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Development of 10-Element Hybrid Simulator and Its Application to Seismic Performance Assessment of Structures with Hysteretic Energy Dissipative Braces

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ABSTRACT
Pseudo-dynamic hybrid simulation is a novel testing method that aims to provide a more realistic prediction of the seismic response of a structural system by integrating the experimental response of structural components with numerical models of the rest of the structural system. Application of this test method to practical research projects, however, is still limited due to the complexity of the test method. In addition, only a few structural components in a structural system can currently be tested experimentally in large-scale, and therefore the contribution of the experimental results on the accuracy of the overall seismic response diminishes. In order to overcome these limitations, a unique hybrid simulation testing apparatus is being developed at the University of Toronto which is capable of performing hybrid simulations on up to 10 large-scale bracing or damping elements simultaneously. This paper first presents an overview of the main hardware and control components of this apparatus. The paper then discusses the design and testing results of an adjustable brace which is capable of simulating hysteretic behavior of Buckling Restrained Braces (BRBs). Finally, a 6-story structure equipped with BRBs is analyzed using nonlinear time-history analyses to investigate the effect of the accuracy of the BRB numerical model on the global response of the structure.

KEYWORDS: *Hybrid simulation, Pseudo-dynamic testing, Buckling Restrained Brace, Seismic performance, Nonlinear time-history analysis*

1. INTRODUCTION

Performance-based seismic design requires an accurate prediction of structural performance under different levels of seismic intensity (ATC, 2006). Because modeling of inelastic cyclic behaviour of structural components is still challenging, it is ideal if the structural performance assessment can be based on experimental results from tests on critical components. Pseudo-dynamic hybrid simulation is one of the structural simulation methods in which the experimental test data is integrated within an entire structural system. Because the hysteretic behaviour of critical elements is physically modeled, the simulation method provides more realistic predictions of structural response in comparison with a purely numerical simulation method. The physical and numerical elements are integrated as a structural system via the transmission of predicted displacements and measured responses of structural components. Despite the vast and ongoing improvements in the hybrid simulation method, its application and implementation in the laboratories is rather restricted due to the complex nature of the simulation method. Development of a user friendly, easy to understand, and reconfigurable hybrid simulation platform is hence one of the essential steps towards further development of the hybrid simulation method (Shao and Griffith, 2013).

The accuracy improvement through hybrid simulation highly depends on the structural system under consideration. For example, if the global response of a structure is dominated by isolation bearings and the behaviour of the bearings can not be numerically modeled with sufficient accuracy, then physically modeling the bearings in the hybrid simulation will greatly improve the accuracy of the prediction. On the other hand, if many structural elements collectively contribute to the lateral load resisting system and the inelastic hysteretic response of these elements is hard to model numerically, then testing only a few structural elements will marginally improve the overall accuracy of the simulation. Examples of the latter are moment resisting frames or braced frames where the inelasticity is distributed along the height of the structure in the connections or braces. In these cases, there is a need to extend the capabilities of the hybrid simulation framework for testing a large number of physical components simultaneously and/or to adopt a model-updating method in which experimental data can be used to update numerical elements in each time step of simulation (Kwon and Kammula, 2013; Elanwar and Elnashai, 2014). Testing a large number of specimens is usually limited by the availability of equipment in the laboratories. There are a few hybrid simulations reported in the literature that use a few physical substructures of similar nature in the simulation. For example, Christenson et al. (2008) performed real time hybrid simulations on a steel moment resisting frame in which three magneto-rheological (MR) fluid dampers were tested as physical substructures. Real time hybrid simulations were also performed by Karavasilis et al. (2011) on a 2- story, four-bay steel moment resisting frame equipped with compressed elastomer dampers where two dampers were tested as physical substructures while the rest of the frame was modeled analytically. There are also other hybrid simulation tests reported in the literature that use a multi-story frame equipped with several damper/braces as physical substructures. In these tests, multiple actuators are used to apply calculated demand displacements at each floor level on the frame. Using this approach, Fahnestock et al. (2007) performed hybrid simulations on a 60% scale 4-story steel frame equipped with eight BRBs. More recently, Friedman et al. (2015) performed hybrid simulations on 60% scale 3-story steel frames equipped with up to two MR dampers. The laboratory space imposes limitations on the scale and the number of stories of the tested frame in this approach. Furthermore, the frame containing the damper/braces should also be constructed that adds to the costs and complexity of the physical substructure.

The main objective of the research presented in this paper is to overcome the above-mentioned limitations in the pseudo-dynamic hybrid simulation method by increasing the number of physical specimens that are integrated in the simulation. This project attempts to develop a simple, robust, and flexible hybrid simulation apparatus to further facilitate the development and application of the testing method in structural laboratories. As part of this project a unique experimental testing apparatus, the *UT10 Hybrid Simulator*, is being developed. This testing facility is able to perform pseudo-dynamic hybrid simulation of up to 10 large-scale uniaxial physical substructures simultaneously. The *UT10 Hybrid Simulator* also features an open-source network interface program for actuator controllers, called *NICON*, which provides a reconfigurable framework for various ramp generation, error compensation, and network communication algorithms (Zhan and Kwon, 2015). An adjustable brace specimen is being designed which is able to simulate the hysteretic response of BRBs, has adjustable stiffness-strength properties, and is reusable. This specimen not only makes it possible to further investigate the effect of BRB modeling inaccuracies on the global seismic performance of multi-story structures, but it also provides a reusable and reconfigurable nonlinear physical component that can be easily produced in large numbers and can be used in multiple hybrid simulations. Combination of the *UT10 Hybrid Simulator* and the adjustable brace will in general form a more extensive and simplified hybrid simulation platform. More specifically, it provides the means for a critical review of the accuracy of existing BRB models and their effect on the global seismic response of multi-story structures.

This paper first presents an overview of the main hardware and control components of the *UT10 Hybrid Simulator*. In the second part, the design details and results of preliminary cyclic tests on the adjustable brace subassemblies is presented. Finally, a fully analytical study is performed to assess the effect of the accuracy of BRB numerical models on the global seismic response of a 6-story building.

2. DEVELOPMENT OF THE UT10 HYBRID SIMULATOR

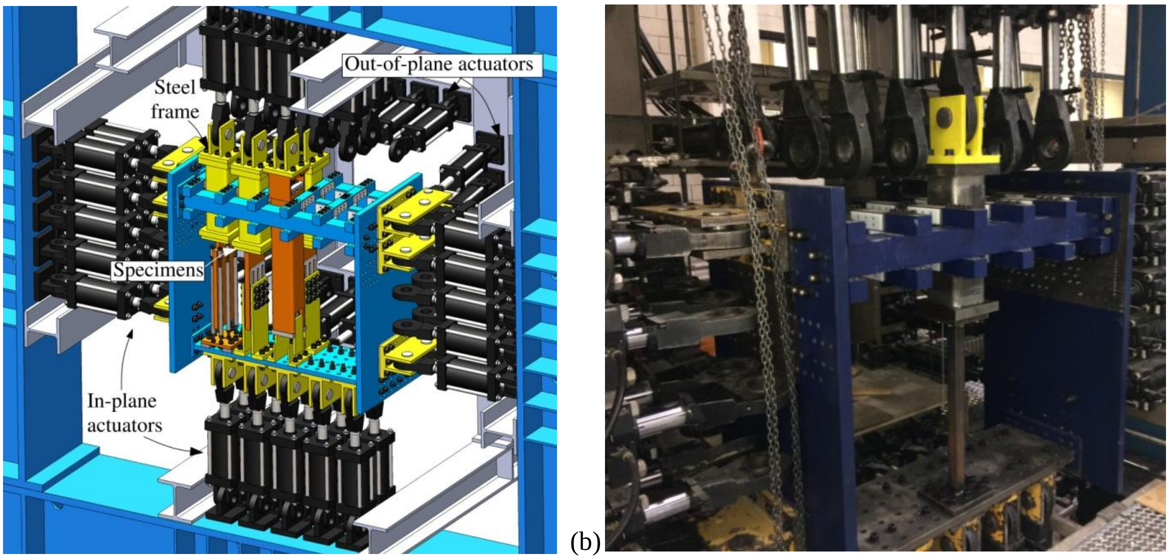
2.1. Axial Loading and Support System

The *UT10 Hybrid Simulator* is mainly suitable for testing uniaxial brace or supplemental damping elements with rate independent behavior but can also be adapted to other structural sub-assemblages like beam-column connections. It can accommodate up to ten 800 kN or five 1,600 kN specimens. The simulator can simultaneously test braces with various sizes and lengths.

The *UT10 Hybrid Simulator* is built on the existing Shell Element Tester (*SET*) at Structural Testing Facilities of University of Toronto. The *SET* was originally developed to study the behaviour of large-scale reinforced concrete (RC) shell elements under various loading configurations (Kirschner and Collins, 1986). The SET is equipped with forty 1,000 kN in-plane and twenty 500 kN out-of-plane actuators. *UT10 Hybrid Simulator* uses the top ten vertical in-plane actuators to apply the predicted target displacements on the uniaxial specimens. The rest of the connected actuators provide axial, lateral in-plane, and lateral out-of-plane supports for the specimens during the tests. This support is provided through a newly designed and fabricated steel frame that allows free in-plane movement of the specimens between the top and bottom vertical in-plane actuators while providing a low friction bearing in the lateral directions. The frame is designed to be installed and removed from the *SET* conveniently making it possible to alternate *SET* tests on a concrete shell element to the *UT10 Hybrid Simulator* and vice versa. Fig. 2.1.a shows a three dimensional drawing of the frame with four specimens installed in the *SET*. Fig. 2.1.b shows the fabricated frame in the laboratory with one mock up specimen. The white PTFE pads that provide low friction bearing support for the specimens are visible in this figure. In order to reduce the forces resulting from second order effects, the frame needs to be properly aligned between the actuators and the specimens. This is achieved by moving the connected support actuators in displacement control prior to conducting hybrid simulations. Once alignment is achieved, three laser diodes installed on the *SET* are used to mark the aligned position of the frame for future re-installations of the system.

2.2. Control and Communication System

An MTS *FlexTest®/AeroPro™* control and data acquisition system is used for independent and simultaneous control of all *SET* actuators both in force and displacement control. The calculated displacement commands to be applied on the specimens are communicated to the controller through an interface program called Network Interface for Controllers (*NICON*). *NICON* has been developed at the University of Toronto to facilitate communication between the numerical model and the MTS controller for hybrid simulations and is comprised of a National Instruments (NI) hardware and a LabVIEW script (Kammula et al, 2014; Zhan and Kwon, 2015). In its current version, *NICON* is able to i) receive displacement commands through network, user input, and time-history files, ii) communicate them to the MTS controller, and iii) receive and send the feedback force and displacements from the controller to the numerical model. It also has some added features such as noise filtering, force and displacement limit checks, ramp generation, and coordinate transformation. A more comprehensive version of NICON with the above features extended for ten independent actuators is currently under development and is planned to be used with the *UT10 Hybrid Simulator* in the near future. Fig. 2.2 shows a schematic of the communication flow between hybrid simulation components.



(a) (b)

Figure 2.1 a) Three dimensional drawing of the frame with four specimens installed in the *SET* ; b) the fabricated frame in the laboratory with one mock up specimen.

Preliminary actuator control verification tests were performed on the *UT10 Hybrid Simulator* with a mockup elastic specimen made of a steel hollow structural section (HSS). These tests confirmed that the *UT10Hybrid Simulator* control and communication system operates flawlessly. However, the tests revealed a maximum difference of about 3 mm between the actuator movements and the specimen deformation measured with an external linear potentiometer. The displacement difference is due to the elastic deformations of the actuator reaction frames and their connections and also to a greater extent due to the slackness in the pin connections between the actuators and loading yokes. An error compensation algorithm is implemented in the current version of *NICON* to compensate for these differences, and to ensure the desired accuracy in the command displacements is achieved. In this algorithm, the actual deformation of the specimen is measured externally (D_{m2} in Fig. 2.2) using a linear potentiometer installed on the specimen and is fed back to *NICON* where it is compared to the target displacement received from network (D_{c1} in Fig. 2.2) and the new displacement command (D_{c2} in Fig. 2.2) is corrected for the difference of D_{c1} and D_{m2}. This process is repeated in a loop for each target displacement step (D_{c1}) until the desired accuracy is achieved. Similar algorithms are used for displacement error correction for hybrid simulation elsewhere (Chang et al., 2015). Further cyclic tests were performed in the elastic range on the mockup specimen using the error compensation algorithm to verify its performance. The results are presented in Fig. 2.3. The figure shows the target displacement commands for each step. It also shows the external linear pot measurement, actual displacement command to MTS controller (servo command), and the actual actuator movement measured internally in the actuator (displacement feedback) when the error compensation algorithm is converged for each step. The results indicate that the error compensation algorithm was successful in reducing the displacement errors in the test setup system to 0.05 mm. The results presented in Fig 2.3 also indicate that the maximum displacement difference due to the slackness at the pin connections is 2 mm which occurs at the instant of axial force direction change. The figure also shows a maximum of 0.75 mm displacement difference resulting from the elastic deformations in the system at the peak loads.

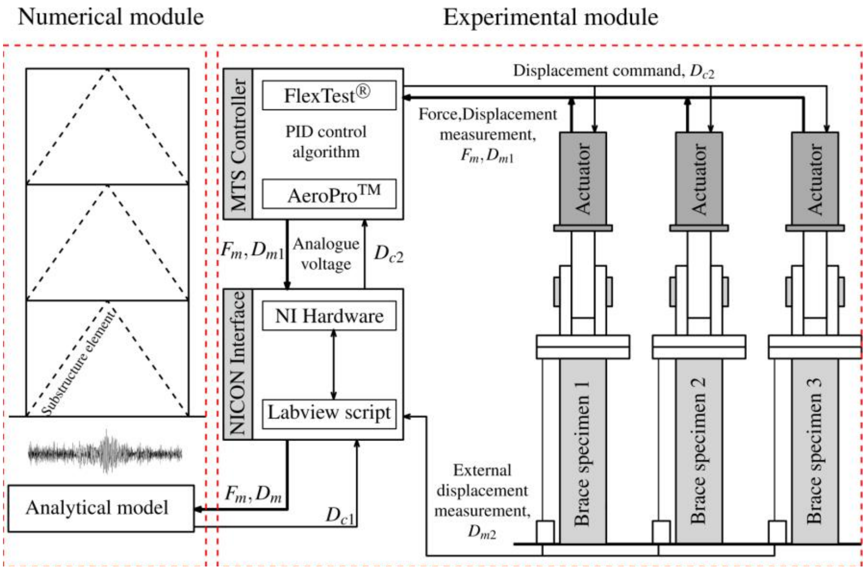


Figure 2.2 Schematic of the communication flow between hybrid simulation components.

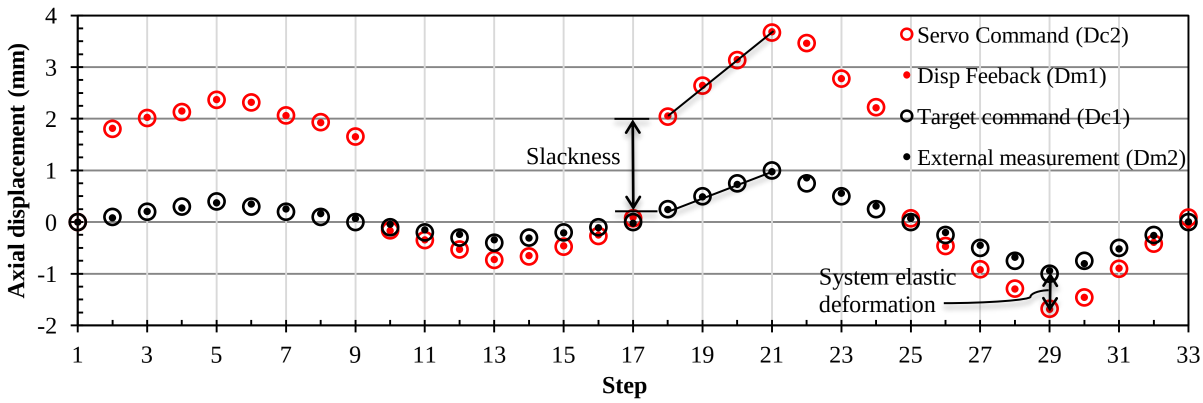


Figure 2.3 Converged command, feedback, and measurement values for each target displacement step

3. DEVELOPMENT OF NONLINEAR ADJUSTABLE BRACE SPECIMEN

3.1. Design Details

A special brace was designed to be used as the nonlinear physical specimen in the hybrid simulation tests. The aim was to design a brace with robust hysteretic response that is able to simulate the hysteretic behaviour of a full-scale BRB. In addition, the brace was designed to be reusable after replacing the damaged parts after each test which will facilitate performing multiple hybrid simulations. Finally, the brace was designed to have adjustable stiffness and strength so that it can represent a BRB at different locations and floor levels of a building. Fig. 3.1.a shows the overview of the designed brace. The specimen consists of a maximum of six threaded rod-pipe elements. These elements can be used in combinations of two, four, and six in each brace providing an adjustable stiffness and strength for the whole brace. The brace is designed to have an overall core cross section area similar to a full-scale BRB. However, due to brace length limitations, the brace will only simulate the response of part of the core of a full-scale BRB. Assuming a uniform state of axial stress and strain throughout the yielding part of a large-scale BRB core, the response of the adjustable brace can be extrapolated to the full BRB core length by multiplying the brace deformations by a length scale factor. This length scale factor is equal to the ratio of the length of the full-scale BRB yielding core and the length of the yielding part of the core rod in the adjustable brace.

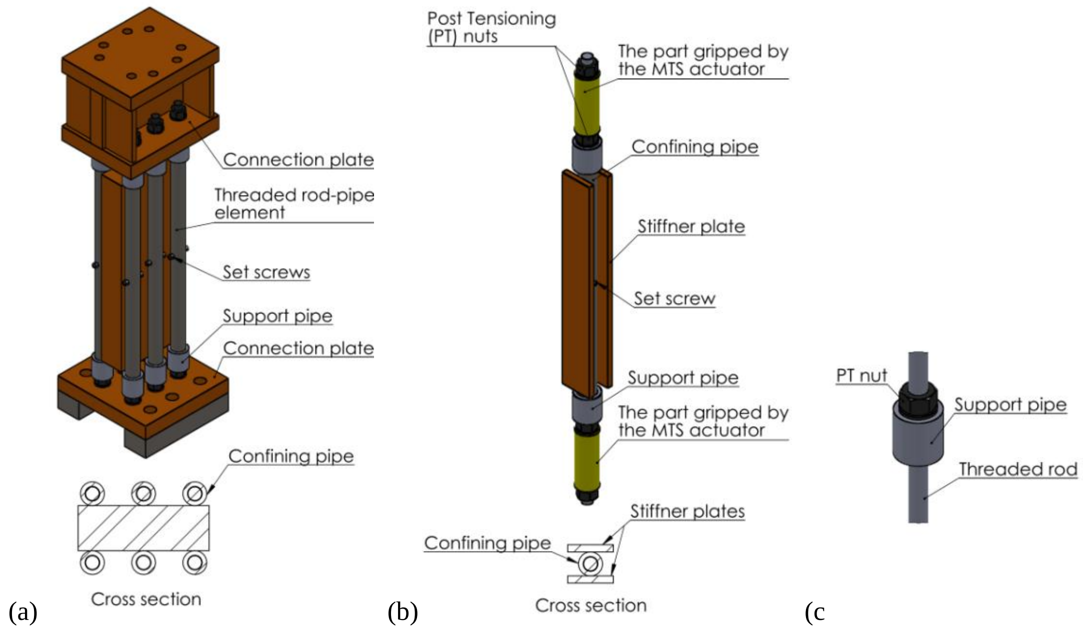


Figure 3.1 Adjustable brace concept: a) full brace; b) threaded rod-pipe element specimen; c) support pipe-threaded rod connection

To investigate the response of individual threaded rod-pipe elements, a specimen was built with a design similar to the threaded rod-pipe elements. Fig. 3.1.b shows the design details of the threaded rod-pipe element specimen. As indicated in Fig. 3.1, each threaded rod-pipe element consists of a fully threaded rod (core rod) that acts as the yielding core and a seamless 1" steel pipe (confining pipe) that provides confinement and buckling resistance for the core. The confining pipe is attached to the core rod at its mid-length by two set screws that are threaded into the confining pipe thickness. This configuration was selected to reduce the effect of friction between the core rod and the confining pipe and keep the confining pipe attached to the core rod during the tests. The core rod will be loaded in axial tension and compression and is designed to dissipate energy through nonlinear axial deformations similarly to a BRB. The unconfined length of the core rod at each end of the confining pipe is protected against local buckling and bending by 1.5" seamless pipes (support pipes). As indicated in Fig. 3.1.c a nut is welded at one end of the cross section of the support pipe, thus providing the connection of the support pipe to the core rod. The support pipe moves with the core rod and is allowed to have free axial movement along the confining pipe in a telescopic configuration. There is 0.3 mm clearance between the inside of the support pipe and the outside of the confining pipe minimizing the lateral movement of the core rod with respect to the confining pipe at its ends. The use of the threaded rod as the yielding core facilitates the connection, replacement, and verification of the core after each test without the need to repair other parts of the brace specimen. It is predicted that at highly nonlinear loading ranges, the permanent deformations in the threads at the core rod connections to the connection plates (see Fig. 3.1.a) can cause slackness in the system during axial load reversals. To eliminate these potential movements, the core rod is post tensioned at its end connections by two post tensioning nuts.

3.2. Cyclic Tests

Quasi static cyclic tests were performed on a threaded rod-pipe element specimen to identify its response characteristics and performance. For these tests, a 535 mm long confining pipe was sandwiched between two 10 mm thick stiffening steel plates that were welded to the confining pipe to provide further buckling resistance for it during cyclic tests (see Fig. 3.1.b). A 20M steel threaded rod with DIN 975 material specification and specified yield and ultimate tensile strengths of 235 MPa and 400 MPa, respectively, was used as the core rod. The rod was post tensioned at its end connection to the parts that were gripped by an MTS actuator (see Fig. 3.1.b). The element was loaded by the MTS actuator to displacements corresponding to 0.7%, 1.5%, and 2.2% of axial strain corresponding to respectively 1%, 2.1%, and 3.2% inter-story drift in full-scale BRBs. The axial deformation demands were calculated assuming that the element is part of a brace specimen that represents the yielding core of a real-scale BRB that is installed in a chevron configuration inside a frame (see section 4). Two complete cycles at each deformation level were performed during the cyclic tests. Fig. 3.2 shows the cyclic hysteretic response of the tested element. In order to compare the hysteresis shape of the tested element with the response of a real BRB, the cyclic response of BRB specimen 99-3 obtained from full-scale cyclic tests performed by Black et al. (2002) are also shown in Fig. 3.2. This specimen was tested cyclically up to several yielding core axial strain levels including 0.7%, 1.4%, and 2.1% that are very close to the axial strain levels of the tested threaded rod-pipe element. The cyclic response of specimen 99-3 presented in Fig. 3.2 is scaled such that the maximum displacement and forces of the last cycle of this specimen matches that of the tested threaded rod-pipe element. It can be observed from the results that the element has repeatable and stable hysteretic response both in tension and compression. It is also capable of simulating the *Bauschinger* effect that is observed in real BRBs (see section 4.2). Furthermore, it is noted that similar to a BRB, the compression strengths are larger than the tensile strengths with an average ratio of 1.09 over all cycles. The results generally indicate that the element can successfully simulate the hysteretic response of a real BRB. Work is still in progress to further optimize the hysteretic response of the element and the design of the brace. The cyclic tests of the full brace with two, four, and six elements are also planned.

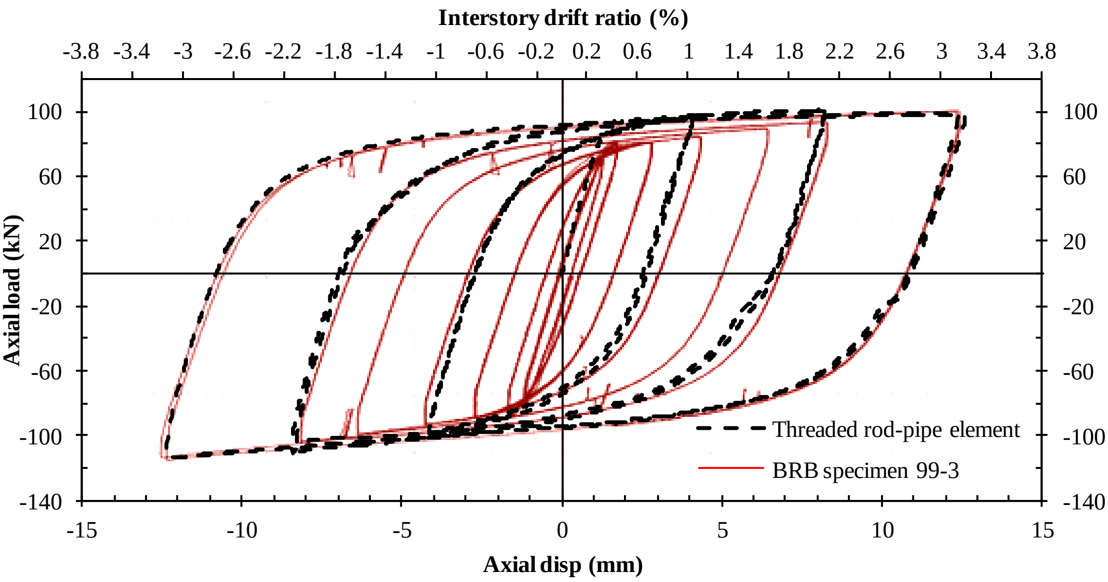


Figure 3.2 Cyclic hysteretic response of the tested threaded rod-pipe element vs. cyclic hysteretic response of BRB specimen 99-3 (Black et al., 2002) scaled to match the maximum force and deformation responses of the tested element

4. PRELIMINARY ANALYTICAL STUDY OF A STEEL FRAME

4.1. Building Selection and Design

As a first application of the *UT10 Hybrid Simulator*, hybrid simulations are planned on a multi-story steel frame equipped with BRBs with the BRBs tested as physical substructures. The use of such systems is steadily increasing in North America. The aim is to investigate the effect of the real properties of BRBs on the accuracy of commonly used numerical models to predict the seismic performance of these structural systems. As a preliminary study and to validate the need for hybrid simulations preliminary analytical study is performed in this section to assess the effect of the accuracy of BRB numerical models on the global seismic response of a 6-story building. The building considered is a steel frame office building located in downtown Los Angeles where the seismic loads are expected to govern the design of the structure for lateral loads. The building was designed by Choi et al. (2008). The loads on the building were obtained based on ASCE7-05 *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2005) and the steel members were designed based on ANSI/AISC 360-05 *Load and Resistance Factor Design Specification for Structural Steel Buildings* (AISC, 2005a) and ANSI/AISC 341-05 *Seismic Provisions for Structural Steel Buildings (including Supplement No. 1)* (AISC, 2005b). The main lateral load-resisting system in the considered direction is comprised of two simple frames with one 9.14 m bay located at the extreme edges of the building. The frames are braced with BRBs in chevron configurations and the beams are connected to columns using pin connections. All columns in the building are continuous over their length with fixed lap splices at 1.52 m above the third and fifth floors and are pinned at their ground base. The gravity loads of the building are mainly supported by gravity columns. The building is symmetric in plan and hence does not have any torsional effects due to intentional eccentricity. The height of each story is 3.66 m. More detailed information on the design of the building can be found in Choi et al. (2008).

4.2. Analytical Model

The building plan is symmetric and hence, neglecting the effect of out-of-plane members and any torsional effects, only one of the braced frames in the considered direction was modeled. The nonlinear modeling and time-history analysis of the frame were performed in OpenSEES (McKenna et al., 2000). The $P-\Delta$ effects caused by the gravity loads were taken into account using leaning columns with linear elastic behaviour and sectional properties equivalent to the number of gravity columns with similar profiles in the building. The leaning columns were pinned at their base to avoid any contribution to the lateral stiffness of the frame. The gravity loads supported by the gravity columns in the building were applied at each story level on the leaning columns. The horizontal movements of all of the nodes in each story were constrained to a master node on the same story to model the diaphragm effect of the floor. The gravity loads were applied on the beams and columns and were calculated from the entire dead and live loads. The story seismic weights were considered equal to the entire story dead loads and were modeled with lumped masses at the story master nodes.

The beam and column elements were modeled with elastic elements with lumped plastic hinges at both ends. The nonlinear flexural response of the beams and columns were modeled with lumped plastic hinges. The plastic hinges were modeled with fiber sections made of steel material with *Giuffre-Menegotto-Pinto* uniaxial stress-strain relationship, isotropic strain hardening, and post yield stiffness ratio of 0.02 (2%). The beams and columns were constructed with ASTM A992 steel material with a yield strength of 345 MPa. Therefore, the Young's modulus and expected yield strength of the steel material model used for beams and columns were 200 GPa and $1.1 \times 345 = 380\ MPa$, respectively. The axial force-bending moment interactions in the plastic hinge sections were automatically considered by the software based on the cross section shape of the beams and columns. Each beam was modeled with two elements with plastic hinges at both ends in order to capture possible formation of a plastic hinge at the beam and chevron brace intersecion. The connection of beams to columns however were modeled with a pin connection.

The real hysteretic behaviour of BRB specimens, like the cyclic response of any other metal, involves strain hardening with the *Bauschinger* effect. The *Bauschinger* effect is attributed to the decrease of yield strength of a metal when the strain direction changes. In the case of cyclic response of BRBs, it results in a reduction in compressive yield strength and softening of the steel on the compression side after being loaded and unloaded in tension or vice-versa (see Fig. 3.2). In addition, the hysteretic response of BRBs is unsymmetrical due to the effect of friction between BRB core and the confinement which results in an increase in the compression resistance of the BRB. The amount of friction increases with an increase of the compressive axial deformation in the brace.

In order to investigate the effect of BRB model inaccuracies on the global response of the structure, several models with varying levels of inaccuracy are used for the analyses. The first model (Model 1) is the *Giuffré-Menegotto-Pinto* model with isotropic and kinematic strain hardening (*"Steel02"* uniaxial material in OpenSEES). This model can simulate the gradual softening of the response due to the *Bauschinger* effect. In this model, the amount of isotropic hardening is a function of nonlinear axial deformations and can be controlled separately for the tension and compression side of the hysteresis. One approach to model the added compressive strength due to the friction effect, which is also used in this study, is to consider more compression hardening than tension hardening in the model. This approach not only considers the added compression strength due to friction, but also it models the increase of friction with the amount of nonlinear deformations. The second model (Model 2) is similar to Model 1 except for the friction effect which is not considered in Model 2. Model 3 is a bilinear model (*"Steel01"* uniaxial material in OpenSEES) which has both isotropic and kinematic hardening and thus is able to capture the *Bauschinger* effect but in this model the transition between the elastic and plastic response is not gradual. Furthermore, like Model 2, this model does not simulate the friction effect. Finally, the fourth model (Model 4) is similar to Model 3 but it does not simulate the isotropic hardening. Table 4.1 summarized different BRB models used in this study and their features. The parameters of all above models were calibrated based on the response of BRB specimen 99-3 obtained from full-scale cyclic tests performed by Black et al. (2002). The actual BRB core is normally attached to a wider part. This wider core, the core end stiffeners, and brace end connections result in an overall axial stiffness more than what can be obtained from BRB core cross section area and length. One approach to consider this effect in the numerical model is to use an increased effective axial stiffness for the element by increasing the Young's modulus of elasticity of the material model. Based on previous experimental studies a value of $E_{eff} = 1.45 \times E$ is used in the numerical model (Choi et al., 2008) where E and E_{eff} are the normal and effective Young's modulus of steel. The BRBs were constructed with ASTM A36 steel material with yield strength of 248 MPa. Therefore, the Young's modulus and expected yield strength of the steel material model used for BRBs were 200 GPa and $1.3 \times 248 = 322\ MPa$, respectively.

Table 4.1 Features of different models used in the analyses

	Kinematic hardening	**Isotropic hardening**	**Friction effect**	**Gradual elastic to plastic transition**
Model 1	X	X	X	X
Model 2	X	X	-	X
Model 3	X	X	-	-
Model 4	X	-	-	-

4.3. Analysis Results

A suit of seven ground motion records compatible with the design response spectrum of Los Angeles were selected from PEER NGA strong motion database (PEER NGA Database, 2013) following the recommendations of ASCE7-10 (ASCE, 2010). Table 4.2 shows the characteristics of the selected ground motion records. Time-history analyses were performed on the frame with different BRB models assuming 3% viscous damping at first and second modes of the structure. The natural period of the frame was 1.06 sec. The maximum values of the main global responses of the structure were averaged over the seven ground motions for each model. The average of maximum responses for Model 1 were 3.2% and 1.0% for transient and residual inter-story drifts, respectively, 2560 kN for the base shear, and 0.6g for the absolute floor acceleration. The average inter-story drifts are more than the 2% design limit values mainly due to the conservative scaling of the ground motions in this study. Table 4.3 shows the percentage differences between the average responses of Model 2, 3, and 4 with respect to Model 1. It can be inferred from Model 2 results that the friction effect has a minor impact on the global response of this structure. The reduction in the amount of base shear in Model 2 is consistent with the decrease of the compressive strength of BRB and hence the base shear due to the lack of friction effect in Model 2. Model 3 results indicate that considering the gradual transition between elastic and plastic response of the BRB can have a significant effect on the predicted global performance of the structure. The 21.5% increase in the maximum absolute floor accelerations compared to Model 1 is a direct result of the sharp transition between elastic and plastic response of BRB resulting in spikes in the acceleration responses. Comparison of the simulation results between Model 3 and 4 reveals that consideration of isotropic hardening has a negligible impact on the response predictions. Finally, Model 4 results clearly indicate that how neglecting some detailed response features of a BRB and accumulation of inaccuracies in the model can result in a potentially significant impact on the accuracy of the predicted responses causing up to 30% difference compared to the more realistic results of Model 1.

Table 4.2 Detailed information of the selected ground motions

Rec. No.	NGA#	Scale F.	Event	Year	Station	Mag.
1	169	2.00	Imperial Valley-06	1979	Delta	6.53
2	1158	1.92	Kocaeli- Turkey	1999	Duzce	7.51
3	721	2.00	Superstition Hills-02	1987	El Centro Imp. Co. Cent	6.54
4	1048	1.63	Northridge-01	1994	Northridge - 17645 Saticoy St	6.69
5	778	2.00	Loma Prieta	1989	Hollister Diff. Array	6.93
6	959	1.89	Northridge-01	1994	Canoga Park - Topanga Can	6.69
7	1602	1.39	Duzce- Turkey	1999	Bolu	7.14

Table 4.3 Percentage differences between the time-history average responses of different models compared to Model 1

	Transient inter-story drift	Residual inter-story drift	Base shear	Floor absolute acceleration
Model 2	1.3	0.6	-1.8	-0.1
Model 3	5.0	31.7	1.3	21.5
Model 4	6.2	29.9	-1.5	20.7

5. CONCLUSIONS

The concept and main components of the *UT10 Hybrid Simulator* and an adjustable brace specimen with nonlinear hysteretic response were presented in this paper. Being able to test up to ten large-scale braces simultaneously, *UT10 Hybrid Simulator* represents the first of its kind for performing hybrid simulations on multi-story structures with several physical substructures. The combination of *UT10 Hybrid Simulator* and the adjustable brace specimen can potentially facilitate application and further developments in the hybrid simulation testing method. It can also aid in obtaining more realistic seismic response of multi-story buildings equipped with BRBs. The preliminary analytical study performed on the effect of BRB modeling inaccuracies on the global seismic response prediction of a 6-story steel frame revealed a potentially large impact of up to 30% on the global response predictions. This indicates the importance of realistic hybrid simulation test results in understanding the real seismic performance of structures and critical review of accuracy of existing numerical models and design code recommendations in predicting seismic response of structures.

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