The MDHTS can be operated using two different interfaces between *OpenFresco* and the Flextest controller: 1) an MTS Computer Simulation Interface (CSI) [21]; or 2) Mathworks Simulink platform with Scramnet communication. The first one is simpler because it handles command and feedback signals; however, it is not possible to modify the signals during the analysis. The Simulink interface offers more flexibility to access and modify the command and feedback signals within the *OpenFresco* and the Flextest controller.

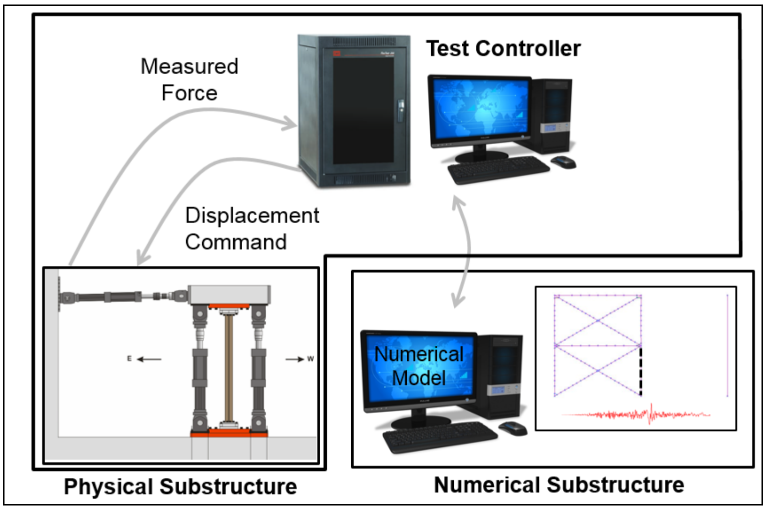

Fig. 2. Hybrid simulation loop.

3 HYBRID SIMULATION OF BUCKLING RESPONSE OF COLUMNS IN MTBFS

3.1 Column buckling in MT-BFs

Past numerical simulations showed that columns of MT-BFs not specially designed to achieve stable inelastic response are prone to instability due to flexural demand resulting from unevenly distributed inelastic response of the bracing members over the frame height. Brace tension yielding only occurs in one tier, leading to large drifts in that tier and, consequently, large in-plane bending moments in the columns. The moments combined with the large axial compression loads due to the gravity and seismic loads may lead to flexural buckling of the columns about their weak-axes, as shown in *Fig. 3*. Typically, column buckling takes place in the plane of the frame within one tier; however, buckling generally changes to biaxial buckling over the full frame height as column out-of-plane instability about the column strong-axis is triggered due to initial imperfections [22]. Results from 3D finite element analysis of MT-BFs confirmed that the buckling mode also includes torsional deformations and the final buckling mode therefore involves complex flexural-torsional response. This unique instability response of MT-BF columns has not been verified experimentally yet. If testing is to be performed on the critical column tier segment, multi-directional hybrid simulation is required, however, as the axial load and in-plane bending demands on the column depends on the inelastic response of the bracing members over the full frame height and boundary conditions of the test specimen must be modified in the course of the test as out-of-plane column buckling develops over the full building height.

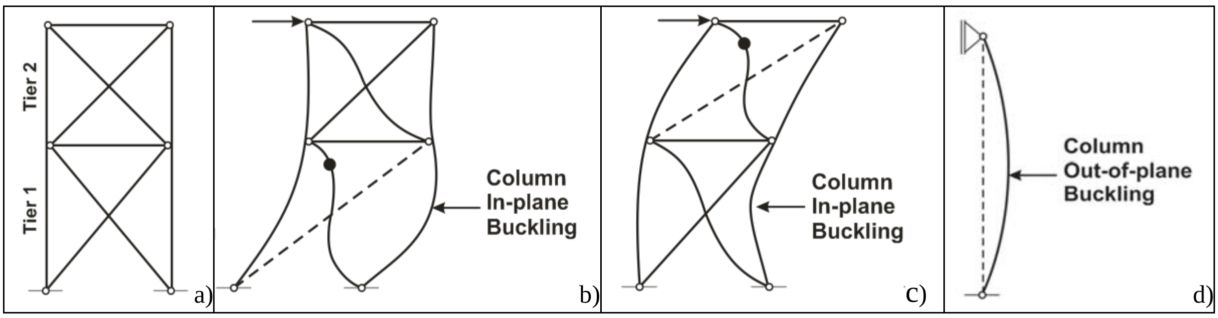

Fig. 3. a) Two-tiered steel braced frame; b) Column in-plane buckling following brace yielding in Tier 1; c) Column in-plane buckling following brace yielding in Tier 2; d) Column out-of-plane buckling.

3.2 MT-BF hybrid loop

A two-tiered steel concentrically braced frame part of an industrial building located in coastal California was selected for the test program. The frame was designed in accordance with the seismic provisions present in the 2010 edition of the building code and standards in the U.S., without applying the new special provisions implemented in 2016 for MT-BFs [18].

Numerical simulations of the braced frame indicated that column buckling would initiate in the first tier of the structure. In the hybrid simulation, physical testing was therefore performed on the first-tier column segment of the structure, as shown in *Fig. 4a*. The remaining portion of the frame was reproduced in the computer model built in the *OpenSees* environment. The *OpenFresco* program was used as a middleware in this test. The hybrid simulation was performed using the MTS CSI system, which links the middleware and MTS Flextest controller. At every analysis step of the simulation, the relative displacements between the two column ends, as predicted by the *OpenSees* analysis, are sent to the controller in the laboratory so that the actuators of the MDHTS can impose them to the test specimen by means of the upper platen (*Fig. 2*). The measured forces from the actuators, as calculated at the system control point, are then fed back to the controller and sent to the *OpenSees* numerical model to determine the structure displacements in the subsequent step. A continuous testing approach was employed to provide a smooth movement of the actuators and, thereby, improve the test accuracy and avoid relaxation of the specimen as would be the case in the conventional pseudo-dynamic testing during the hold-phase time.

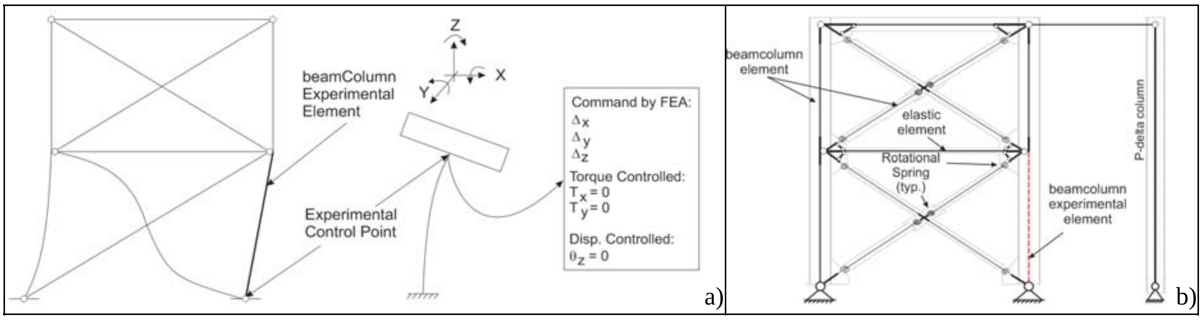

Fig. 4. a) Experimental control point assigned to the numerical substructure and experimental substructure; b) Hybrid numerical model of two-tiered concentrically braced frame.

3.3 Hybrid simulation model

The numerical substructure is shown in *Fig. 4b*. The braces and columns were modelled using nonlinear force-based beam-column elements with fiber discretization of the cross-section. The nominal yield strength F_y = 345 MPa was assigned to the steel material for the struts. The expected steel yield stress, R_yF_y = 431 MPa was utilized for the bracing members. For the columns, the measured yield strength of the test specimen was used (F_{y-m} = 398 MPa). Initial out-of-plane sinusoidal out-of-straightness with maximum amplitude of 1/500 of the unsupported brace length was specified for the braces to trigger brace out-of-plane buckling. Initial sinusoidal out-of-straightness with maximum amplitude of 1/1000 of the length between base and roof was specified in both orthogonal directions for the columns. Mass proportional damping corresponding to 2% of critical in the first structure lateral vibration mode was specified. Detailed information regarding the computational model used in the hybrid simulation can be found in [15].

In the numerical model, the experimental substructure is represented using a two-node beam-column experimental element as shown in *Fig. 4b*. The measured properties of the physical column specimen were assigned to the experimental element. To reproduce the complex loading and boundary conditions of the two-tiered braced frame column segment along 6 DOFs in the physical test, the node at the base of the experimental element in the numerical model was set as the control point for the test. In the laboratory, the column was placed upside down with the base connected to the upper platen. In this way, a pinned condition at the column base could be easily reproduced by setting the moments about X and Y axes equal to zero at the control points. In the laboratory, the

upper end of the column was fixed to the laboratory strong floor. Hence, the displacements and rotations of the control point were defined as the relative displacements and rotations between the two ends of the experimental element in the numerical model [20].
Displacement commands along X, Y, and Z directions obtained from the numerical substructure were fed to the MTS controller. The force signals along these three translational DOFs as obtained from the test were fed back to the numerical model. Rotations of the control point about X and Y axes were controlled in the load-control mode of the MDHTS controller to maintain the corresponding moments equal to zero. The rotation of the control point about Z axis was set equal to zero (using displacement-controlled mode) to simulate a torsional restraint at the column base.

4 CHALLENGES FACED WITH THE HYBRID SIMULATION

The elements of the stiffness matrix of the experimental element of the numerical model were determined experimentally prior to starting the hybrid simulation. Preliminary hybrid simulations tests were then conducted to verify communications between the system components and fixed possible bugs. Note that a few of the preliminary tests were performed in large amplitude in the elastic range of the specimen. Several challenges were then faced when performing the hybrid simulation and the most important ones are briefly described in this section.

4.1 Numerical integration algorithm

An appropriate numerical integration algorithm had to be selected to adequately predict the buckling response of the braces and columns while ensuring accuracy and stability of the solution. The applicability of the several integration schemes available for hybrid simulations in the *OpenSees* program had to be evaluated through analytical hybrid simulations and representative tests. The Newmark method with a fixed number (= 5) of iterations was found to be the most suitable one for this two-tiered concentrically braced frame.

4.2 Numerical convergence

During the preliminary hybrid simulations, the test has to be interrupted several times due to convergence issues in the numerical substructure. This was due to the highly nonlinear elements used in the model, especially the bracing members. This problem could be resolved by employing smaller time steps in the integration when the axial load was reversed in the braces. The appropriate time steps were obtained from numerical hybrid simulations, which will be discussed in Section 5.

4.3 Feedback instabilities

Testing of a multi-degree of freedom column specimen with the potential interaction between actuators may result in instabilities in the force feedback signals returned to the MTS controller. To resolve this problem, a polynomial function was implemented in the MTS Controller to smooth the force feedback signals before they were sent to the numerical model. So doing, the numerical substructure received smooth and stable force feedback signals, which helped convergence. The selected function used a quadratic formulation based on the history of force signals and was applied to the translational DOFs. Force feedback signals before and after the application of the smoothing function are compared in *Fig. 5*.

4.4 Delay in feedback signals

Two-way communication is necessary (*Fig. 2*) in hybrid simulations: one way for sending the displacement commands and one way for receiving the force feedback signals. Preliminary simulations were carried out to verify the communication loop between all system components and measure delays in the feedback signals along each DOF. Delays of approximately 100 milliseconds were found along all DOFs, which was too small to cause problems in a pseudo-dynamic hybrid simulation as planned for this test program. Hence, delay compensators were not used in this study.

4.5 Friction generated in the MDHTS

The preliminary simulations revealed that frictional forces develop in the swivels of the 8 actuators of the MDHTS setup. These forces represent fictitious feedback forces that add to the specimen force response and have detrimental effect on the accuracy of the hybrid simulation. Different schemes were examined to overcome this difficulty. The solution that was adopted to mitigate the effects of these frictional forces consisted in adding to the numerical substructure an *OpenSees* model of the MDHTS setup that acted in parallel with the structure FE model. The added numerical model is shown in *Fig. 6*. In this model, negative frictional properties were assigned to the actuator swivels to produce frictional forces equal to but of the opposite signs of the friction forces that developed in the actual swivels of the laboratory test setup. Negative forces generated by the added numerical model therefore cancelled the forces generated by the friction in the actuator swivels in the force feedback signals received from the test. The corrected force feedback signals were therefore representative of the actual stiffness of the test specimen along each DOF.

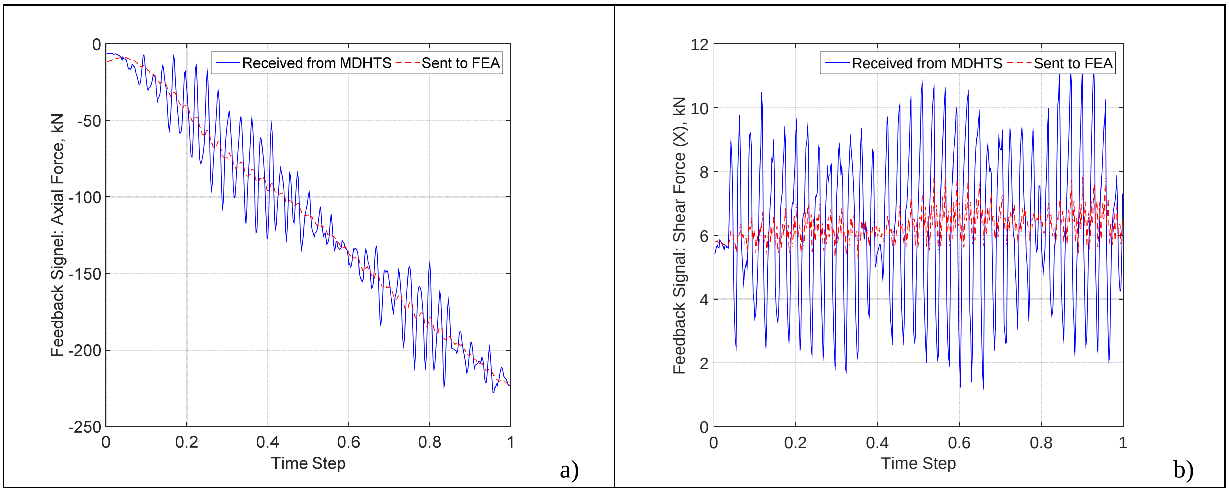

Fig. 5. Feedback signals: a) Axial force during gravity analysis; and b) Shear force during dynamic analysis.

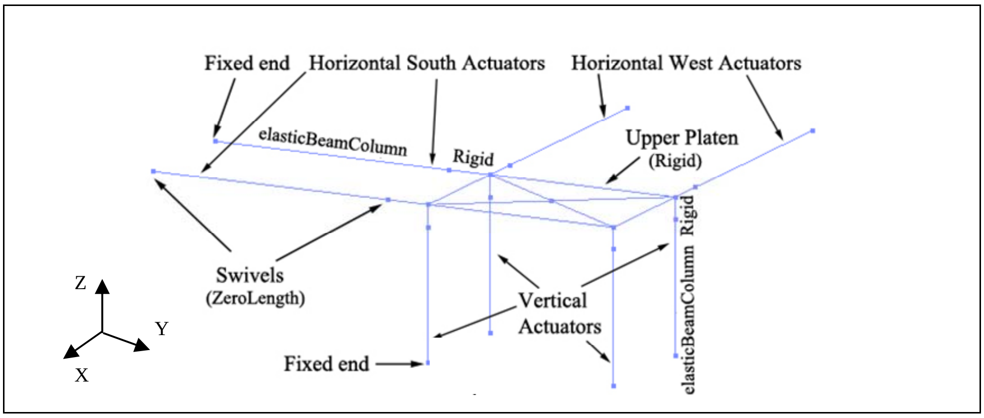

Fig. 6. *OpenSees* model of the MDHTS used to remove friction forces developing in the physical testing system.

5 HYBRID SIMULATION RESULTS

5.1 Hybrid simulation

Prior to performing the hybrid simulation, numerical hybrid simulations were performed to verify the adequacy of and compatibility between the numerical and physical substructures. This verification was completed using a Master model numerically coupled to a Slave model. The former is the numerical substructure to be used in the actual hybrid simulation whereas the Slave model includes the column specimen simulated using the *OpenSees* program. *OpenFresco* was used as the middleware to connect the Slave model to the Master model, as is the case in the actual hybrid simulation. In *Fig. 7*, the displacements along X and Y axes at the upper end of the column specimen from the numerical hybrid simulation are compared to those obtained from pure numerical simulations performed using a single numerical model of the entire structure. The analyses were carried out under the 1971 San Fernando LA - Hollywood Storage record scaled to match the MCE level. The comparison is presented up to t = 8 s, after buckling of the column has occurred. As shown, the coupled numerical hybrid simulation model gives results that are identical to the pure numerical model of the two-tiered braced frame. The slight differences between the two sets of results are attributed to the differences in the integration methods used in each simulation. This verification shows that the hybrid simulation scheme correctly represent the structural system studied. The numerical hybrid simulation therefore represents a proper tool to validate the selection of the numerical integration algorithms, the integration time step chosen and the boundary conditions considered for the experimental setup.

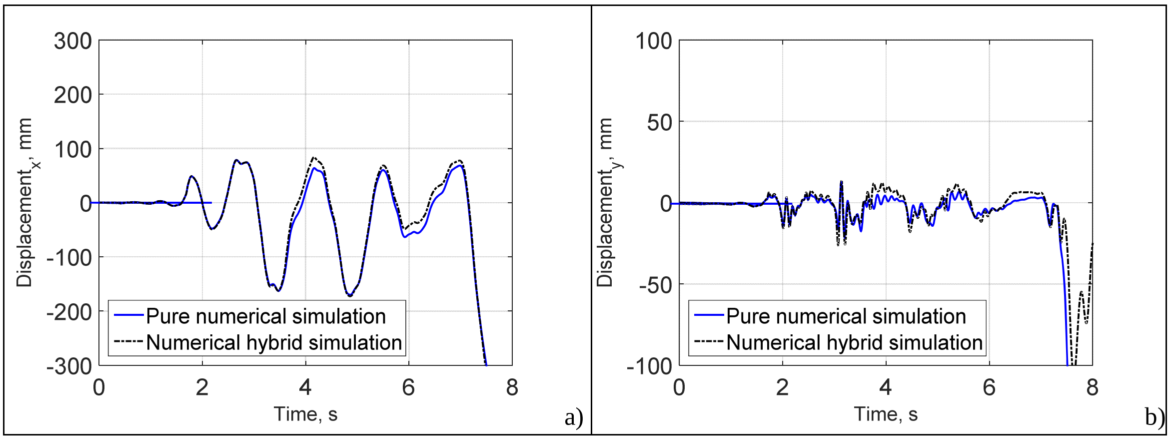

Fig. 7. Comparison of the displacements along X (in-plane) and Y (out-of-plane) axes at the top of the first-tier column segment as predicted by the pure numerical and numerical hybrid simulations.

5.2 Hybrid simulation results

The hybrid simulation of the two-tiered braced frame structure aimed at investigating the buckling response of MT-BF columns under severe seismic loading. The hybrid simulation started with the application of the gravity loads at top of the two braced frame columns as a dynamic analysis using a Generalized Alpha method. The portion of the gravity load resisted by the test specimen was simultaneously applied to the column in the laboratory. The response history analysis was then performed under the 1971 San Fernando LA - Hollywood Storage record by controlling the three translational DOFs at the control point of the test specimen, as described in Section 3. The delay measured in the system actuators is approximately 100 millisecond and a ramp time of 2.0 s was considered for this test to provide sufficient time to complete the numerical integration step, send the command signals, obtain and return the actuators response, and perform data acquisition. Furthermore, strain rate effects on material properties were eliminated by using such a slow testing rate during the hybrid simulation.

The Newmark integration algorithm with a fixed number of iterations per time step (HHTHSFixedNumIter) that was used in the hybrid simulation was selected based on the preliminary simulations. The number of iterations was set to five to accurately approximate the behaviour while minimizing the testing time. Newton's solution was employed to update tangent stiffness at every iteration. Due to the nature of the hybrid simulation, the division of ground motion time steps was not allowed in the simulation; instead, the dynamic nonlinear analysis was performed in seven phases with various time steps. In each phase, an integration time step was chosen to achieve convergence in the numerical substructure and minimize the real time required to perform the hybrid simulation.

Fig. 8 shows displacements along X and Y axes at the upper end of the column specimen obtained from the hybrid simulation, numerical hybrid simulation and pure numerical analysis. The hybrid simulation was initiated in December 2016. The simulation was performed until a time of 7.4 s of the ground motion time, where the simulation had to be halted because the displacement capacity of the system was reached in the X direction. At the time of writing, additional simulations imposing lower displacement demands were being conducted to complete the test program.

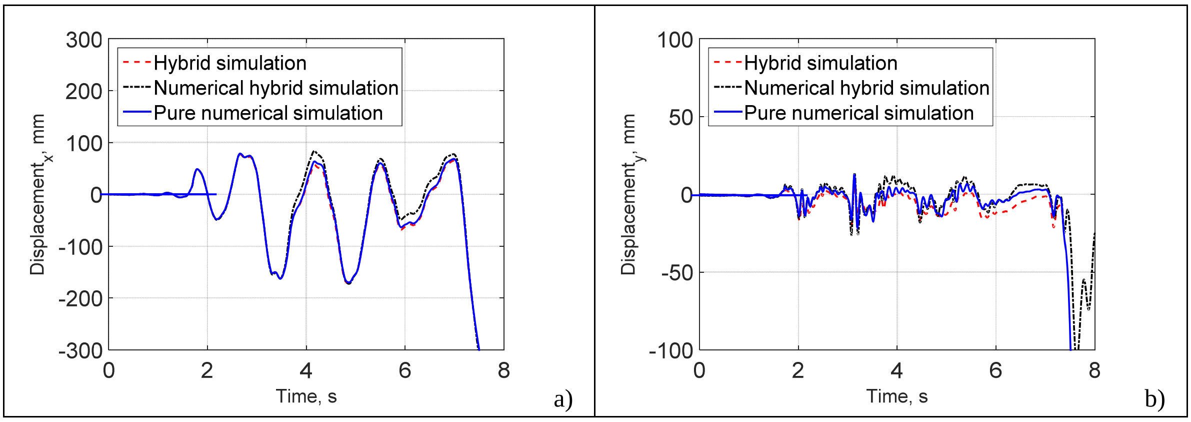

Fig. 8. Comparison of the displacements along X (in-plane) and Y (out-of-plane) axes at the top of the first-tier column segment as obtained from the pure numerical, hybrid simulations and hybrid testing.

6 CONCLUSIONS

This paper presented the development of a hybrid simulation that was completed to study the buckling response of columns part of multi-tiered braced frames. A two-tiered frame was investigated for which one of the two first-tier column segment was the physical substructure. The remaining components of the frame were numerically modelled with the *OpenSees* program. Physical testing was carried out using an advanced multi-directional hybrid testing system (MDHTS) capable of applying complex loading and boundary conditions along six degrees of freedom to the test specimens. Some of the challenges faced in the implementation of the simulation were described together with the solutions proposed. Key findings from this study can be summarized as follows:

– Pseudo-dynamic hybrid simulation represents a cost-effective solution for the large-scale testing of steel braced frame columns that are expected to fail by inelastic flexural-torsional buckling due to complex loading and boundary conditions that are imposed as a result of the nonlinear seismic response of the structure.
– The main challenges of the hybrid simulation include the selection of an effective and robust numerical integration scheme, achievement of numerical convergence, prevention of instability in the force feedback signals and mitigation of friction forces developing in the testing system.
– Numerical hybrid simulation is an effective technique to verify the adequacy of and compatibility between the numerical and physical substructures. The technique is also useful to verify the suitability of the numerical integration scheme.
– A smoothing function was needed to stabilize the force feedback signals received from the physical testing system.
– A friction compensation technique was developed and implemented to reduce the unavoidable friction forces that develop in the physical testing system.
– Preliminary hybrid simulation confirmed the inelastic buckling response of steel columns part of multi-tiered braced frames as obtained from numerical simulations.
– Additional work is needed to further improve the efficiency of hybrid simulations for the study of complex limit states such as column inelastic buckling in structures subjected to highly nonlinear seismic response.

7 ACKNOWLEDGMENTS

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