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HYBRID SIMULATION: EMPOWERING EARTHQUAKE ENGINEERING EXPERIMENTATION

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Abstract

Hybrid Simulation is being increasingly used as a powerful and cost-effective technique for dynamic analysis of structural systems. It enables research related to global and local assessment of civil infrastructure systems subject to dynamic loads. In hybrid simulation, a reference structure is split into two substructures. The physical portion of the structural system is tested in the laboratory while the other components of the structure are substituted with a computational model. Many projects have used hybrid simulation (HS) and real-time hybrid simulation (RTHS) methods for examining and verifying new analysis and design concepts. This paper provides a review of these recent HS and RTHS implementations and their role in advancing the practice of earthquake engineering. Applications in seismic engineering have been considered, especially in large-scale NEES projects, and those with publicly available data in the NEEShub data repository. The paper concludes that these projects have successfully used hybrid simulation to develop new knowledge intended to reduce earthquake risk in a built environment. However, while hybrid testing has facilitated the completion of high impact projects, the full power of this approach has yet to be unleashed.

Keywords: earthquake engineering, seismic experimentation, hybrid simulation, real-time hybrid simulation, design guidelines, building code.

1. Introduction

Catastrophic natural disasters, as earthquakes, are the primary cause of loss of human life and civil infrastructure. In order to advance the knowledge of seismic processes and their consequences, different experimental methods are generally used to simulate and evaluate structural behavior subject to severe loading such as quasi-static testing, shake table testing, effective force testing, and hybrid simulation (HS). In quasi-static tests, loads or displacements are applied at a slow speed to study structural response however, the influence of inertial and damping forces are neglected. As a result, shake table testing has been used to evaluate the structural dynamic response performing realistic conditions [1]. Nevertheless, full-scale shake table tests are expensive and time-consuming thus, those tests are usually limited to scaled models and prototypes [2].

The necessity to validate results, calibrate analytical models, and develop new design guidelines have demanded more complex simulations. In particular, the requirement to increase the size of the specimens for more realistic evaluations has been raised the cost of testing, which often exceeds the capacity of the facilities. These conditions have stimulated the use of new testing methods that combine experimental test with computational simulation. In this hybrid simulation (HS), the numerical portion of the system, which runs on a computer, usually includes the well-known part of the structure is called numerical (analytical) substructure, in contrast, the most complex component, which is tested in the laboratory, is often called the experimental (physical) substructure [3]. Both subsystems interact each other by enforcing boundary and equilibrium conditions at the interface zone [4] (see Fig. 1).

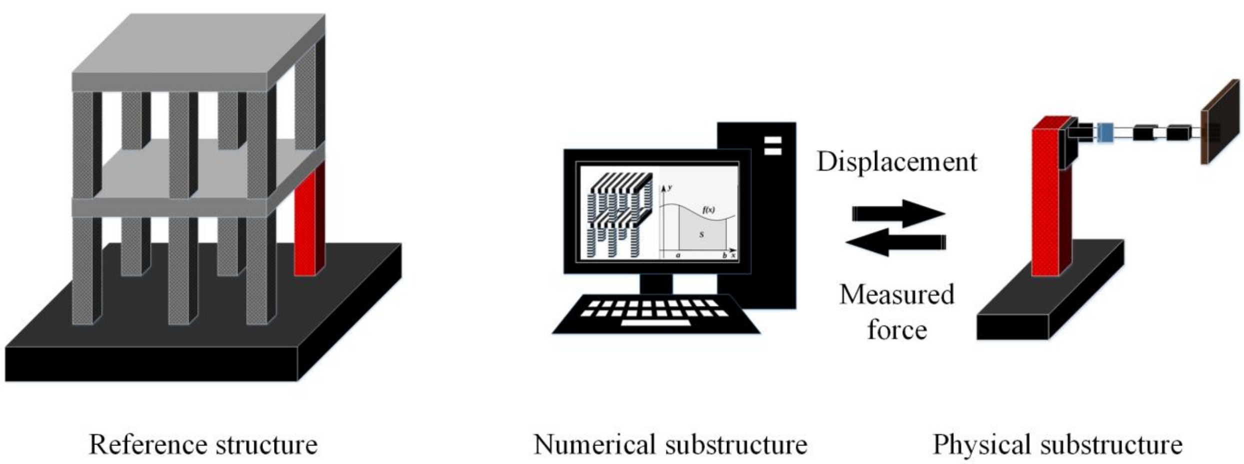

Fig. 1 –Concept of hybrid simulation

Halbert [5] developed the concept of partitioning a system into experimental and numerical substructure using a coupled digital and analog computers, through a two-way data transfer system, in which actuators were excluded from the physical substructure. In this study, path control of a maneuver under lunar attraction was simulated using the first hybrid simulation. In each step, the digital computer performed a simulation of the rocket motion and sent its position and velocity to an analog computer. Then, the analog computer solved the corresponding boundary value problem and sent the results back to the digital computer [5]. Similarly, a hybrid simulation of space vehicle guidance in a lunar landing was developed using a small digital computer connected to two fully-expanded analog computers [6].

In the structural engineering field, a hybrid simulation to conduct a dynamic test of a cantilever beam using an online system consisting of an analog computer and an electro-magnetic actuator was implemented by Hakuno et. al [7]. In this study, an online computer-actuator system to generate earthquake responses of linear and nonlinear steel and concrete structures was developed. Henceforth, structural engineers emerged the newly developed concept into a new experimental technique to evaluate the dynamic response of large civil structures in a cost-effective manner. In the late 1980s, researchers had shown that results of hybrid simulation and shake table tests are similar if experimental errors are effectively decreased [8, 9].

The necessity to examine the dynamic performance of rate-dependent structural components, combined with recent advances in embedded systems with hard real-time computing capabilities, has led researchers to utilize fast hybrid simulation and real-time hybrid simulation. With the introduction of new structural components and devices, such as rubber bearings, viscous dampers, friction dampers, sloshing dampers, magneto-rheological dampers, and electro-rheological dampers, structural engineers developed a new technique, real-time hybrid simulation (RTHS), to evaluate structural dynamic response due to dynamic loading. In RTHS, the interface interaction between the substructures is enforced by servo-hydraulic actuators or a shake table which act as the transfer system. A transfer system must be controlled to ensure that all interface boundary conditions are satisfied in real time.

This paper presents a detailed review of the role that HS and RTHS have played in encouraging the practice of earthquake engineering. Data retrieved from NEES projects which are summarized in this paper are available in their entirety in the NEES data repository (https://nees.org/). The important progress made through the projects summarized herein demonstrates that hybrid simulation offers a versatile and cost-effective alternative to developing new knowledge related to resilient infrastructure systems [3].

2. Hybrid simulation in earthquake engineering

In the past decade, HS methods have been used as an alternative method to quasi-static or shake table testing. Its ability to induce realistic loading to generate local and global response results in an attractive way to compare various aspects related to design guidelines, particularly design codes without limitations in size or shape that usually govern shake table tests. Within NEEShub, 29 projects have used HS/RTHS to investigate a variety of topics related to seismic engineering. These projects have clearly demonstrated the promising role of this method.

Recently, researchers have begun to rely on HS or RTHS to assess local and global responses, to compare various aspects related to design guidelines, particularly design codes. Two principal orientations can be identified in NEES projects using HS or RTHS in earthquake engineering: (i) to review, support, oppose, or improve design guidelines in building code requirements, and (ii) to develop and validate new structural systems or new devices to modify the structural response [3]. A diagram summarizing the directions and some of the corresponding projects is provided in Fig. 2. In many cases, hybrid simulations were more economical than full-scale shake table experiments, and sometimes the only way to achieve the goals of the projects.

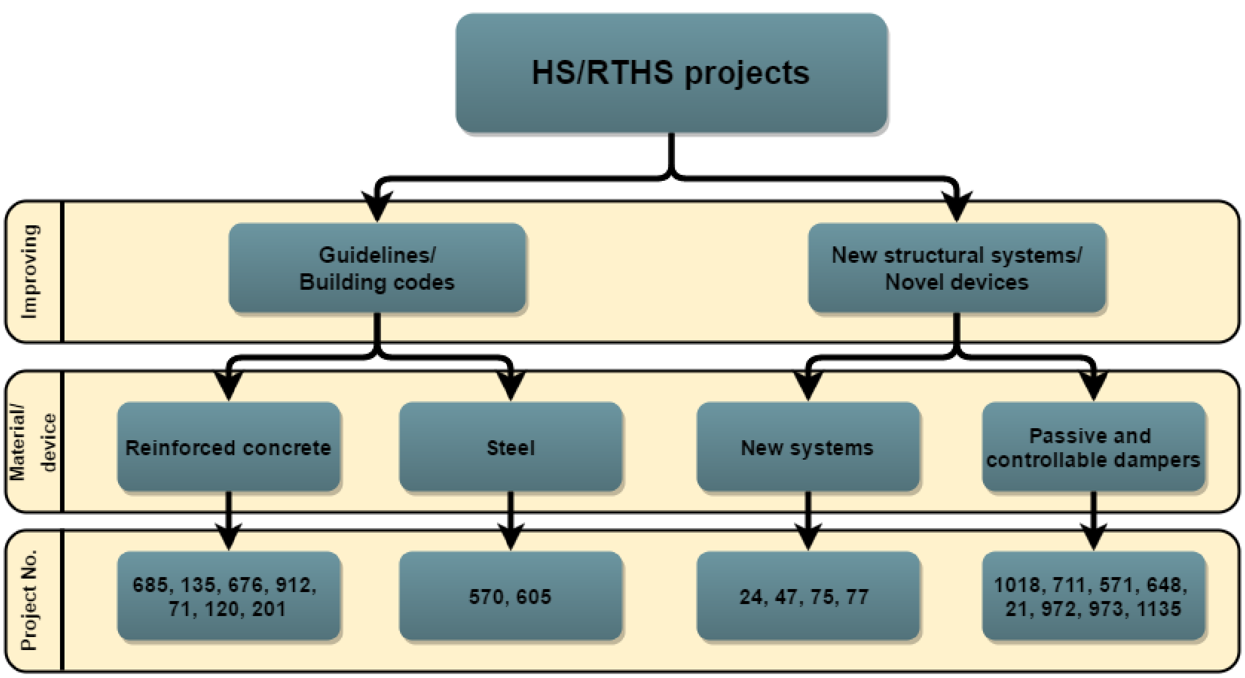

Fig. 2 –Selected HS/RTHS projects in earthquake engineering.

2.1 Hybrid simulation for improving and studying standards and guidelines in design codes

The progress made using HS in the establishment of guidelines and codes toward the design of civil infrastructure systems to resist natural hazards will be illustrated with several project's results.

2.1.1 Seismic simulation and design of bridge columns under combined actions, and implications on system response (Project 71)

The objective of this project was to evaluate the impact of earthquake ground motions in bridge piers. An extensive test program was carried out to understand the effect of combined demands (vertical and horizontal that may result in large deformation), excessive structural damage, and structural performance degradation. Two hybrid simulations were performed at the multi-axial full-scale sub-structured testing and simulation (MUST-SIM) facility at the University of Illinois at Urbana Champaign. In these hybrid simulations, a pier was constructed as the experimental substructure, and the remainder of the bridge was modeled as the numerical substructure (see Fig. 3). In the first HS called IPH, the bridge was subjected to a horizontal ground motion. In the second HS called IPV, the bridge was subjected to a combination of horizontal and vertical components ground motion. The shear strengths of the piers were evaluated and compared with ACI 318-08 [10] and AASHTO LRFD Bridge Design Specifications (1995) [11]. Researchers concluded that some guidelines predicted the shear capacity of the pier in IPH conservatively, but in IPV, the pier suffered significant damage producing a broadband range for shear capacities calculated with different methods. The effect of the combined, horizontal and vertical ground motion, produce a decrease in shear capacity in piers. Furthermore neglecting the vertical component of the ground motion in the design procedure can underestimate the effect of the earthquake in the seismic design of RC bridges [12].

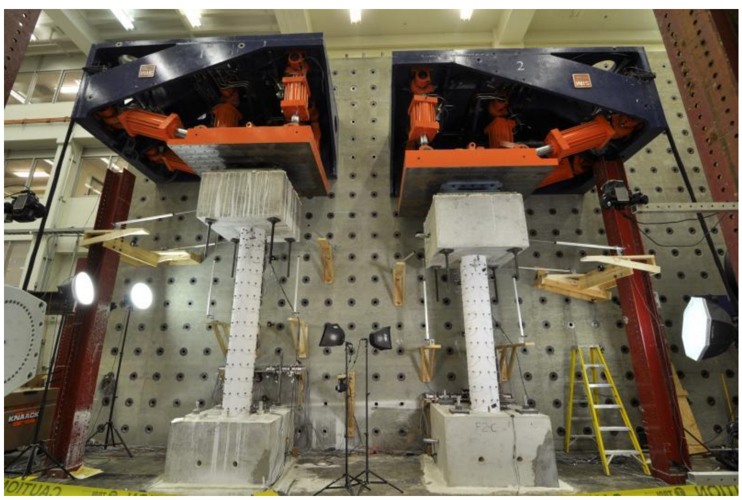

Fig. 3 –Specimens in HS tests (NEES project 71, https://nees.org/warehouse/hybrid/4176/project/71)

2.1.2 Framework for development of hybrid simulation in an earthquake impact assessment context (Project 685)

In this project, HS provided an innovative way to utilize field measurement data combined with system identification, model updating, probabilistic fragility analysis, and earthquake impact assessment packages to evaluate the impact of earthquakes on civil infrastructures in a robust framework. In the proposed framework, free-field measurements were used to define and characterize strong motion records. Structural sensors were employed to update the bridge-foundation-soil model. Eight HS tests and one cyclic test were conducted using 1/25-scale RC pier specimens. For the HS test, three synthetic ground motions were used with a PGA between 0.2 and 0.9 g, corresponding to three different hazard levels. Simulation results indicated that the model calibrated with cyclic tests accurately predicts the response in cases with a lower PGA. However, the model underestimates the peak lateral drift response under large PGAs. HS is shown to provide an updated model that produces a more realistic failure probability in fragility functions in the range of high ground motion intensity [13]. An important outcome of this project was the development of a tool that integrates and combines components of earthquake impact assessment such as structural damage, loss assessment, estimation of nonstructural damage, economic cost, retrofit cost, etc. [14]. This project demonstrated that hybrid simulation is an economical and efficient technique with many capabilities and applications.

2.1.3 Hybrid simulation and shake-table tests on RC buildings with masonry infill walls (Project 135)

One of the objectives of this project was to improve the modeling techniques of hysteretic response and stiffness degradation in elements of RC moment frames interacting with unreinforced masonry (URM) infill walls. The numerical substructure consisted of a ¾ scale five-story prototype moment-resisting frame structure designed with its exterior columns as the primary lateral load resisting system. The experimental substructure was the middle bays of the first story. This project concluded in [15] that URM infill walls need to be incorporated in the analysis and design of the structure. The experimental results showed that the interaction between the RC frame and the infill wall made the test structure 3.8 times stiffer, reduced the initial natural period by 50\%, and revealed an increase in the structural damping as a function of the inter-story drift. Finally, experimental results confirmed that the URM infill walls resulted in a 30\% increase in the demand on the diaphragm, which directly affected the RC columns at the top and bottom of the infill wall [15].

2.1.4 Performance-based design of squat concrete walls of conventional and composite construction (Project 676)

In this project, researchers conducted hybrid simulations to investigate the behavior of squat reinforced concrete structural walls commonly used in nuclear energy plants as a seismic lateral force resisting system. Squat shear walls are those designed with an aspect ratio around 0.5 and are quite thick to provide protection against radiation and fire [16]. The experimental substructure was 0.2 m thick, 3 m long and 1.65 m tall shear wall (See Fig. 4). To simulate the excessive weight of a nuclear power plant, the extra mass was modeled in the numerical substructure and it was adjusted to achieve a 0.14 sec fundamental natural period, which is a realistic value. Various design code procedures were employed to predict the observed responses. In some cases, the recommended methods over predict the peak shear strength of squalls walls by almost a factor of 1.8 [16]. However, more results are required to draw conclusions about the displacement capacities of thick walls.

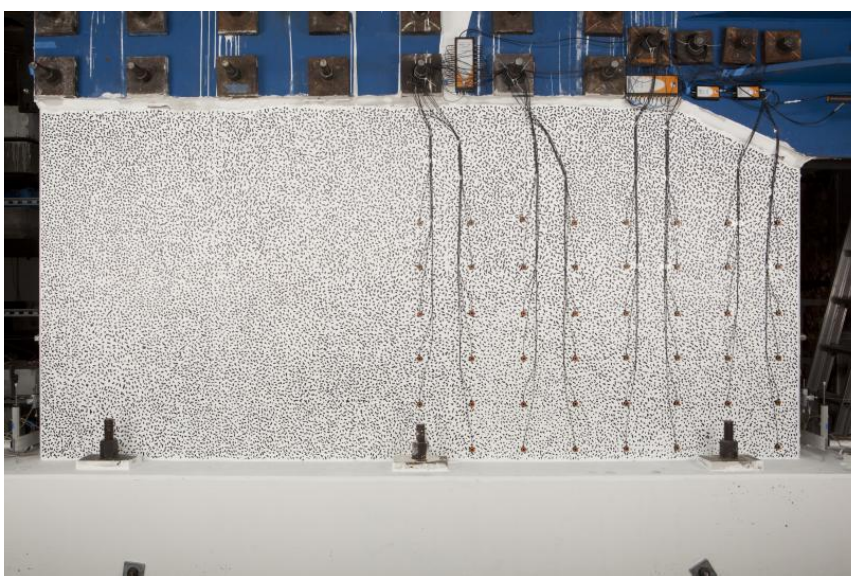

Fig. 4 –Experimental substructure compose by a thick wall specimen (NEES project 676 [17], https://nees.org/warehouse/project/676)

2.1.5 Collapse simulation of multi-story buildings through hybrid testing (Project 912), and Near collapse performance of existing reinforced concrete frame buildings (Project 1084)

In these projects, a number of specific tests were conducted to predict and evaluate structural collapse responses. A progressive collapse program was conducted to study the structural failure in each project using HS. Here, the adoption of hybrid simulation eliminated or alleviated a number of safety concerns related to experiments with structural collapse. In project 912, a large-scale shake table test was conducted to study collapse in a 2D four-story steel structure [18]. Using a similar frame, several hybrid simulations were performed to compare the results with the shake table results, demonstrating hybrid simulation flexibility, cost-effectiveness and safety (See Fig. 5). In project 1084, researchers evaluated the reinforced concrete buildings constructed before the mid 1970's. Some of these buildings have structural elements with low capacity to resist shear-axial stress. Although this project has not publicly published any results yet, the results will potentially provide earthquake engineers with more effective rehabilitation methods for existing non-ductile RC buildings [19].

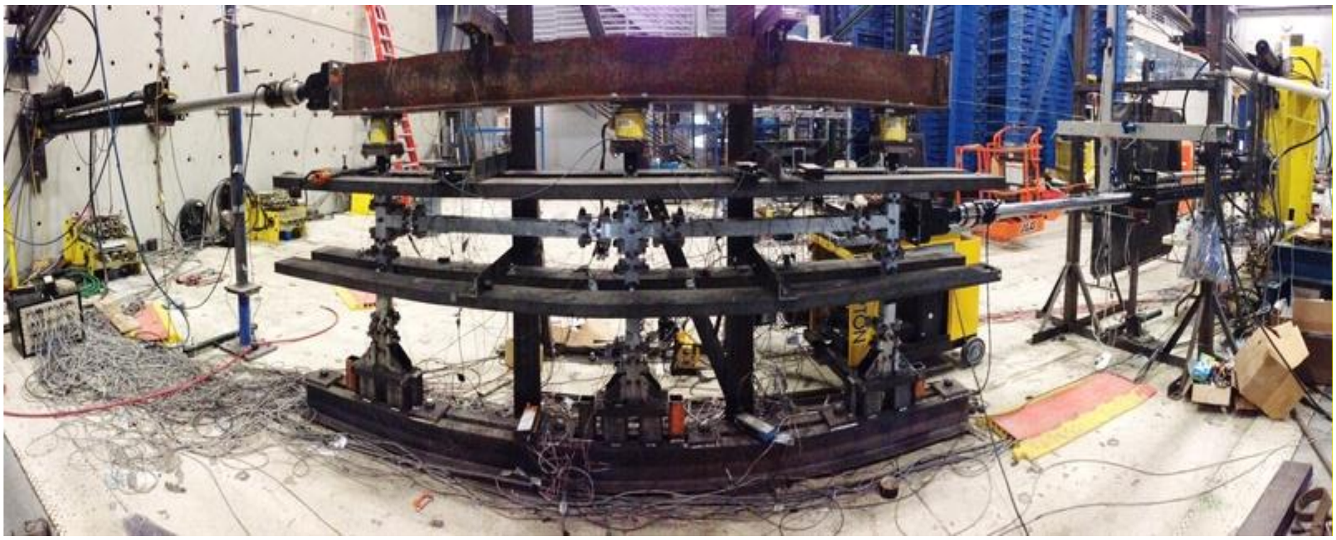

Fig. 5 –Experimental substructure in collapse test (NEES project 912, https://nees.org/warehouse/project/912)

2.1.6 International Hybrid Simulation of Tomorrow's Braced Frame Systems (Project 605)

A series of tests were performed in order to evaluate different bracing configurations and various design strategies intended to improve structural earthquake-resistant systems by increasing the ductility (See Fig. 6). A series of HS and cyclic tests were conducted using a three-story single-bay concentrically brace steel frames as the experimental substructure to obtain the response of the different buckling restrained brace frames (BRBF) and to investigate the brace-to-gusset connections. The numerical substructure consisted of two five-bay steel moment resisting frames and two one-bay concentrically brace frames in the longitudinal and transversal directions, respectively. The results of these tests recommend 3tp clearance in the knife plate, unlike AISC (2010) [20] suggestion of 2tp clearance, to provide an adequate space for welding and allow enough rotations in the knife plate [21]. Also, Lin et al. [22] proposed a design procedure for BRBF to avoid local failure produced for bulging of steel casing in the buckling restrained brace elements. In this project, hybrid simulation and real-time hybrid simulation have also been used extensively to evaluate the capabilities of new materials, advanced damping devices, and novel structural systems to improve the seismic response of buildings and bridges.

Fig. 6 –Experimental substructure in composed by breaced frame system (NEES project 605, https://nees.org/warehouse/project/605)

2.2 Hybrid simulation for developing novel structural systems and response modification devices

In this section, a review of large-scale hybrid simulation projects with innovative structural systems and response modification devices is provided

2.2.1 Behavior of braced steel frames with innovative bracing schemes - a NEES collaboratory project (Project 24)

In this project, the system consisted of a bracing scheme using a suspended "zipper" frame. Conventional concentrically braced steel frames have the potential to lose stiffness and strength when buckling occurs in the brace, producing undesired vertical forces. In response, a new braced steel frame configuration was developed to meet the objective of providing an efficient seismic response. Due to high nonlinearity of brace buckling, a hybrid simulation was conducted to capture the complex chevron brace buckling behavior. Although the zipper frame was not a new idea, the modification proposed in this project was intended to avoid undesirable loss of lateral strength in the frame and resist the potentially post-buckling force redistribution, resulting in very strong beams [23]. In this new concept, the top story bracing members were designed to remain elastic while all the other compression braces buckled and the tension braces and zipper elements yielded. In conducting hybrid simulation, the experimental substructure, which was scaled to 1/3, represented the first-story braces and consisted of two braces along with the gusset plates connecting the braces to the beam at the top. The numerical substructure was a FEM model built in OpenSees [24]. This model used a flexibility-formulation nonlinear beam-column elements with fiber sections for the beams, columns, and zipper columns, and zero-length elements for the connections. A second-order displacement formulation was used to include the nonlinear buckling behavior [25]. The results indicated that the suspended zipper column would successfully achieve the goal of redistributing the force along the frame height, although large inter-story drifts produced permanent deformation in the first floor. For this project, hybrid simulation was particularly useful in capturing the complex responses of the system subject to large deformation and buckling.

2.2.2 Self-centering damage-free seismic-resistant steel frame systems (Project 77)

An innovative structural system was developed to ensure that a moment-resisting frame would be able to resist the design basis earthquake (DBE) without any structural damage. In the design, post-tensioning strands would pre-compress the beams to the columns yielding a passive device with self-centering moment resisting frame

(SC-MRF). The system was designed to return to its initial position while dissipating significant amount energy under large seismic loads. A hybrid simulation was implemented to evaluate a 7-bay, 4-story SC-MRF building designed for a location in the Los Angeles area. The experimental substructure was a 2-bay, 4-story structure scaled to 60% and the remainder of the reference structure was the numerical substructure. Using HS, the structure was subject to four DBE level ground motions, and each floor was able to return to its initial position after the structure was excited (thus, there were no residual drifts). These experiments demonstrated that the system has sufficient capacity for Immediate Occupancy (IO). Besides, the holes in the beam web dissipate considerable energy under earthquake producing a structure 10% lighter than a traditional welded seismic moment resisting frame W-SMRF [26]. Specifically for this project, the hybrid simulation capabilities enabled a large number of evaluation tests to be performed rapidly and cost-effectively, and with fewer safety concerns.

2.2.3 Controlled rocking of steel-framed buildings (Project 75)

In this project, a novel passive device was designed to concentrate structural damage in a fuse element that is replaceable after yielding. The structural system includes three components. First, steel frames that remain in the elastic range and allowed to rock in the column base. Second, vertical post-tensioning strands provide self-centering forces. Third, fuse elements that dissipate energy while yielding. Nine large-scale quasi-static and hybrid simulation tests were conducted at the University of Illinois at Urbana-Champaign to demonstrate the performance of the controlled rocking system. Particularly, HS was used to show the robustness of the system to remain elastic, even when drift ratio was approximately 4%, without any damage in the braced frame [27]. Since the damage was located in the removable fuse, a considerable amount of energy was dissipated [28].

2.2.4 Innovative applications of damage tolerant fiber-reinforced cementitious materials for new earthquake-resistant structural systems and retrofit of existing structures (Project 47)

A retrofit system was developed and evaluated to enhance the seismic performance of existing steel buildings. A 1980's steel building design in California was considered for the proposed retrofit. The proposed system consists of high-performance fiber-reinforced concrete (HPFRC) infill panels acting as energy dissipation elements that could easily be replaced after a major earthquake. The numerical substructure consisted of a 2-bay, 2-story SMRF building, and the experimental substructure consisted of a 2/3-scale model of 1-bay and 2- stories with 5 double infill panels per story. The hybrid simulation allowed global assessment of the system and showed that during a DBE the retrofit system reduces seismic demands by approximately 40\% in terms of story and residual drift ratios compared with the un-retrofitted frame [29].

2.2.5 Tools to facilitate widespread use of isolation and protective systems, a NEES/E-defense collaboration (Project 571)

The project was a collaborative effort between researchers in the U.S and Japan to create and promote tools to facilitate the adoption of isolation and protective systems in structures. The existence of such tools would simplify design procedures, disseminate knowledge regarding the use of seismic isolation technology, establish a linkage to building codes, and confirm the impact of such isolators on seismic response of the buildings [30]. A series of hybrid simulations were performed using shake tables. A 2-story, 2-bay steel moment frame was the experimental substructure, representing the top two stories of a building. The numerical substructure consisted of the lower portion of the building. The response of the numerical substructure was calculated and used as input to the upper stories (the experimental substructure) mounted on the shake table. The benefits of seismic isolation in such buildings were demonstrated. However, changes in building codes and guidelines to simplify the use of seismic isolators are necessary. Moreover, these tests would not have been possible at this scale were it not for the hybrid simulation method.

2.2.6 Performance-based design for cost-effective seismic hazard mitigation in new buildings using supplemental passive damper systems (Project 1018) and Advanced servo-hydraulic control and real-time testing of damped structures (Project 711)

More than 170 RTHS were conducted on 3-story steel buildings and 2-story MRF buildings equipped with supplemental passive dampers. Both viscous fluid and elastomeric dampers were used to assess their impact on the performance of the buildings, and to evaluate and validate the proposed design procedures. The experimental substructure was scaled to 60% with dampers. The numerical substructure was the remainder of the MRF building. The results showed that when the elastomeric dampers were included in the MRF frame, the base shear was less than the design shear base specified by current specifications, producing a structure lighter than a conventional SMRF [31].

Advanced damping systems like magneto-rheological (MR) dampers have demonstrated great potential for mitigating the impact of earthquakes on structures and meeting the objectives of performance-based design. Realistic evaluations are required to encourage their adoption. However, the velocity dependent nature of the device and the need for including interaction between the device and the frame necessitated the development of advances in RTHS.

2.2.7 Semi-active control of nonlinear structures (Project 21), Performance-based design and real-time large-scale testing to enable implementation of advanced damping systems (Project 648), Development of a real-time multi-site hybrid testing tool for NEES (Project 972), Development and validation of a robust framework for real-time hybrid testing (Project 1135), and Real-time hybrid simulation test-bed for structural systems with smart dampers (Project 973)

These NEES projects were among the very first to successfully develop and validate RTHS methods to assess global structural response. Initially, RTHS was conducted with a damper alone as the experimental substructure. After advancements were made in the actuator controllers, more complex testing was performed using a damped steel frame as the experimental substructure and RTHS was shown to be successful in a structure. Once RTHS methods were further developed and demonstrated, they were used to evaluate the global performance of structures. Shared facilities capable of implementing large-scale RTHS were utilized to develop performance-based design methodologies for advanced damping systems, high fidelity models for devices, and improved control algorithms for model-based simulation studies. New MR damper control strategies were also developed and validated [32]. The results indicated that large-scale MR dampers could provide significant seismic response reduction even with the maximum credible earthquake (MCE). RTHS was essential to perform these tests as it provided an efficient and cost-effective tool for global evaluation of novel devices, such as MR damper controllers that exhibit rate dependent behavior [33].

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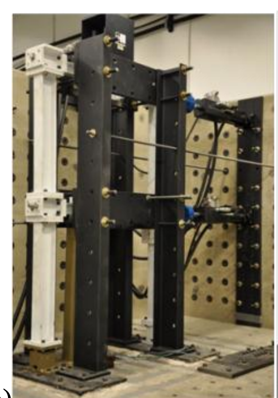
b) 

Fig. 7 – a) MR damper setup at Lehigh NEES facility (NEES project 648, https://nees.org/warehouse/project/648). b) Cyber-physical instrument for real-time hybrid structural testing at Purdue University (NEES Project 1135, https://nees.org/warehouse/project/1135)

Each project produced an important contribution to different subjects. For instance, Project 21, demonstrated the ability of semi-active control devices to improve the structural response subject to earthquake ground motion. Project 648, conducted the first large-scale RTHS on a complex frame system using multiple actuators (See Fig. 7a). Project 972, developed and demonstrated the capacity of NEES labs to conduct geographically-distributed RTHS tests. Project 1135, concentrated on the evaluation of new hydraulic actuator control strategies to implement successful RTHS (See Fig. 7b). Project 973 attempted to improve the performance of structures controlled by semi-active devices.

3. Conclusions

Establishing resilient and sustainable communities will require some creativity in the ways that researchers conduct experiments and perform simulations [34]. Infrastructure system design procedures must be supported by experiments that represent realistic conditions while those structures are in service. Hybrid simulation and real-time hybrid simulation have clearly expanded the types of testing that are possibles, to improve resilience and reduce earthquake risk in a built environment. The role of hybrid simulation in enabling these tests has been exploited to evaluate the performance of new design concepts and structural systems and novel devices, as well as providing code provisions to be examined with most realistic loading conditions. The projects discussed herein encompass only projects within the NEES network, providing a broad view albeit still a subset of what is possible through HS. A broad set of projects has been considered, including masonry, reinforced concrete, steel, dampers, bracing systems, and other novel concepts. Together these projects have demonstrated that HS and RTHS are versatile, effective, economical and reliable for obtaining realistic responses from complex structural systems because the numerical substructure can readily be replaced/modified, an unlimited number of structures and configurations can be examined with a single physical specimen. Furthermore, it enables the testing of structural configurations which are too tall or too long to be adequately considered in a laboratory, such as long-span bridges and high rise buildings. Several of these projects concluded that their results were achieved through the use of hybrid simulation over traditional methods (quasi-static and shake table test). Also, when a test proves to be particularly costly or present certain safety concerns, HS and RTHS provide alternative approaches. Note that although hybrid simulation has a bright future, researchers such as those recognized herein are still working on bringing this technology to maturity. A great deal is being learned about employing the methods in new situations and to consider new behaviors. Each successful test represents a success story that takes the community one step forward. Each success leads hybrid simulation and thus earthquake engineering toward achieving resilience through the examination and validation of novel systems under realistic situations. The possibility of conducting geographically distributed tests, as some of these projects have done, opens new doors to testing complex systems. The promise of this technology will be further explored in several projects in progress. For instance, NEES projects in progress are: “Rapid return to occupancy in unbraced steel frames” (707), “Seismic rehabilitation of substandard building structures through implementation of stiff rocking cores” (1085), “NEES soft-seismic risk reduction for soft-story, wood frame buildings” (934), “Post-tensioned coupled shear wall systems” (922), and “The multi-site soil-structure-foundation interaction test (MISST)” (201).

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5. References

[1] Schellenberg A, and Mahin S (2006): Integration of hybrid simulation within the general-purpose computational framework OpenSees. *In Proc. of 100th Anniversary Earthquake Conference*, San Francisco, California.

[2] Shing PB, Nakashima M, and Bursi OS (1996): Application of pseudodynamic test method to structural research. *Earthquake Spectra*, **12**(1), 29-56.

[3] Gomez D, Dyke SJ, and Maghareh A (2015): Enabling role of hybrid simulation across NEES in advancing earthquake engineering. *Smart Structures and Systems*, **15**(3), 913-929.

[4] Chen J, Ricles M, Karavasilis TL, Chae Y, and Sause R (2012): Evaluation of a real-time hybrid simulation system for performance evaluation of structures with rate dependent devices subjected to seismic loading. *Engineering Structures*, **35**, 71-82.

[5] Halbert PW, Landauer JP, and Witsenhausen HS (1963): Hybrid simulation of adapt path control. *Proceedings of the AIAA Simulation for Aerospace Flight Conference*, Columbus, Ohio, USA.

[6] Heartz RA, and Jones TH (1964): Hybrid simulation of space vehicle guidance system. *Proceedings of the International Space Electronics Symposium*, Las Vegas, Nevada, USA.

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

[8] Takanashi K, and Nakashima M (1987): Japanese activities on on-line Testing. *Journal of Engineering Mechanics*, **113**(7), 1014-1032.

[9] Mahin SA, Shing PB, Thewalt CR, and Hanson RD (1989): Pseudodynamic test method current status and future directions. *Journal of Structural Engineering*, **115**(8), 2113-2128.

[10] American Concrete Institute (ACI) Committee 318-08 (2008): Building code requirements for structural concrete and commentary (ACI 318-08). Farmington Hills, MI.

[11] Standard specifications for highway bridges (AASHTO) division I-A (1995): Seismic design American association of state highway and transportation officials, Inc., 15th edition, as amended by the Interim Specification - Bridges, Washington, DC.

[12] Kim SJ, Holub CJ, and Elnashai AS (2011): Experimental investigation of the behavior of RC bridge piers subjected to horizontal and vertical earthquake motion. *Engineering Structures*, **33**, 2221-2235.

[13] Li J, Spencer BF, and Elnashai AS (2013): Bayesian updating of fragility functions using hybrid simulation. *J. Struct. Eng.*, **139**, 1160-1171.

[14] Lin SL, Li J, Elnashai AS, and Spencer BF (2012): NEES integrated seismic risk assessment framework (NISRAF). *Soil Dynamics and Earthquake Engineering*, **42**, 219-228.

[15] Hashemi A, and Mosalam KM (2006): Shake-table experiment on reinforced concrete structure containing masonry infill wall. *Earthquake Engng Struct. Dyn.*, **35**, 1827-1852.

[16] Whyte CA, and Stojadinovic B (2012): Hybrid simulation of the seismic response of squat reinforced concrete shear walls. *Proceedings of the 15th World Conference on Earthquake Engineering*, Lisbon, Portugal.

[17] Whyte CA, Barthes C, Gunay S, Park S, Patterson D, Takhirov S, and Stojadinovic B (2013): "Hybrid simulation of the seismic response of squat reinforced concrete walls - Wall 1 Test", Network for Earthquake Engineering Simulation (distributor), Dataset, DOI:10.4231/D34T6F32M

[18] Lignos, D (2008): Sidesway collapse of deteriorating structural systems under seismic excitations. *Ph.D Dissertation*, Stanford University, California.

[19] Sasani M, and Shao X (2012): Near collapse performance of existing reinforced concrete frame building", April 24. https://nees.org/warehouse/project/1084

[20] American Institute of Steel Construction (AISC) (2010): Seismic provisions for structural steel buildings, Chicago, IL.

[21] Tsai CY, Tsai KC, Lin PC, Ao WH, Roeder CW, Mahin SA, Lin CH, Yu YJ, Wang KJ, Wu AC, Chen JC, and Lin TH (2013): Seismic design and hybrid tests of a full-scale three-story concentrically braced frame using in-plane buckling braces. *Earthquake Spectra*, **29**(3), 1043-1067.

[22] Lin PC, Tsai KC, Wang KJ, Yu YJ, Wei CY, Wu AC, Tsai CY, Lin CH, Chen JC, Schellenberg AH, Mahin SA, and Roeder CW (2012): Seismic design and hybrid tests of a full-scale three-story buckling-restrained braced frame using welded end connections and thin profile. *Earthquake Engng Struct. Dyn.*, **41**, 1001-1020.

[23] Leon R, Yang C, DesRochers R, Reinhorn A, Schacter M, Stojadinovic B, Yang T, Shing B, and Wei Z (2005): Results of early collaborative research on behavior of braced steel frames with innovative bracing schemes (Zipper Frames). *Proceedings of the First International Conference on Advances in Experimental Structural Engineering*, AESE, Nagoya, Japan.

[24] OpenSees (2014): Open System for Earthquake Engineering Simulation. April 18. http://opensees.berkeley.edu

[25] Yang TY, Stojadinovic B, and Moehle J (2009): Hybrid simulation of a zipper-braced steel frame under earthquake excitation. *Earthquake Engng Struct*. *Dyn*., **38**, 95-113.

[26] Lin Y, Sause R, and Ricles J (2013): Seismic performance of steel self-centering, moment-resisting frame: hybrid simulations under design basis earthquake. *J. Struct. Eng.*, **139**(11), 1823-1832.

[27] Deierlein GG, Billington S, Hajjar JF (2005): Controlled rocking of steel-framed buildings. April 24, 2014. https://nees.org/warehouse/project/75

[28] Eatherton M, Hajjar JF, Deierlein GG, Ma X, and Krawinkler H (2010): Hybrid simulation testing of a controlled rocking steel braced frame system. *Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering*, Toronto, Canada, July.

[29] Lignos D, Moreno D, and Billington S (2014): Seismic retrofit of steel moment-resisting frames with high-performance fiber-reinforced concrete infill panels: large-scale hybrid simulation experiments. *J. Struct. Eng.*, **140**(3).

[30] Arendt LA, Earle S, and Meyers R (2010): Results of a cross-disciplinary survey on isolation systems decision making. *Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering*, Toronto, Canada, July.

[31] Mahvashmohammadi A, Sause R, Ricles J, Marullo T (2013): Real-Time Hybrid Simulations on a Large-Scale Steel MRF Building with Elastomeric Dampers. *Technical Report ATLSS Center*, Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, Pennsylvania.

[32] Friedman A (2012): Development and experimental validation of a new control strategy considering device dynamics for large-scale MR dampers using real-time hybrid simulation. *Ph.D Dissertation*, Purdue University, Indiana.

[33] Phillips BM, Chae Y, Jiang Z, Spencer BF, Ricles JM, Christenson RE, Dyke SJ, and Agrawal A (2010): Real-time hybrid simulation benchmark study with a large-scale MR damper. *5th World Conference on Structural Control and Monitoring*, Shinjuku, Tokio, July.

[34] Dyke SJ (2010): 2020 Vision for earthquake engineering research: report on an open space technology workshop on the future of earthquake engineering. March 18, 2014. https://nees.org/resources/1636