Performance Assessment of the Self Centering Energy Dissipative (SCED) Bracing System using Hybrid Simulation

V. Kammula, J. Erochko, O. Kwon, & C. Christopoulos
Department of Civil Engineering, University of Toronto

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SUMMARY:
The objective of this paper is to present results from the latest experiments for the system level validation of the self-centering energy dissipative (SCED) braced system through pseudo-dynamic (PsD) hybrid simulation. A full scale SCED brace with maximum force capacity of approximately 800 KN was validated through component tests. The system level performance of a six-storey structure with SCED braces was then validated through PsD hybrid simulation. The six-storey structure is divided into two substructures. The SCED brace on the first floor of a six-storey structure is physically tested while the rest of the structure is numerically modelled. The interaction between the two substructures during earthquake excitations is taken into account through PsD hybrid simulation utilizing UI-SimCor. This paper presents the configuration of the hybrid simulation, the newly developed control software for PsD hybrid simulation which can integrate generic hydraulic actuators into PsD hybrid simulation, and preliminary results showing the performance of a structure equipped with SCED braces.

Keywords: Hybrid Simulation, Self-Centering Systems, Performance Evaluation

1 INTRODUCTION

In the Performance Based Seismic Design (PBSD) approach, structures are designed to satisfy multiple performance objectives depending on the severity of the seismic excitation. For example, the safety critical performance objective (SEAOC, 1995) mandates that the structure should be fully operational after a frequent earthquake and shouldn't collapse even due to a rare seismic event with a return period of 2500 years. Even if structures are designed to meet multiple performance criteria, they are designed to behave in the inelastic range during the design level earthquake, acknowledging the economic disadvantages of designing buildings to sustain earthquakes elastically. Therefore, even though a structure designed using PBSD approach may not collapse and will protect the lives of occupants; it is expected to undergo large inelastic cycles and will likely have residual deformations after a design-level earthquake event (Pampanin and Christopoulos, 2004). It has also been inferred that above a certain level of residual drift (approximately 0.5%) it may not be economical to repair a structure, and the structure would have to be demolished and replaced (McCormick et al. 2008). For ductile steel structures it has been shown that residual deformations are expected to exceed this threshold even under design level earthquakes (Erochko et al. 2011).

In order to mitigate these residual deformations, self-centering systems have been actively developed in the past decade. These systems allow for rapid recovery after major earthquake events by dissipating seismic energy and containing a mechanism that restores a structure to its original configuration even after experiencing large inelastic cycles. Several self-centering systems have been developed in recent years for application to building or bridge structures such as for example controlled-rocking systems (Azuhata et al. 2008, Eatherton et al. 2010), post-tensioned steel moment frames (Christopoulos et al. 2002, Herning et al.

2009), self-centering systems with shape memory alloys (Wilson and Wesolowsky, 2005), self-centering energy dissipative (SCED) bracing systems (Christopoulos et al. 2008), and self-centering precast segmental bridge bents (ElGawady and Sha'lan 2011). The main focus of the study is on the system level performance of self-centering energy dissipative (SCED) bracing system as assessed using hybrid simulation.

The seismic performance of structures can be evaluated using several methods ranging from dynamic tests of physical specimens to purely numerical modeling. Some of the well-established dynamic physical testing techniques include the quasi-static testing method, shaking table test method, and the hybrid simulation (pseudo-dynamic testing). In the quasi-static testing method the structure is subjected to a predefined displacement history; however the applied loading history does not accurately represent the interaction of the specimen responding in the nonlinear range with the rest of the system. Shaking table tests provide the most realistic response of an investigated structure to a dynamic excitation; however, the limited capacity and size of most available shaking tables place significant restrictions on the size, weight and strength of a specimen that can be tested. As a result, reduced scale or highly simplified specimens are commonly used, which may not prove to be realistic. The hybrid simulation technique enables the evaluation of the dynamic response of large full-scale specimens. In a hybrid simulation a step-by-step numerical integration method is used to solve the governing equations of motion for a model that is formulated combining both analytical and physical components of a structural system. Contrary to purely numerical simulation, in the hybrid simulation part of the structure is physically tested in the laboratory using computer-controlled actuators and the rest of the structure is modeled analytically, while the interface between the two substructures is coordinated through a computer. This provides a complete picture of how earthquake events can affect large structures such as buildings and bridges without having to physically test the entire structure, enabling civil engineers to accurately and efficiently capture the effects that a substructure has on the overall structure, while subjecting the substructure to the same forces and motions it would experience within the complete structure.

The main objective of the paper is to present the latest progress in seismic performance assessment of a self-centering energy dissipative (SCED) bracing system using hybrid simulation. A six-storey structure is designed using SCED braces as the lateral force resisting system. The brace on the first floor is experimentally represented while the rest of the structure is numerically modeled. Several earthquake ground motions with varying seismic intensities are applied to the system to evaluate its seismic performance. In subsequent sections, a short background on SCED mechanics, the design of reference structure, the configuration of hybrid simulation framework and the simulation results are presented.

2 SELF-CENTERING ENERGY DISSIPATIVE (SCED) BRACE

The SCED brace system consists of two rigid longitudinal members, pretensioned tendons and an energy dissipative mechanism comprising a friction device, viscous device, or other mechanism. The brace is assembled such that the tendons always elongate, regardless of whether the brace is acting in tension and compression. This behaviour results in a generally symmetric flag-shaped hysteretic response, shown in Fig 1. The self-centering capability is achieved by pretensioning tendons to produce a resisting force. The number of tendons, modulus of elasticity, initial pretensioning force, ultimate elongation capacity, and length are selected to achieve the desired strength, post elastic stiffness, and deformation capacity. Several prototype specimens designed using the SCED concept have been tested and numerical studies have been carried out to assess the performance of buildings equipped with SCED braces (Tremblay et al. 2008). A thorough explanation of SCED brace concept and validation can be found in Christopoulos et al. (2008).

Compared to traditional bracing systems like buckling restrained braced system, the SCED bracing system has the added advantage of its self-centering capability in addition to providing energy dissipation. This capability reduces or eliminates the residual deformations after a seismic event which facilitates the timely reoccupation of a structure and minimizes both direct monetary and logistic losses.

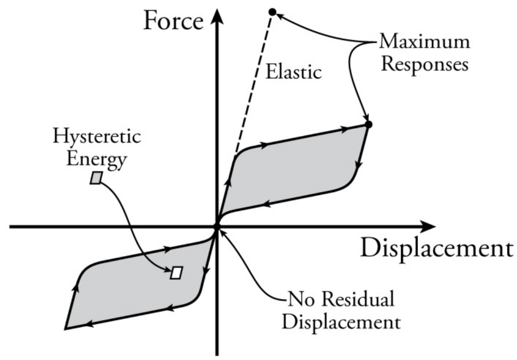


Figure 1. Symmetric Flag Shaped Hysteresis

3 REFERENCE STRUCTURE

A regular six-storey office building that was previously studied numerically (Choi et al. 2008) was chosen for this study. The building was assumed to be located in downtown Los Angeles, California where seismic loads are expected to govern the design of the lateral force resisting system. The plan of the office building consists of three 9.14 m bays in the north-south direction and five 9.14 m bays in the east-west direction. The lateral force-resisting system in the east west direction consists of two special steel moment-resisting frames with three bays each (along the north and south edges of the building). The lateral force-resisting system in the north-south direction consists of two SCED braced frames located in the center bays of the north-south frames as shown in Figure 3.The building was designed according to ASCE 7-05 (ASCE 2006). The design response spectrum of the building site is shown in Fig 2. Since the SCED brace is a new system, in the design a response modification coefficient (R) factor of 7 was used, which is consistent with other advanced bracing systems (Choi et al. 2008). An analytical model of the reference structure was developed in OpenSees (McKenna and Fenves, 2001). In the analytical model, all columns were pinned at the base and were considered to be continuous members. Additional leaning columns with gravity loads were modelled to account for P-Delta effects. The beam to column connections were treated as pinned connections. Rigid end offsets were included at both ends of the beams whose length was equal to half the depth of the column section. The plan and elevation of the reference structure is shown in Fig 3. For this steel building, a global damping of 3% of critical was implemented in the model using a Rayleigh damping model with 3% damping in modes 1 and 2.

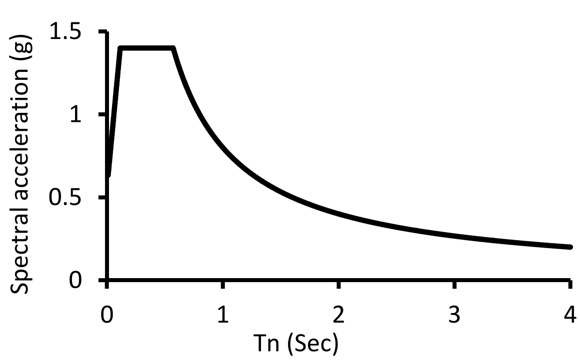
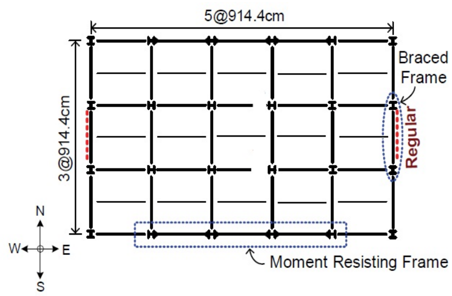
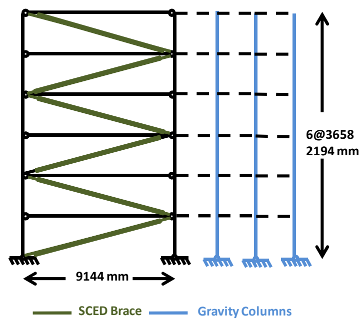


Figure 2. Design Spectra



a) Plan View



b) Elevation View of braced frame

Figure 3. Elevation of the 6-storey SCED structure

Since the experimental portion of this model was designed as part of a separate project, the properties of the experimental specimen available were different from the SCED braces in the reference building. The experimental specimen has lower initial stiffness and strength when compared to the brace properties in the reference building. Though the brace could be represented by applying different scale factors for force and displacement to match the experimental specimen properties, applying the scale factor for displacement was deemed unrealistic. Hence the six-storey structure was redesigned such that the SCED brace could be represented as scalar multiples of the experimental SCED using a scale factor on the force alone.

4 HYBRID SIMULATIONS

Due to the practical benefits of hybrid (numerical-experimental) simulation, seismic performance assessment of structures using this method has been actively used for over ten years. The procedure for hybrid simulation involves: selection of a suitable simulation platform which can communicate and integrate the results from different components of the substructured hybrid model; developing the substructured model of the structure comprising of both the physical and experimental modules; and establishing proper communication among all the modules. UI-SimCor (Kwon et al. 2005, 2008) was used as the main hybrid simulation platform, for these tests. UI-SimCor runs the time integration scheme of the system. In UI-SimCor, all dynamic degrees of freedom and the degrees of freedom of the nodes at the interface of the model substructures both experimental and numerical are included. These nodes at the interface are termed as control point nodes in UI-SimCor. The program is capable of communicating with multiple research software packages including OpenSees, laboratory modules and data/image acquisition devices through Ethernet network. The dynamic analysis is carried out in UI-SimCor where as all the experimental and analytical components perform static analysis by imposing the target displacement command received from the UI-SimCor, either using the physical actuator or inside the model. The target displacement is predicted with the Alpha-Operator Splitting integration scheme (Combescure and Pegon, 1997) using measured displacements and forces. The static analysis and data/image acquisition modules were referred to as restoring force and auxiliary modules respectively. The complete capabilities of UI-SimCor with detailed examples can be found in Kwon et al. (2008).

The second step in the preparation of the hybrid simulation was to develop the substructured model. The substructured model for the present tests consisted of two restoring force modules and one auxiliary module. One of the two restoring modules was the experimental module in which the first storey brace was represented as the physical component and the second was the analytical module in which the remainder of the structure was modelled. A schematic illustrating the different components and the control point node is shown in Fig 4. The auxiliary model comprised a new application (Application for Camera

Triggering and Image Acquisition - ACTIA) that was developed to acquire synchronized images at every time step of the simulation. ACTIA can be called from the main hybrid simulation platform UI-SimCor and can simultaneously trigger multiple cameras and acquire images.

The last step in the preparation of the hybrid simulation test was to establish flawless communication among different components. Communication between UI-SimCor to OpenSees was established with Network Interface for Console Applications (NICA). NICA is an interface program developed for hybrid simulation with UI-SimCor. It can provide network interface for OpenSees, Zeus-NL, Abaqus, and other user-developed analysis applications. The laboratory specimen was controlled through MTS controllers which were not capable of receiving commands over the network. So, to facilitate communication with the specimen, additional hardware from National Instruments (NI) was acquired and a script was developed in LabVIEW that could receive a command through the network from UI-SimCor and impose it on the laboratory specimen and then feedback both the measured forces and displacements to UI-SimCor. This script is hereafter referred to as Network Interface for Controllers (NICON). Some of the important functionalities included communication with UI-SimCor, ramp generation (- the received command from UI-SimCor was imposed as a smooth sinusoidal ramp), displacement limit and force limit checks, accommodation of any initial displacement and force offsets, and the capability to perform coordinate system transformations. Since the MTS controller controlled the laboratory actuators in real time based on voltage signals from NICON, it was imperative to verify each functionality thoroughly, to avoid unexpected movement of actuators. A schematic showing the communication is given in Fig 5.

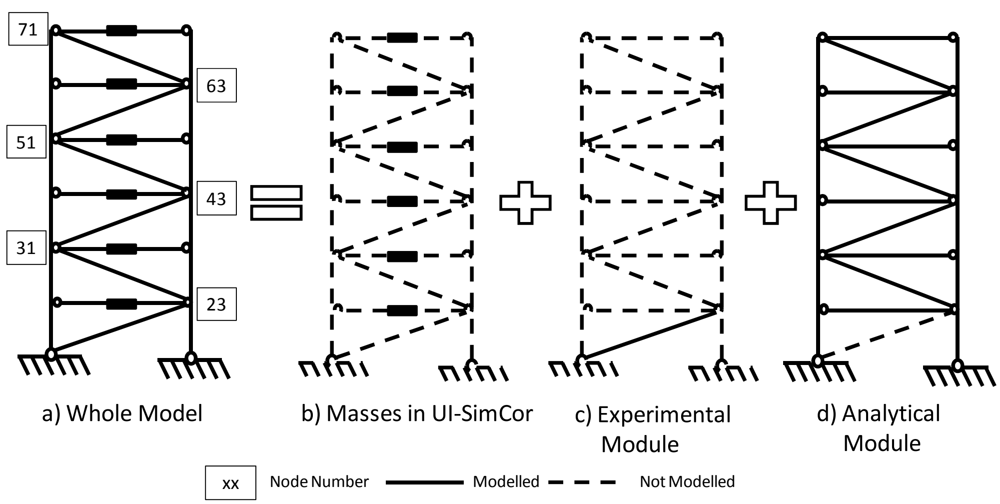


Figure 4. Hybrid Model with the different components

A picture of the experimental module is shown in Fig 6. A single storey vertical steel frame with a SCED brace was assembled. The two vertical columns were pinned at the base. The beam to column connection was a bolted connection with slotted holes. The frame was controlled using two dynamic actuators mounted to the reaction wall. From the initial tests it was observed that there was some movement in the frame external to the brace, termed as slackness. This slackness needed to be accounted for in the hybrid simulations to accurately impose the target displacement to the brace specimen and to obtain restoring forces. This was done by measuring the actual brace deformation and then iteratively modifying the command until the target displacement command in the brace from the UI-SimCor was achieved.

Hybrid simulations were carried out after verifying that every component and functionality was working properly. Since the SCED brace does not sustain any notable strength, stiffness or energy dissipation degradation within a large range of displacements, thirty hybrid simulation tests were performed on the same specimen each with a different ground excitation. The spectral acceleration of the ground excitations at the fundamental period of the reference structure represented varying seismic hazard from frequent to very rare earthquake events. The spectral acceleration values are shown in Fig.9.

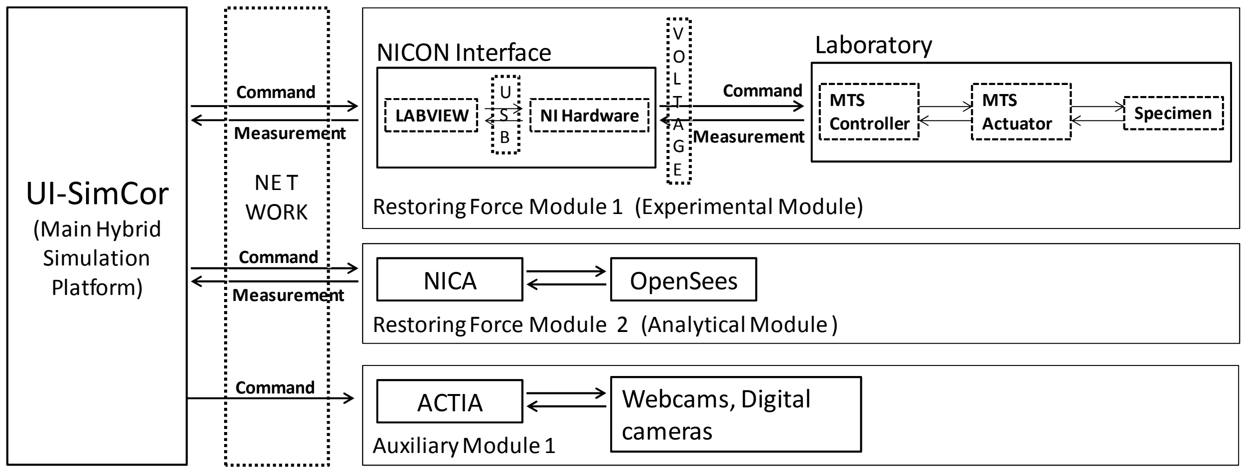
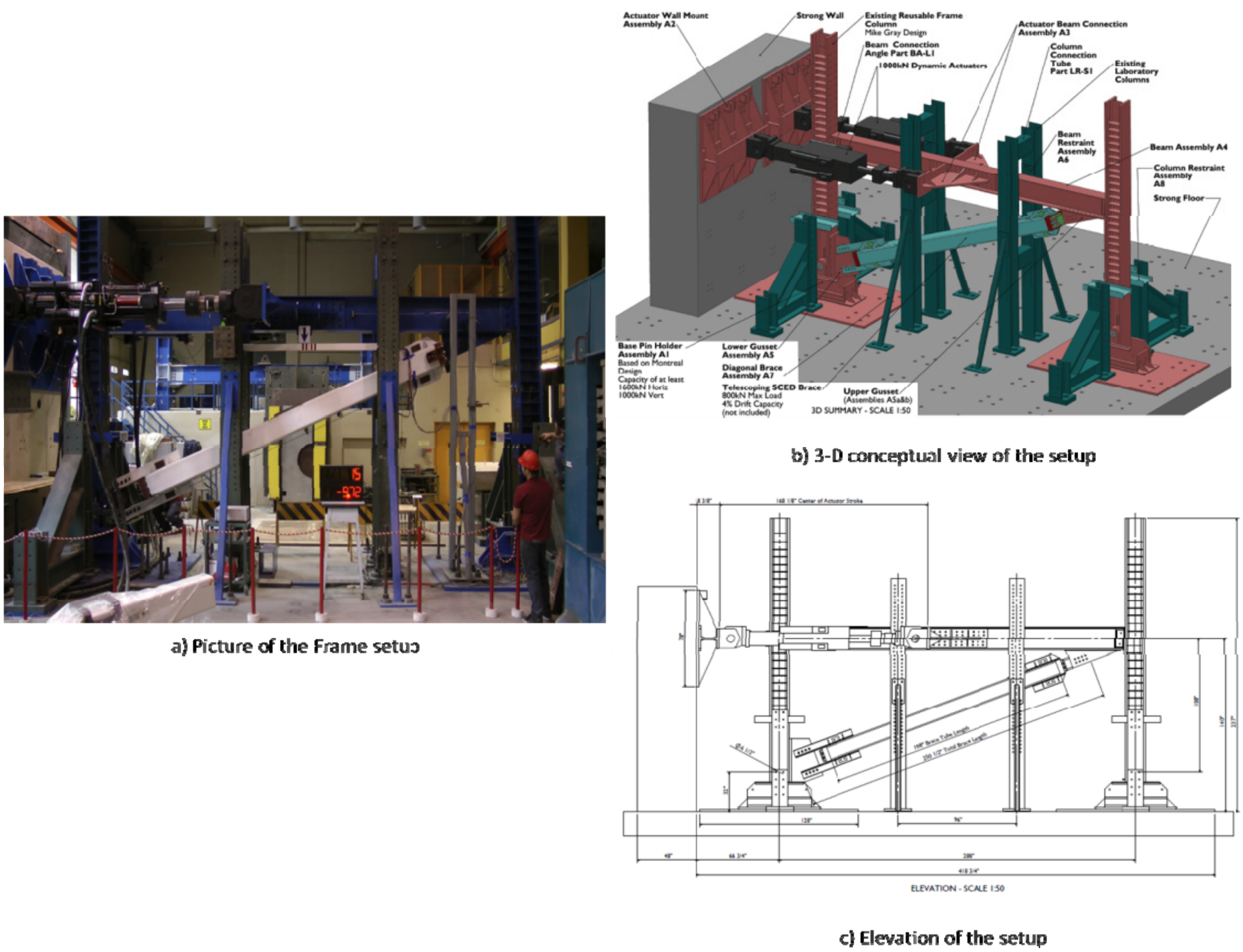


Figure 5. Communication flow among components of the hybrid simulation framework

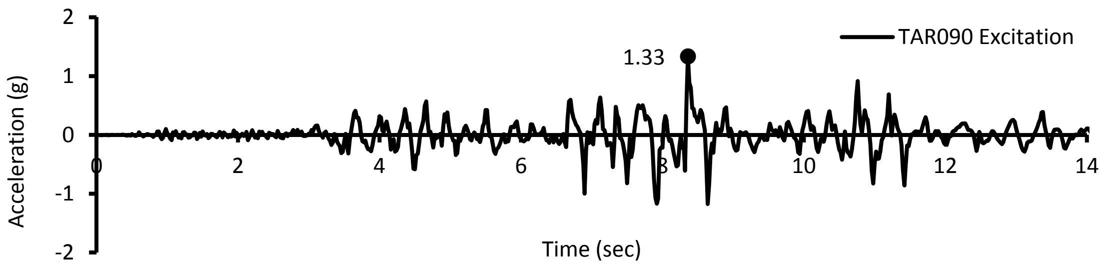


a) Picture of the Frame setup

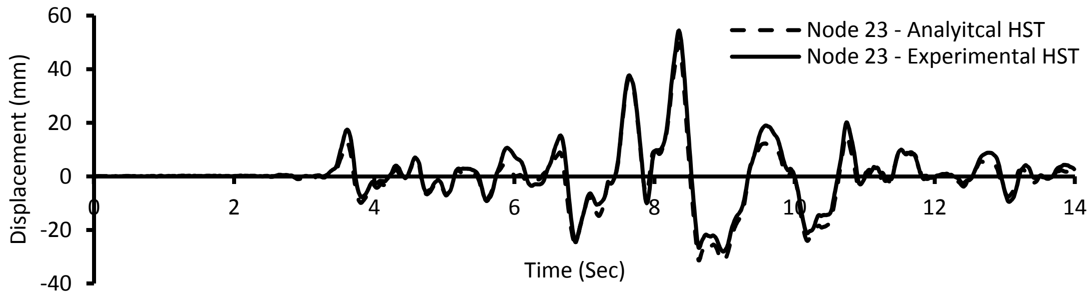
b) 3-D conceptual view of the setup

c) Elevation of the setup

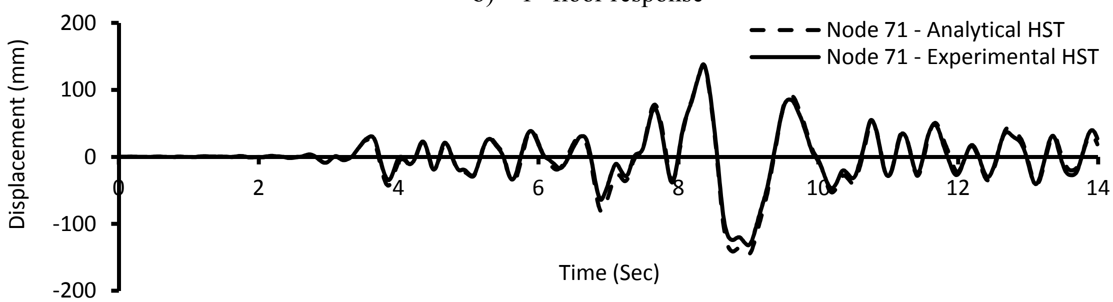
Figure 6. Illustration of the laboratory setup (Full Scale Vertical Steel Frame)



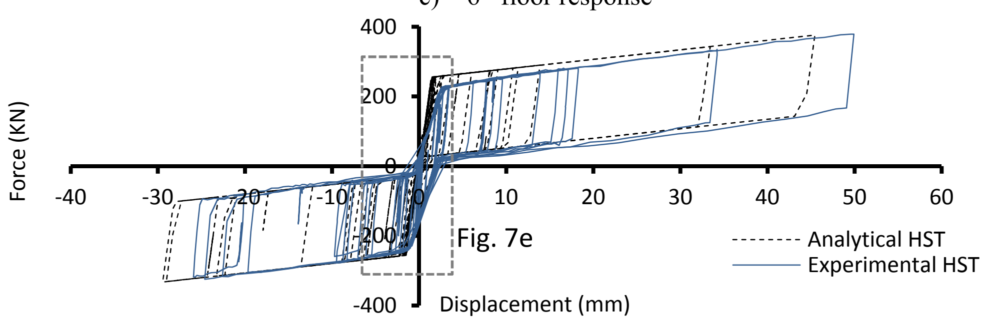
a) Input ground Motion (Northridge-01, 1994, Tarzana - Cedar hill A)



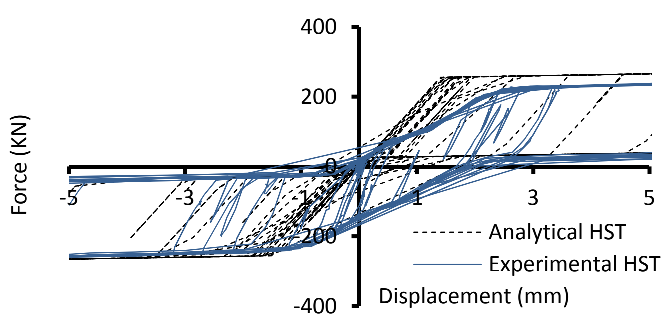
b) 1st floor response



c) 6th floor response



d) Brace hysteresis



e) Magnified view of brace hysteresis in dashed rectangle in Fig 7d

Figure 7. Comparison of responses from hybrid simulation and analytical prediction

5 SIMULATION RESULTS

Simulation results from one of the hybrid simulation tests are presented in Fig 7. The time history responses of the 1st and the 6th floor, and the brace hysteresis are shown. On the same graphs analytically predicted responses are overlapped for comparison. The peak ground acceleration (PGA) of the applied excitation was 1.33g, which represents a high-intensity earthquake. From the graphs it can be inferred that the experimental response is in good agreement with the analytical prediction. The slight difference in the response could be due to the difference in the brace hysteresis of the idealized numerical model when compared to the experimental specimen as shown in Fig 7d. From the same figure it can also be observed that the experimental SCED hysteresis is symmetric in terms of strength and stiffness in both directions.

The experimental response of the 6th floor shown in Fig 7c is from the hybrid model where the 1st storey is represented as the physical component. It is speculated that this response would vary with the storey brace selected to represent as the physical component in the hybrid model. For instance from Fig 7, it can be observed that the magnitude of difference between the experimental result and the analytical prediction for the top storey node shown in Fig 7c is less than that of the first floor node shown in Fig 7a. A series of tests were performed to investigate this issue, however, are not included in this paper due to limited space.

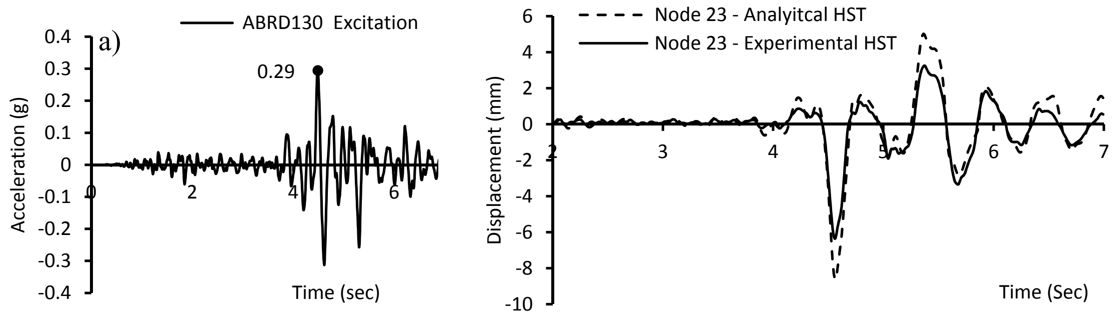
The response of the control point node from several different excitations is shown in Fig 8. In general the experimental response tends to be lower by an average of 18% than the analytical prediction with only a few exceptions as shown in Fig 8 and Fig 9. It is expected that these differences result from the idealization of the true experimental hysteretic curve using an ideal flag shape in the numerical model as shown in Fig 7d. The behavior of experimental specimen shows that the hysteretic curve, especially when the deformation is small, is relatively smooth without a sharp transition between the elastic state and the activated state as shown in Fig 7d and Fig. 7e. Since the hysteresis loop in the small displacement range forms a loop, the experimental specimen dissipates certain amount of seismic energy, which may also have resulted in relatively lower response in comparison with analytical predicted response.

Fig 9 also shows that the structure meets the life-safety performance criteria at design base earthquake (DBE) level, whose transient drift limit is 1.5% (ASCE, 2006), and the collapse prevention performance level at maximum credible earthquake (MCE) level whose transient drift limit is 2.0% (ASCE, 2006) for braced steel frame systems.

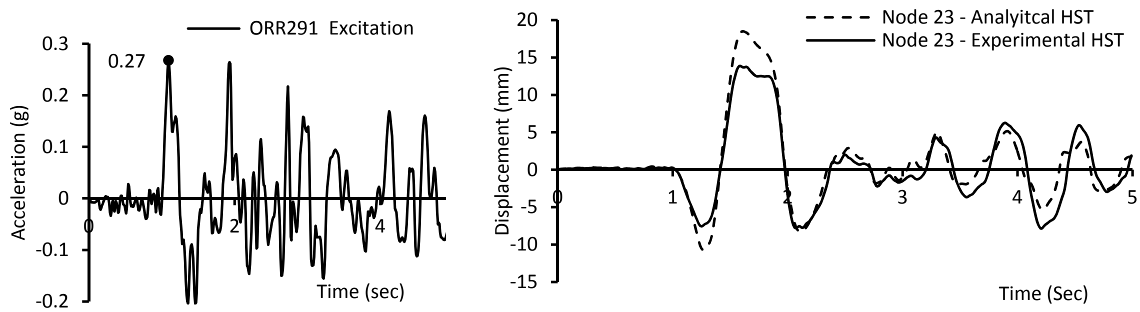
6 CONCLUSIONS

In this study, the seismic performance of a structural system with SCED brace is assessed using hybrid simulation. The configuration used for the hybrid simulation setup is explained and the results are discussed. The following are the main observations from the experiments.

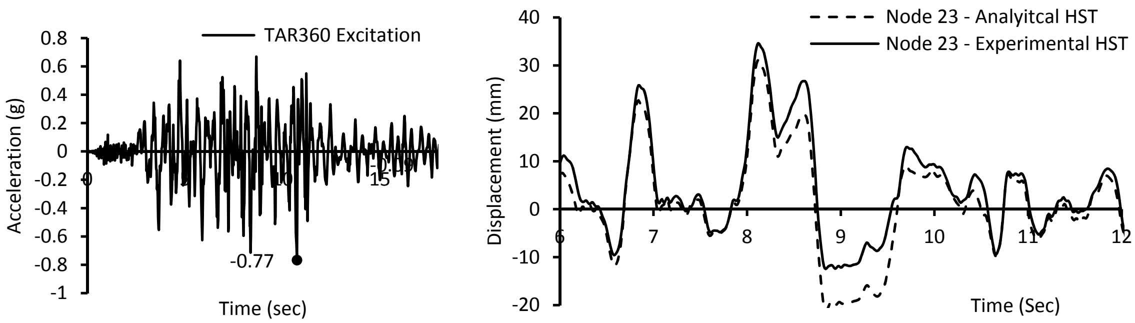
- The hysteretic curve from both the experiment and analytical simulations are in good agreement with only minor differences. The experimental specimen does not show transition as sharp as the analytical model from the elastic state to the yielded state.
- In general, the nodal displacement responses from both simulations match well. The maximum response from the experimental results tends to be smaller than the maximum responses from analytical predictions.
- The structure meets the life-safety performance criteria at design level hazard and the collapse prevention performance level at maximum credible seismic hazard and mitigates residual deformations that would otherwise be expected in yielding bracing systems.
- In this study the SCED system was subjected to more than 30 earthquakes without sustaining any notable damage or response deterioration



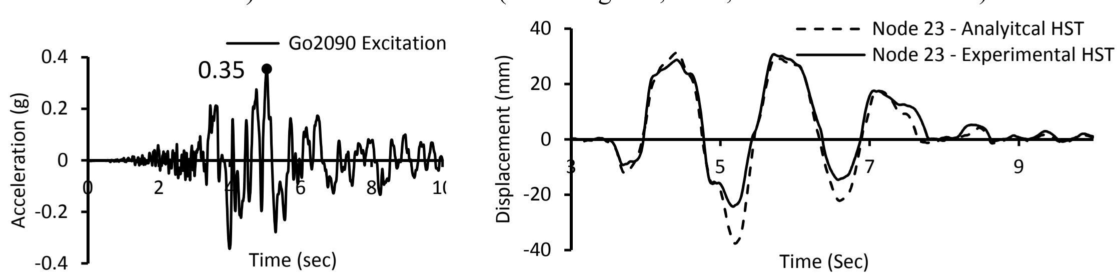
a) ABRD 130 Excitation (Whittier Narrows-01, 1987, Brea Dam (Downstream))



b) ORR291 Excitation (San Fernando, 1971, Castaic – Old Ridge Route)



c) TAR360 Excitation (Northridge-01, 1994, Tarzana - Cedar hill A)



d) GO2090 Excitation (Loma Prieta, 1989, Gilroy Array#2)

Figure 8. Comparison of dynamic analysis for different ground excitations; earthquake name, year and recorded station are shown in the brackets.

This particular research into seismic performance assessment of SCED braced structures using hybrid simulation is still in progress. Based on the experimental results, seismic fragility functions of a structural system with SCED Brace are currently being developed.

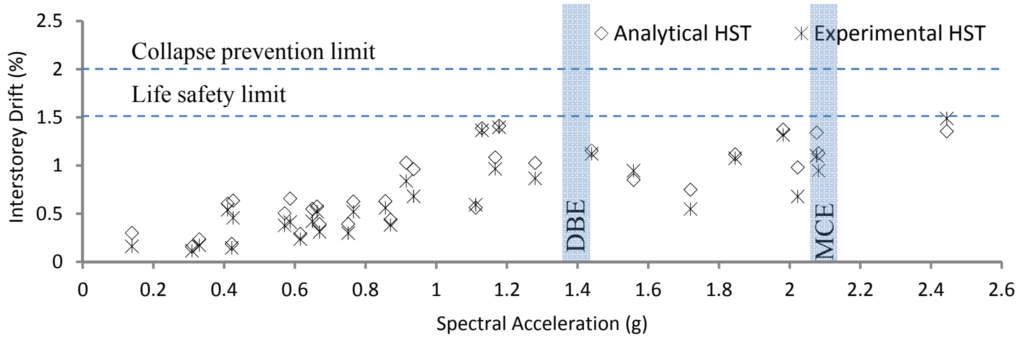


Figure 9. Graph showing the variation of interstorey drift with spectral acceleration

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