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FOUR-ELEMENT HYBRID SIMULATION OF A STEEL FRAME WITH CAST STEEL YIELDING CONNECTORS

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Abstract

Cast steel structural components, and in particular, cast steel energy dissipative components have been developed and used in order to enhance the seismic performance of structures due to their reliable energy dissipation capacity, improved ductility, and highly increased low-cycle fatigue life. One such device is the *Cast Steel Yielding Connector* (YC); an innovative cast steel energy dissipative hysteretic brace connector. Cast steel yielding connectors have a unique and desirably symmetrical hysteretic response, demonstrating increased post-yield stiffness at large deformations due to geometric second order effects. This behaviour makes numerical modelling of these systems more challenging than typical yielding systems under earthquake excitations. In the present study, a set of full-scale four-element pseudo-dynamic hybrid simulations are carried out on a four-story steel frame equipped with cast steel YCs. The pseudo dynamic hybrid simulations are followed by cyclic tests on two YC elements using the ASCE-SEI 41-13 protocol to evaluate the remaining low cycle fatigue capacity of the elements after the seismic events. The results of the hybrid simulations indicate that available numerical models for YCs tend to over-predict their maximum deformations under earthquake excitations. The over-prediction is within acceptable margins for the first floor; however, the numerical results tend to further deviate from the experiments at upper floors. In addition, cast steel YCs were shown to have a very reliable low-cycle fatigue life; being able to sustain most of the cyclic loading protocol even after several major earthquakes. The study is then extended to a numerical study where the response of the four-story reference steel structure with the *Yielding Brace System* (YBS) is evaluated under a suite of 40 ground motions, selected and scaled to match the Uniform Hazard Spectrum and to be representative of the seismological characteristics of the site. The YBS, in the reference structure, is replaced with a *Buckling-Restrained braced Frame* (BRBFs) and the study is repeated to underline the advantages of each system. The results of this preliminary numerical study indicate that mid-rise Steel Frames with the YBS manifest a more uniform inelastic response along the structures' height and are less prone to soft-story mechanism formation on the first floor, when compared to their BRBF counterparts.

Keywords: Steel Structures, Multi-Element Hybrid Simulation, Steel Casting, Hysteretic Dampers, Energy Dissipation

1. Introduction

Steel Casting technology offers many advantages in structural design. It facilitates manufacturing of custom-designed geometries for steel elements to benefit the structural behavior, results in lower stress concentration and residual stresses [1], results in cost savings for complex geometries [2] or mass produced shapes, and enhances many structural response attributes such as ductility and low-cycle fatigue life; all highly attractive features for structural components in earthquake engineering. These advantages have led to the development of many cast steel structural components as energy dissipative devices in steel structures. For moment resisting frames, cast steel Panel Zone Dissipator Modular Node [3-4] and Cast Steel Modular Connectors [5] were proposed. In concentrically braced frames (CBFs), the Cast Modular Ductile Bracing System [6] and the Cast Steel Yielding Connector [7] have been proposed. The latter has been validated and implemented in real buildings. Lastly, for steel eccentrically braced frames, Cast Steel Replaceable Links have recently been proposed [8] and are currently being experimentally validated at the University of Toronto [9].

Special Concentrically Braced Frames (SCBFs), which are the most ductile type of Concentrically Braced Frames (CBFs), demonstrate high elastic stiffness. This results in effective control of drifts, but could lead to large forces in the system, which makes the design of the capacity protected elements a challenge. Moreover, in highly seismically active regions, the designer would often be faced with a choice between having redundant adjacent braced bays, to reduce the loads on the foundations, or using more expensive foundation systems to safely transfer the large forces associated with the capacity of braces to the ground. In addition to these design challenges, the energy dissipation of SCBF is achieved through yielding of braces in tension and their buckling in compression. The latter has been shown to critically affect the low-cycle fatigue life of SCBFs [10] and, in some extreme examples, could cause them to fracture within just a few cycles.

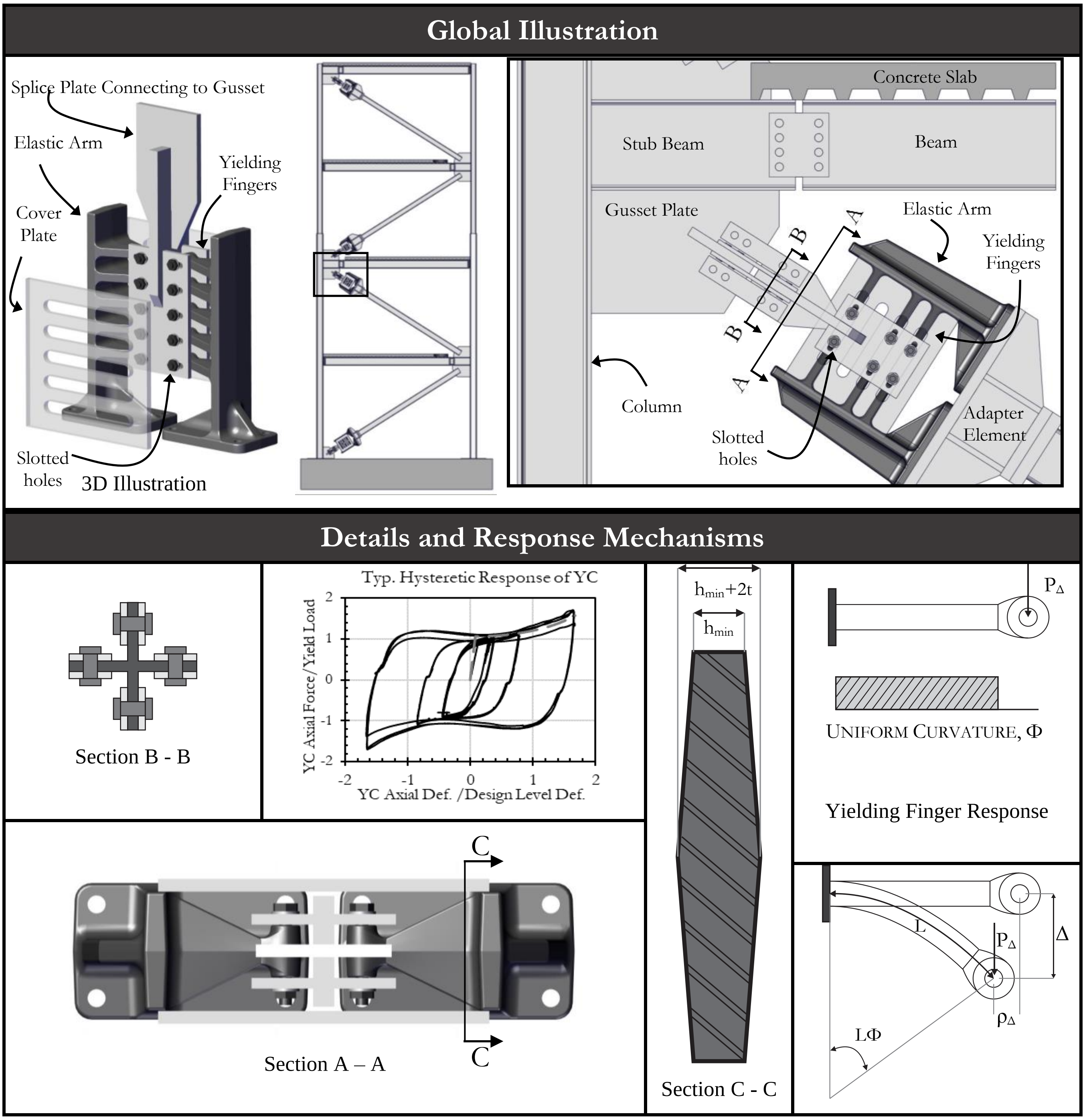


Fig. 1 – Illustration of the cast steel YC and its mechanics

Buckling Restrained Braced Frames (BRBFs) were proposed to address some of these challenges [11]. They offer the same level of simplicity in design and erection as conventional braces but allow the brace to yield in both tension and compression. Therefore, they demonstrate a much-improved low-cycle fatigue life and better energy dissipation mechanism compared to conventional SCBFs. In addition, BRBFs are not as stiff as SCBF and better control the forces imposed on the capacity protected elements. However, the low post-yield stiffness of BRBs makes these systems susceptible to excessive residual deformations and formation of soft stories.

These challenges led to the development of Cast Steel YCs by Gray et al. [7], which uses steel casting technology to facilitate the use of a complex geometry to benefit the design and seismic performance of concentrically braced frames. The mechanics and different parts of YCs along with its configuration in a steel frame are shown in Fig. 1. The device consists of two cast steel parts, which form the elastic arms and the yielding fingers. The geometry of the cantilever yielding fingers, similar to the triangular added damping and stiffness (TADAS) system [12], follows the moment diagram. This results in a uniform curvature ($\Phi = M / EI$) and simultaneous yielding along the length of the fingers. Further, given that the energy dissipation, for both tension and compression, relies on the same mechanism, the YC provides a symmetrical hysteretic response for energy dissipation; an attractive response attribute in concentrically braced frames. The tip of the yielding fingers has a cylindrical hole to facilitate the use of bolted connection to the splice plate, which connects to the gusset plate. The slotted holes on the splice plate allow the bolts to slide back and forth within the holes during the response. This would accommodate the cantilever deformation of the fingers during the response of the device. On the other end, the cast steel elastic arms are connected to the brace member, which could be a W-Section or a Hollow Structural Steel (HSS) section. In addition, two cover plates are welded to the elastic arms to balance the forces between the two elastic arms and keep the two parts connected throughout the response.

The cantilever deformation of the yielding fingers is shown in Fig. 1. As can be observed, as the finger deforms, a tensile force component is developed on the finger and is further increased as this deformation continues. This causes a second order geometric effect, which results in an increased post-yield stiffness in the response, especially at extreme deformations. A typical hysteretic response of a YC is shown in Fig. 1, under cyclic tests, which were carried out as part of the present study. Gray et al. [7] provide additional background on the development and validation of cast steel YCs. Further, the low-cycle fatigue life of YCs is studied by Zhong et al. [13].

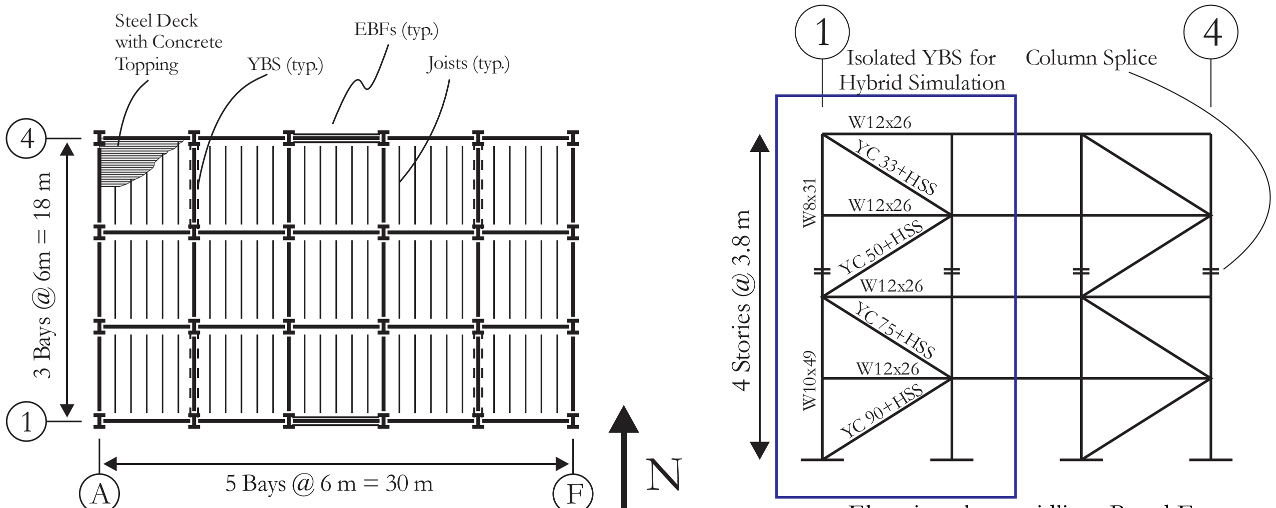
2. Motivation and Objectives

Since its development and validation, many conventional cyclic tests have been carried out on the cast steel YC, both on a component-level and a system-level [7]. These tests paved the way for better understanding the behaviour of the YC and the characterization of low-cycle fatigue models [13]. However, as shown in the literature, the hysteretic response of structural elements could be affected by the loading protocol [14]. This requires a careful and thorough calibration process when using stick elements in the numerical models. The unique mechanics and hysteretic response of the YC further underlines the importance of considering random loading protocols in the numerical modelling of these elements. Therefore, through using multi-element *pseudo-dynamic hybrid simulations* (PsDHS), this study sets out to establish a series of benchmark tests on a *Yielding Brace System* (YBS). The results of the benchmark tests can be used to advance the understanding of the behaviour of YCs, assess the accuracy of the available numerical models for the YCs, propose improved numerical models, and calibrate the low-cycle fatigue life models of steel casting devices.

This paper provides an overview of a series of four-element pseudo-dynamic hybrid simulations on a four-story steel structure with the Yielding Brace System (YBS). The study is the first sub-structuring PsDHS where all the yielding elements that affect the response of the structure, are physically represented in the experiment. Therefore, other than studying the local response of the cast steel YC, the effectiveness of available numerical models is evaluated for global seismic performance assessments of the YBS. In the following, the design of the reference building structure, the ground motions, and the numerical model used in the experimental program are discussed. The experimental setup and instrumentation are presented. Preliminary results of the PsDHSs and conclusions are presented. Lastly, a preliminary numerical study is carried out on the reference structure, once designed using the YBS and once using BRBFs, under a suite of 40 records selected and scaled to match the Uniform Hazard Spectrum (UHS).

3. Reference Building Structure

The prototype building structure is a 4-story steel structure located in downtown Los Angeles, California. The seismic force resisting system (SFRS) is formed by YBS in the North-South direction and by eccentrically braced frames (EBFs) in the E-W direction. The structure is designed as per ASCE 7-16 [15], AISC 360-16 [16], and AISC 341-16 [17]. The building plan and the elevation including the YBSs are shown in Fig. 2. The floor systems are formed by corrugated steel decks with concrete topping and, therefore, can be regarded as rigid diaphragms [18-19]. Gusset plates are designed to be capacity protected. A stub beam detail is used at the location of the gusset plates, similar to that shown in Fig. 1. The splice member is designed based on AISC 360-16 [16]. The shear tabs consist of double angles welded to the columns and bolted to the beams.



Elevation along gridlines B and E

Fig. 2 – Structural configuration of the reference structure

4. Numerical Model

In sub-structuring pseudo dynamic hybrid simulation, it is essential to capture the numerical response of the numerical sub-structure with a high level of accuracy. Accurate modelling of the structure is also important in the preliminary stages of the study to assess the necessity for hybrid simulation.

The modelling approach adopted in the present study is similar to what was done in previous tests on concentrically braced frames [20]. Given that the YBSs in the N-S direction of the structure are identical, the seismic performance assessment is carried out on a single frame. As such, a numerical model is developed only for the single YBS, shown in Fig. 1. Also, a leaning column is modeled, with the weight of a quarter of the structure, to capture the P-Δ effects in the performance assessment.

A schematic representation of the numerical model is provided is Fig. 3. The program OpenSees [21] is used for developing the numerical models. All beams and columns are modelled using BeamWithHinges elements with fiber sections. The shear tabs and the stub beam splices are modelled as zero length elements. The spring is calibrated using the method given by [22]. Rigid zone offsets are used to represent the effect of beams and columns on each other's response close to the nodes. Rigid elements are used to model the effect of gusset plates on beams and columns, as recommended by [23]. The HSS braces are modelled using

ForceBeamColumns with fiber sections. The YCs were modelled and calibrated following the procedure given by Gray [24]. The calibrations are done for several different YC sizes. The results of the calibrations for YC50 and YC100 are given in Fig. 3, when compared to available experimental cyclic results [7]. An additional element is superimposed on the YC, to represent the flexural rigidity of the YC while having negligible axial stiffness. The gusset plates are modeled with a stick element with high flexural rigidity, capturing the axial behavior, and a rotational spring at its end, capturing the flexural behavior.

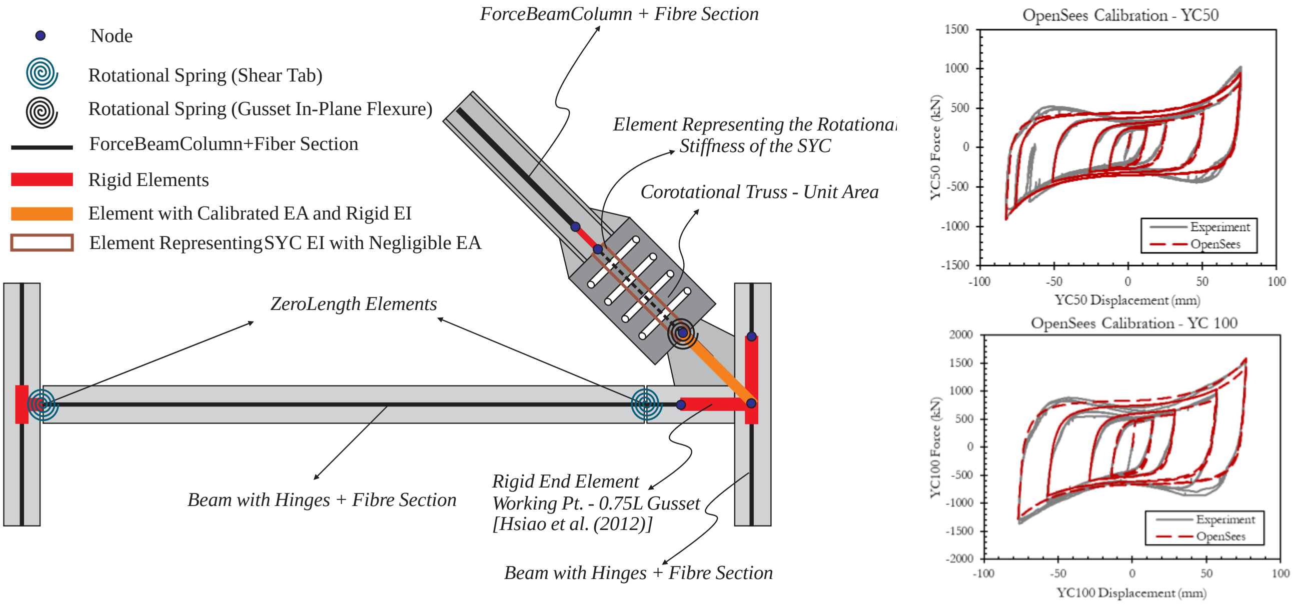


Fig. 3 – Schematic illustration of the numerical model (left) Comparison of the calibrated numerical model versus experimental cyclic response of YCs (right)

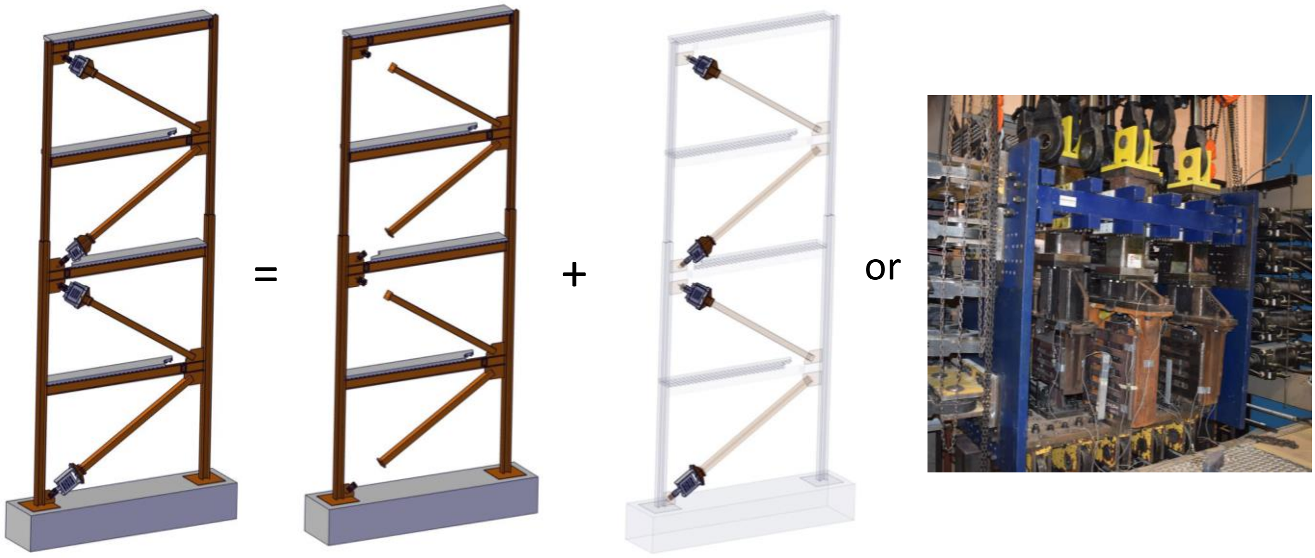
5. Pseudo-Dynamic Hybrid Simulation

5.1 Sub Structuring Scheme

The level of accuracy that is achieved in PsDHS is critically dependent on the sub-structuring strategy. This involves the number of physical substructures and strategically selecting them from the critical structural components [25]. For instance, if a five-story steel frame with chevron braces is being tested (total of ten braces), it is important to test a sufficient number of braces physically to achieve the desired level of accuracy. Moreover, it must be determined which braces must be given the priority in terms of being selected (i.e. if only four braces will be represented physically, which floors should the braces be selected from). The University of Toronto Ten Element Hybrid Simulation Platform (UT-10) has been developed to test up to ten physical substructures in PsDHSs which minimize the need to give priority to specific structural components in the sub-structuring scheme [26-28]. In the present study, four element PsDHSs are carried out on the single YBS illustrated in Fig. 2. Given the capabilities of the UT-10, all four YCs are physically represented in the UT-10 as physical substructures, while the rest of the structure is modelled numerically in OpenSees. This is also illustrated in Fig. 4. These tests mark the first application of the UT-10, where the behaviour of all inelastic elements in the structure, in this case the response of four YCs, is captured experimentally.

5.2 Experimental Setup (UT-10) and Instrumentation

The UT-10 Hybrid Simulation Platform [16] is capable of testing up to ten uniaxially-loaded rate-independent elements with a force capacity of +/- 800 kN each and a displacement capacity of +/- 125 mm. The device is built on the Shell Element Tester (SET) at the University of Toronto [29]; a testing apparatus that historically was mainly used for testing concrete shells. The SET consists of forty +/- 800 kN in-plane actuators and twenty +/- 400 kN out-of-plane actuators. A picture of the SET actuators without the UT10 frame or any concrete shells is provided in Fig. 5. Figure 5 also shows a picture of the UT-10 and the YC specimens within the SET. The top actuators are used to impose predicted displacements during the PsDHS, while the rest of the actuators are used to provide support, as required, to the specimens and the UT-10 frame. The unique actuator configuration of the UT10 gives the setup the versatility to be changed based on needs in each experiment.



Integrated Model (OpenSees + UT10)

Integration Module (OpenSees)

Physical Substructures (UT10) – Global Configuration

Physical Substructures (UT10) – in the structure's lab

Fig. 4 – Sub structuring scheme in the pseudo-dynamic hybrid simulations

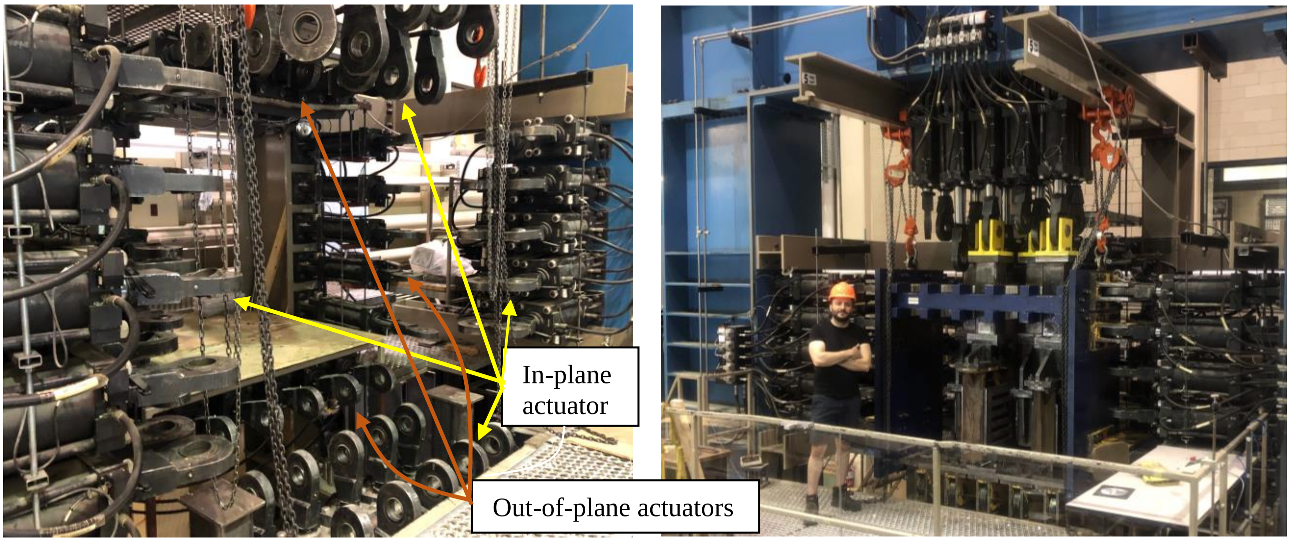


Fig. 5 – Experimental setup, SET actuator configuration (left), UT10 with the YC specimens (right)

For controlling the sixty actuators, two MTS® Flex Test 200 controllers are used. The actuators can be used in both force- or -displacement controlled configuration. The program AeroPro™ provides the users with the interface to control and monitor the actuator channels. UT-10 uses the *SubStructure* element in OpenSees, to integrate the response of the physical substructures into the PsDHS. The *SubStructure* element was developed as part of the UT-SIM framework (ut-sim.ca) [30-32], which allows data communication between OpenSees and other experimental or numerical modules. The Network Interface for Actuator Controller (NICON-10) program, which is a LabVIEW based program connects and communicates the commands between the integration module and the MTS controllers, which in turn send the commands to, and receive the readings from the actuators [33,26]. A schematic illustration of the UT-10 network communication is shown in Fig. 6. Further details about the development of the UT-10 is provided by Mojiri et al [26].

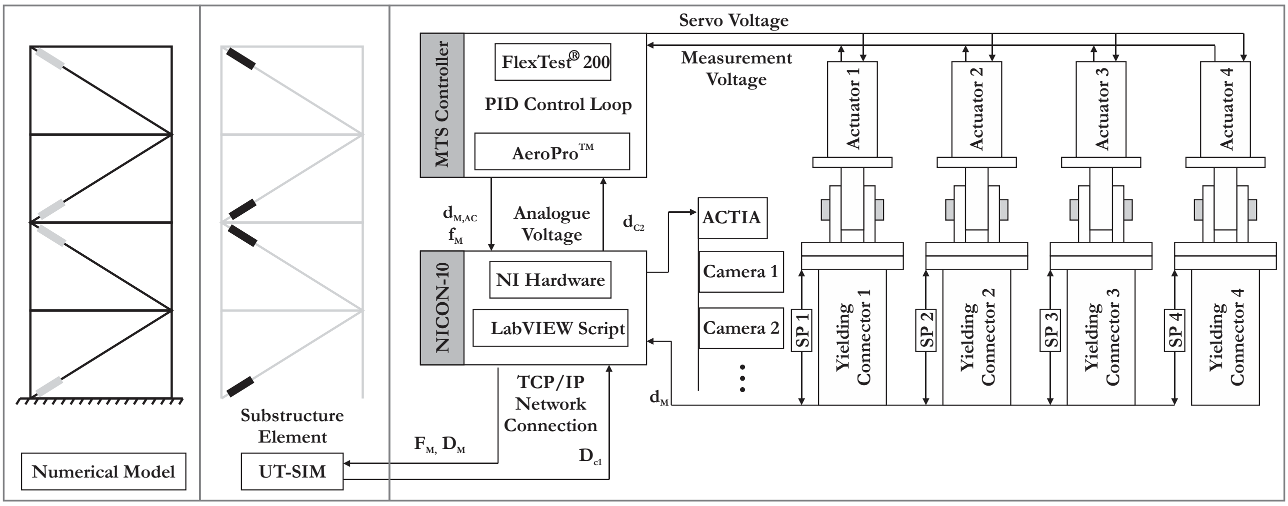


Fig. 6 – UT-10 Communication in the Current Test Adopted from Mojiri et al [26]

In the present test, four of the top actuators are used in displacement-controlled mode to apply displacements from the numerical model to the YC specimens. The actuators below the specimens are force-controlled and slaved to the force reading of the loading actuators of the specimens. The rest of the actuators are used to support the testing frame and balance the forces. Each actuator is equipped with a string potentiometer to measure the actuator movements. In addition, two string potentiometers are placed on both sides of each YC specimens to measure actual deformation of the specimens. The average reading of the two is used to monitor the axial deformation of the specimens.

5.4 Ground Motions

As part of the present performance assessment, forty ground motions are selected and scaled to match the uniform hazard spectrum at the MCE level. A comprehensive numerical study on the YBS and BRBFs is carried out as part of this study using the suite of ground motions. Three ground motions within the suite of ground motions are used for the PsDHSs. The response spectra of the records are given in Fig. 7 and details about the records used in the PsDHSs are provided in Table 1. Additional details on selection and scaling of the complete set of the records will be presented in future publications along with more details on the comprehensive numerical study on the YBS performance.

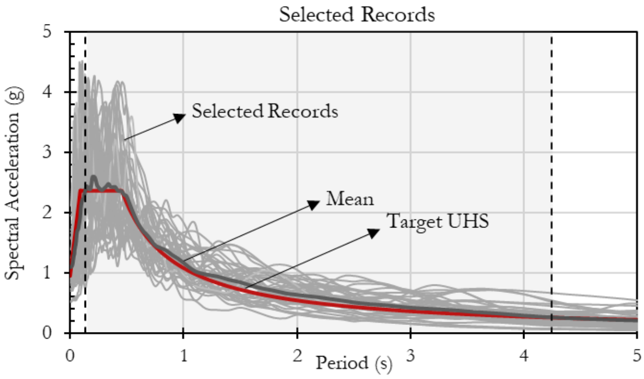


Fig. 7 – PSA of the selected records vs. the UHS

Table 1 – Earthquake Records for PsDHS

Rec. No.	EQ Name	Station Name	Scale Factor
1	Northridge-01	N Hollywood – Coldwater Can	3.37
2	Imperial Valley-06	El Centro Array #8	2.57
3	Loma Prieta	Gilroy Array #3	3.32

6. Preliminary Results

Response of the structure in terms of first-floor drift response history, under the first two MCE-level records is given in Fig. 8 (left). As can be observed, the global response of the first floor in terms peak drift response is in good agreement with the experimental results, with the numerical results somewhat over-predicting the maximum drifts. The results indicated that the numerical model overpredicts the response at upper floors more notably. After the first two MCE-level earthquakes, the specimens were re-centered for the third earthquake. This was done by knowing the specimen's elastic stiffness and the maximum force. The re-centering graph is shown for the YC on the first floor in Fig. 8 (right).

The third MCE-Level earthquake gave similar results to the first two records. It can be concluded that in general, the numerical model of the YBS in OpenSees could over-predict the local response of the YC connector, but not necessarily the global response of the system. The latter is highly dependent on the ground motion While this local over-prediction is not severe on the first floor, it tends to increase at upper floors. The PsDHSs were followed by cyclic tests on the YC90 and the YC75 on the first and second floors, respectively. The ASCE-SEI 41-13 [34] protocol for prequalification of dampers for seismic applications was used for this purpose. It is observed that the YCs, despite having sustained three MCE-level earthquakes and the re-centering process, survived most of the loading protocol. The loading protocol and the response of YC90 (1st floor specimen) is qualitatively shown in Fig. 9.

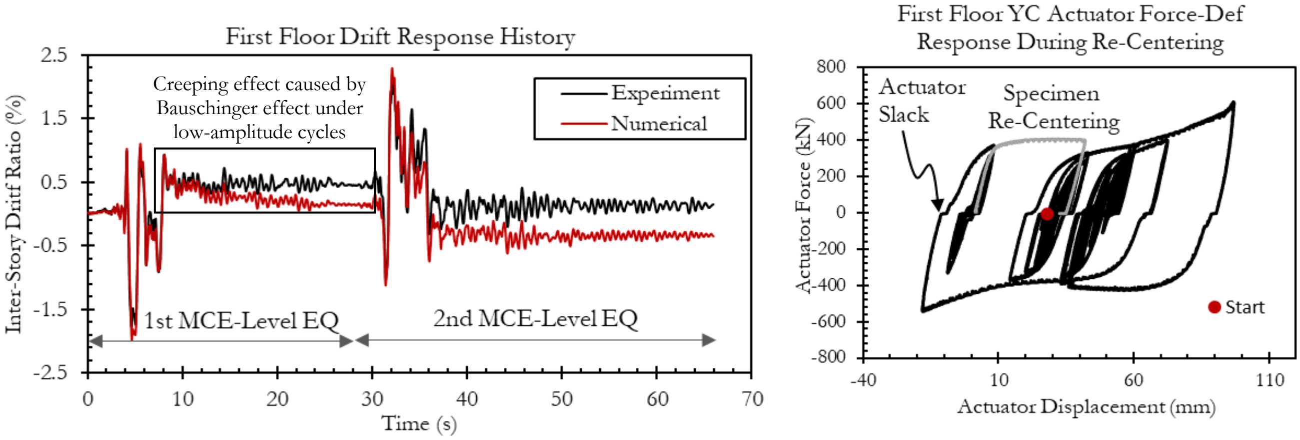


Fig. 8 – Drift response history of the first floor under the first two MCE records (left), Re-centering (right)

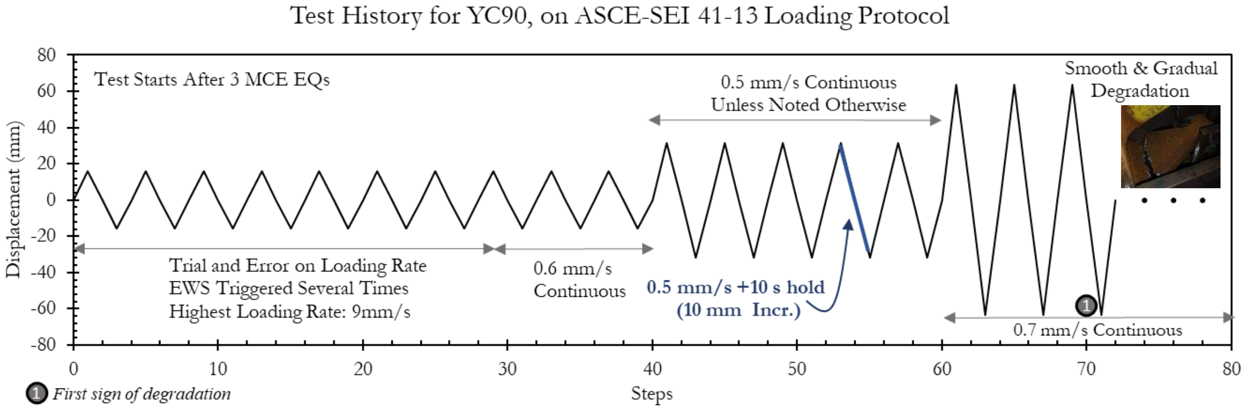


Fig. 9 – Loading protocol on the YC90 and load application

Several sources of discrepancy between the numerical model and the experimental results have been identified. The first phenomenon causes the numerical model to develop artificial hardening upon very small amplitude unloading and reloading. This is caused by a restart of the Bauschinger effect upon unloading and reloading, which alters the course of the response. Fig. 10 shows part of the hysteretic response of the first floor YC after 6 seconds into the earthquake and till the 27th second of the response. The restart of the Bauschinger effect, described above is shown in Fig. 10. It can be observed how a local effect in the numerical model could have the potential to change the global response. The occurrence of this effect and the level with which it affects the response is highly dependent on the loading history.

The second discrepancy that was observed between experimental results and the numerical model is due to repeated premature activation of the Bauschinger effect under intermediate amplitude cycles, in the same direction. This can be understood by studying the encircled area in the hysteretic response of the first floor YC within the encircled area. In several repeated intermediate cycles, the Bauschinger effect has developed unrealistically and consistently in the same direction. This causes the response to creep toward a certain direction. In this particular case, the response crept back towards zero, leading to underpredicting the residual deformations after the first MCE-level earthquake. This portion of the response is also shown in a box in Fig. 8. Similarly, this effect is primarily dependent on the loading history. The frequency of this occurrence in numerical analyses must be studied.

The third difference between the numerical model and the experimental results is observed at zero force crossings in the response. Due to the movement of the YC finger bolts within the slotted holes, the real response develops minimal deformations without any force developments whenever crossing the displacement axis (zero force crossing).

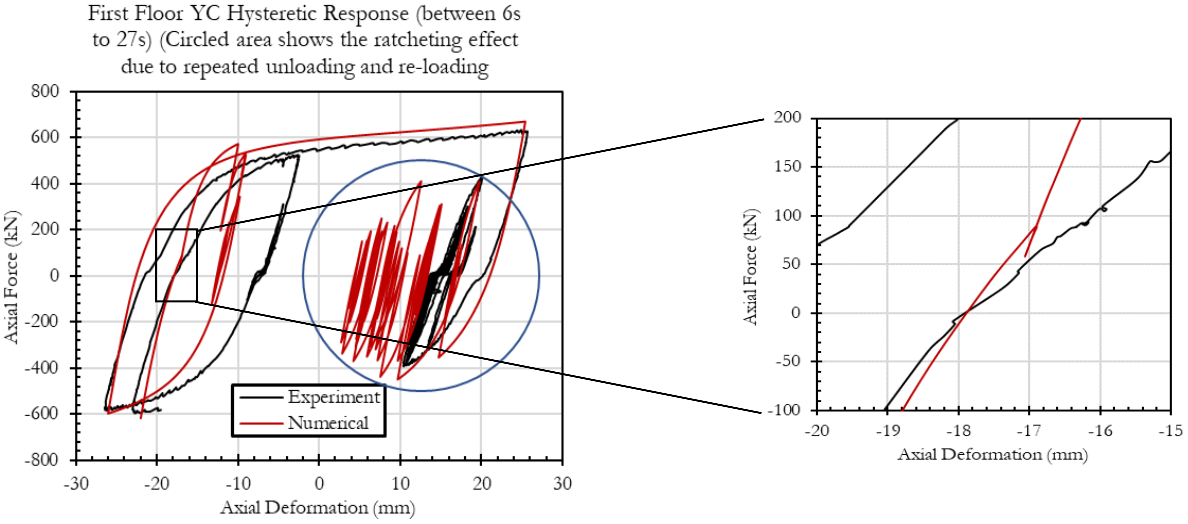


Fig. 10 – partial hysteretic response of the first floor YC indicating the differences between the numerical model and real behavior

7. Numerical Study on YBS vs. BRBF

The currently available numerical model for the YBS was developed by Gray [31] based on the first principles. The results of the present study indicate that although this model could use improvements, it predicts the global response at the first floor with reasonable accuracy. In the first MCE earthquake, the numerical model predicted the maximum drift with an error of 11%. Under the second MCE earthquake, the error was even lower (4.5%). Considering that the highest demands are usually present at first floors in mid-rise steel structure, where higher mode effects are limited, the available numerical model for the YBS can be used in numerical performance assessments until a better model is proposed. A preliminary numerical study is performed to compare the global response of YBS to BRBF. For this purpose, the reference structure is re-designed using BRBs. The area of the yielding core for stories one to four are determined to be 1143 mm^2, 1020 mm^2, 712 mm^2, and 455 mm^2, respectively. All girders are sized to be W12x26. W10x45 sections are used for columns below the splice where W8x21 sections are used for columns above the splice. The numerical models for the BRBFs follow the same approach as previous studies on BRBFs [27]. Both designs are subjected to the suite of 40 records and a comparison of the results is performed and presented in Fig. 11. As can be observed, the design using the YBS leads to a much better drift control. The residuals are also better controlled for the YBS design. In addition, in both maximum drifts and residuals, the design with the YBS shows less dispersion in the response.

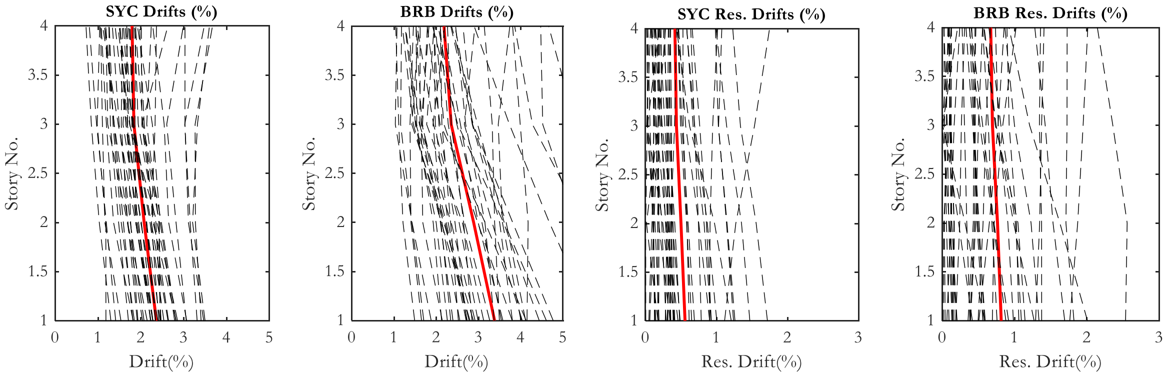


Fig. 11 – Cyclic response of the YC90 (left), the effect of ramp and hold loading on the response (right)

8. Conclusions

This paper presents the preliminary results of several four-element hybrid simulations on a steel frame with the YBS. These experiments mark the first full-scale application of the UT-10 and the first hybrid simulation on the cast steel YBS. The results of experiments demonstrated several differences between the prediction of the available numerical models for the YCs and the real behaviour, which can affect the response under earthquake excitations. Due to their nature, such discrepancies would be overlooked in conventional reversed cyclic tests. Therefore, these PsDHSs proved to be a crucial step towards better understanding the performance of the YBS and will be used as a benchmark to better calibrate the numerical models for the global performance assessment of the YBS. The experimental program is concluded with a set of cyclic tests on the cast steel YCs on the first and the second floor. It is observed that not only are the YCs able to survive three MCE-level earthquakes, but they are also able to almost sustain the ASCE-SEI 41-13 protocol for prequalification of dampers for seismic applications. The results of the PsDHs and the cyclic tests will be used for calibration of ultralow-cycle fatigue life models of cast steel components. A general global comparison between the numerical model and the experimental results indicate that the YC numerical model tend to over predict their peak deformation response. This over-prediction is within a reasonable margin on the first floor. However, the numerical results tend to further depart from the experimental results at upper floors. As such, the model could be used in the performance assessment of mid-rise structures with the YBS, with limited higher mode effects, where the maximum response is expected to be developed at the first floor. A limited numerical study is presented to compare the response of the YBS with the performance of the reference structure designed with BRBFs. The results indicate a better drift control for the reference structure designed with the YBS and lower residual drifts.

9. Acknowledgements

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