Research Highlights

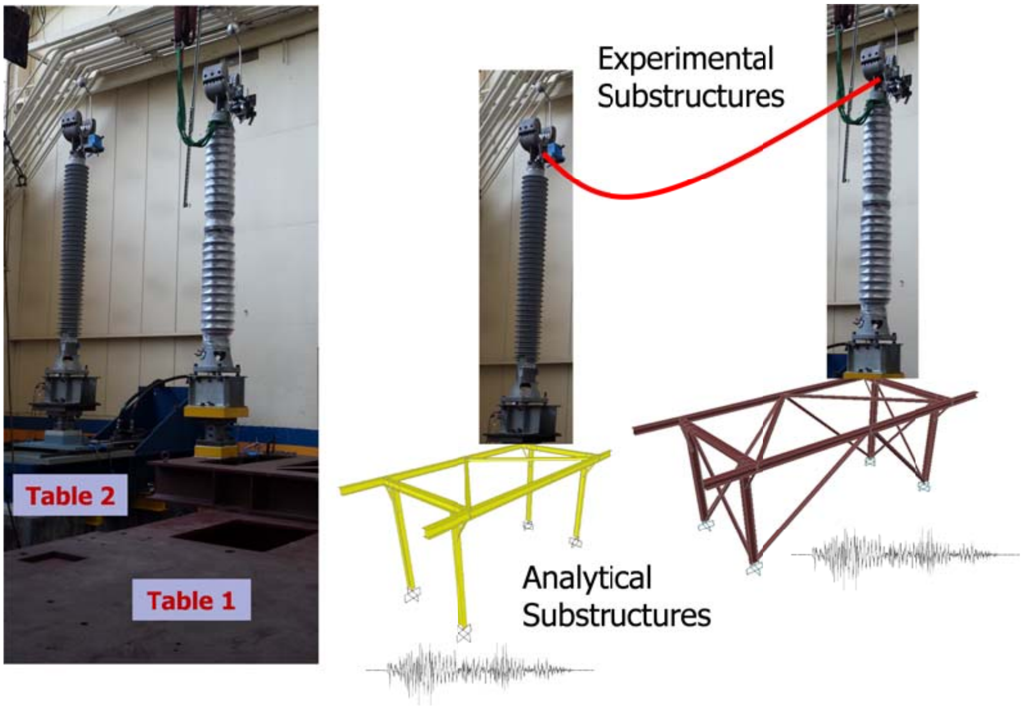
NEES@Berkeley: Khalid Mosalam, **“Next Generation Hybrid Simulation-Evaluation and Theory”**

Hybrid simulation (HS) is a testing method to examine the dynamic, e.g. seismic, response of structures using a hybrid model comprised of both physical and computational substructures. Because of the unique feature of the method, combining physical testing with numerical simulations, it provides an opportunity to investigate the seismic response of structures in an efficient and economically feasible manner. It is this ability that has caused HS to gain widespread use in recent years. HS can be divided into three categories: I) Slow HS in a discrete actuator configuration, II) Real-time HS (RTHS) in a discrete actuator configuration, and III) RTHS in a shaking table configuration. There have been a considerable number of HS tests conducted for category I, which constitutes the most common HS. On the other hand, categories II and III have gained popularity in recent years. Unfortunately, sufficient theoretical and experimental investigations are still lacking and this project attempts to fill this gap, particularly for category III HS.

The benefits of HS categories II and III (RTHS in actuator and shaking table configurations) are enormous. HS conducted within the scope of the project demonstrates that it is possible to obtain the same amount of information that would be obtained from conventional testing in a much shorter duration and in an economically feasible manner. However, RTHS in a shaking table configuration involves significantly more challenges than slow HS because of the need for accurate control of velocity and acceleration in addition to the conventional displacement control. The research in this project contributes to the enhancement of these beneficial RTHS categories by improving the conventional displacement control via inclusion of velocity and acceleration in the control process. For this purpose, an advanced control method, namely the Three Variable Control (TVC), developed by the MTS Corporation, is implemented in the RTHS system of the NEES@Berkeley laboratory.

Once the challenges of test setup are overcome, RTHS provides unique opportunities to investigate the behavior of complex structures such as power substations. The equipment components located in a substation, such as disconnect switches and surge arrestors, are mounted on a variety of support structures, which are two or three dimensional steel frames with well-defined geometry. Furthermore, these equipment components are connected to each other with a variety of cable conductors. Although these cables possess slacks in the undeformed configurations, they change the dynamic behavior at displacements smaller than the slack value and apply additional forces on the equipment when the displacements exceed the slack value and the cables become tight. In general, it is practically not possible to investigate the earthquake response of interconnected electrical equipment on shaking tables because of size limitations and constraints of cost and time. Because it is straightforward to model the support structures analytically, RTHS becomes the only practical way to test interconnected equipment by locating them on different shaking tables and modeling the support structures analytically.

During Q3 of 2014, two specimens were tested. Specimen 1 consisted of two hybrid simulation models computed/tested simultaneously in real time by utilizing two shakers. The shakers were tuned individually to improve their performance and minimize errors during hybrid simulation. Both shakers were controlled from the same Simulink model with different tuning parameters. A three-variable-control technique was used to control the shakers. Specimen 2 represented a sophisticated hybrid model which physical substructure had complex dynamic properties. The specimen was tested in real time with hybrid simulation that exposed nonlinear performance of the physical substructure.



Above: Setup for RTHS testing of interconnected electrical equipment

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NEES@Buffalo: Andrew Whittaker, **“Full-Scale Seismically Isolated Bridge Testing”**

The analysis and design of seismically isolated structures are based on bounding procedures that accounts for plausible changes in mechanical properties of isolation hardware (elastomeric, lead-rubber or sliding bearings) due to natural occurring phenomena during the lifetime of the structure. In order to better understand how seasonal changes effects the behavior of such structures, two full-scale bridges were constructed at Ashford, in Western New York, and are dynamically tested on a weekly basis over the period of multiple years.

The two 72-foot long adjacent single-lane girder bridges are constructed at a distance of six feet from each other and supported on elastomeric bearings. The superstructure consists of ten girder beams that are post-tensioned in the longitudinal direction, whereas the uniform behavior of the superstructure is achieved through transverse post-tensioning of the girders. Each deck has been filled with 9 inches of gravel to account for the permanent loads applied to the bridge's superstructure.

Eight elastomeric low-damping bearings of circular cross-section were donated for the test by Dynamic Isolation. The design displacement of the bearings have been set to 4.0 inches given that the target period of the isolated bridge is 2.0 seconds and the total weight per bearing is 100 kips. Two different elastomeric compounds have been selected, resulting in two groups of bearings with different stiffness properties, with one being assigned to each of the two bridges. Prior to installation, the bearings were tested by NEES@Buffalo to obtain their initial mechanical properties.

A hydraulic actuator spans the gap between the two bridges and can slowly push them apart at the design displacement, and upon release, the two spans are subjected to free vibration.

Several data acquisition channels, digital cameras and a weather station are in place to collect information on the structural behavior of the system and the change of properties of the isolation bearings due to time and environmental conditions (temperature, humidity, frost, etc.).

This project will contribute to a better understanding of the effects that temperature, environmental conditions, and wear have on the mechanical properties of isolation bearings. It will also provide a more realistic determination of bounding values of isolator properties for analysis and design based on better estimated Property Modification Factors (λ-factors). Given that the bridges can incorporate different seismic isolation systems, this bridge field station can provide insight to the effect of these systems on the resilience of bridges due to naturally-occurring phenomena.

Tests on these bridges began in November of 2010 and are ongoing. In Q3 and Q4 of FY 2014, the bridges were tested every week by the team from NEES@Buffalo.

Left: General view of the full-scale seismically isolated bridge

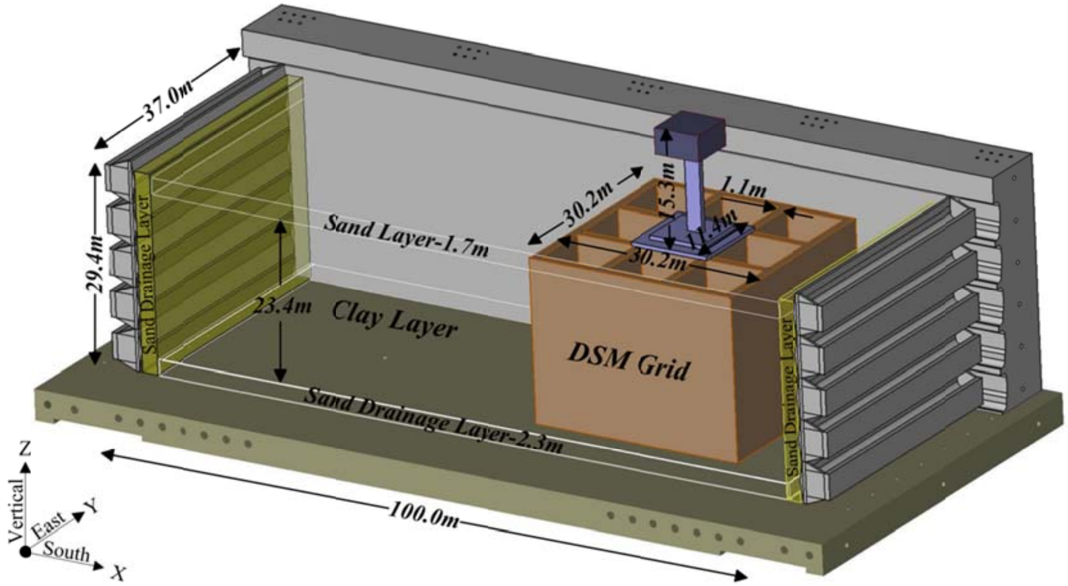
Right: Hydraulic actuator between the two adjacent single span bridges

NEES@Davis: Celal Guney Olgun, **"Reduction of Seismic Shaking Intensity on Soft Soil Sites Using Stiff Ground Reinforcement"**

The mitigation of the earthquake damage potential of soft soil sites remains one of the leading challenges in earthquake engineering. It is well-established through observations of earthquake damage patterns that structural damage is strongly correlated with local geological and soil conditions. Soft, weak sites generally fare worse than stiff sites. This is because soft sites tend to amplify the intensity of ground shaking and often undergo large deformations that can cause major structural damage. Earthquake damage potential can be significantly reduced by reinforcing and effectively stiffening such sites. Preliminary studies suggest that mixing cement with the soft soils to form stiff soil-cement panels in the ground (i.e., "deep soil mixing") can be an effective ground reinforcement technique for such purposes. Using this technique, soft soil sites can be transformed to behave like stiff sites, thereby greatly reducing earthquake vulnerability. This work has the potential to improve building performance, increase safety margins, and reduce development costs in earthquake prone regions.

The primary objective of this project is to develop a new seismic design concept for reinforced ground that can be used to reduce the intensity of strong ground shaking on soft sites. The study involves centrifuge and shake table testing as well as numerical modeling to demonstrate that stiff soil-mix panels, installed in lattice-type grids, can reduce the amplification of seismic energy up through soft soil profiles. In most cases, such ground reinforcement is used to increase bearing support, limit permanent deformations, and/or reduce liquefaction potential. Additional benefits, such as favorably altering the dynamic transfer function of the soil profile and thereby reducing the shaking levels input into the superstructure are not considered in current design provisions. Such reductions in ground shaking can lead to safer and more economical designs. This work represents an unprecedented approach to design ground improvement to reduce surface ground motions and base input into structures at seismically vulnerable soil sites.

During Q4 of FY 2014 two tests were run on the 9 m centrifuge at the NEES@Davis facilty. The setups for these tests were based on findings from previous quarters of testing. Unlike previous tests, one of these centrifuge tests included a floating grid system. This grid system has a much lower depth to grid spacing ratio than prior experiments. Q4 tests also had an improved area replacement ratio of A_r=34%, which is greater than the A_r=25% used on the last set of 9 m centrifuge tests.



Above: A buckled HSS brace after testing in a full scale concentrically braced frame.

NEES@Lehigh: Larry Fahnestock, **"Reserve Capacity in New and Existing Low-Ductility Braced Frames"**

Steel concentrically-braced frames (CBFs) are commonly used to resist lateral loads due to their efficiency and the simplicity that they afford in design, fabrication, and erection. CBFs in moderate seismic regions of the United States are typically not detailed for ductile seismic response and acceptable performance under earthquake loading is assumed to be provided through some combination of system overstrength, reserve capacity, and the inherent ductility of steel. Since there is minimal evidence to support these assumptions, this project was initiated to systemically evaluate the seismic behavior and performance of low-ductility CBFs in moderate seismic regions of the United States. In particular, the project is studying sources of reserve capacity within CBF building systems and determining their impact on seismic collapse through component tests, nonlinear analysis, and full-scale frame tests. Potential sources of reserve capacity include: column continuity, column base connections, brace re-engagement after weld fracture, braced frame connections, and gravity connections.

Nonlinear static and dynamic analyses have been conducted to evaluate the impact of various forms of reserve capacity on braced frame system behavior. Three-story prototype buildings, which are located in Boston, MA, have been the focus of the analyses, and these buildings are also the basis for the full-scale testing that was recently conducted in the NEES@Lehigh facility. Two one-bay two-story concentrically-braced frame (CBF) test specimens, which correspond to the bottom two stories of prototype buildings, were evaluated under cyclic loading protocols to examine low-ductility limit states, progression of damage and reserve capacity mechanisms within the braced frame.

Two tests were run during Q4 of FY 2014 using NEES@Lehigh's facilities.

In July, a chevron configuration CBF with R=3 was tested. This frame is representative of a typical moderate seismic CBF design that does not include any specific seismic detailing. It initially developed brace buckling in the second story around 0.3% roof drift, and significant strength degradation followed. Subsequently, a weld fracture at the brace-to-gusset plate interface was induced in the first story. In the first story, brace re-engagement, with strength similar to the pre-fracture condition, and a ductile long-link EBF mechanism, which was stable up to 6% story drift with beam flexural hinging, characterized the remainder of the test.

In September, a split-X configuration OCBF was tested. This frame is representative of a design that has a basic level of seismic detailing, but not enough that ductile response is anticipated. It exhibited stable cyclic response, with brace buckling and yielding, up to 1.5% roof drift when a second story brace-to-gusset plate weld fractured at nearly three times the design base shear. Subsequently, the brace re-engaged in compression and the prior peak base shear in the opposite direction was nearly reached at -1.5% roof drift. In the next cycle, heading towards -2.0% roof drift, the first story beam-to-gusset plate weld fractured and concluded the primary portion of testing.

These tests provide valuable new data on braced frame inelastic behavior, particularly mechanisms that develop after a primary limit state such as brace buckling or weld fracture. The experimental data, along with results from companion numerical earthquake simulations, will provide significant new knowledge about the seismic response of low-ductility CBFs and support the development of design strategies that can be implemented to achieve adequate collapse prevention performance for CBFs in moderate seismic regions while still preserving the economy of the system.

Above: The split-X OCBF at 2% roof drift. Buckling of the brace can be seen in the upper left bay.

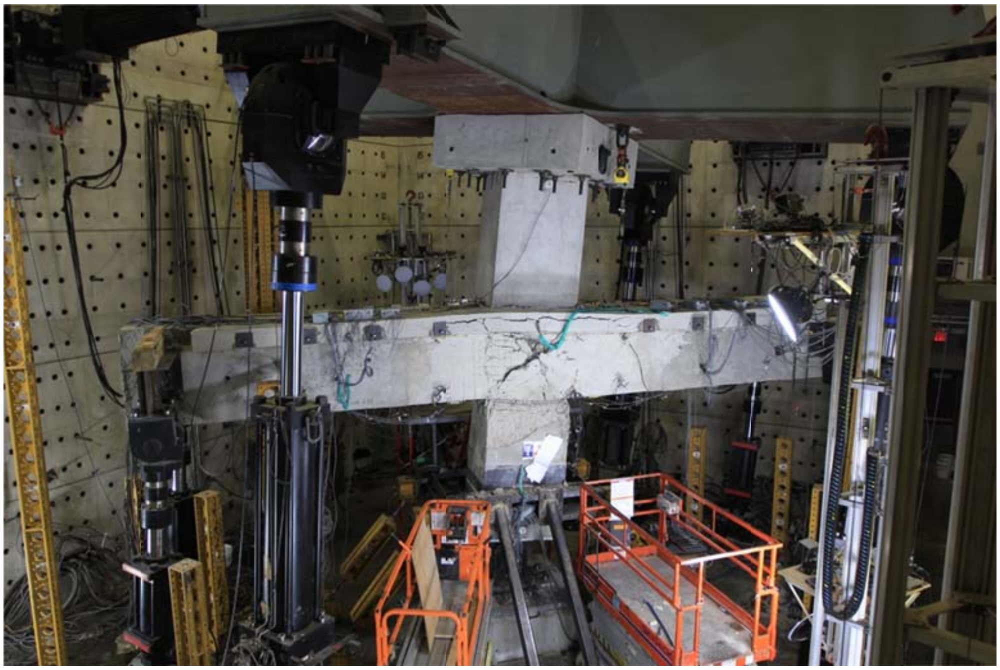
Above: A buckled HSS brace after testing in a full scale concentrically braced frame.

NEES@Minnesota: Shih-Ho Chao, **"Full-Scale RC and HPFRC Frame Subassemblages Subjected to Collapse-Consistent Loading Protocols for Enhanced Collapse Simulation and Internal Damage Characterization"**

The reinforced concrete moment frame is one of the most commonly used seismic force resisting systems. However, can modern RC moment frames survive the earthquake forces created when the "Big One" comes? Previously, no experimental testing has been carried out on full-scale structural members to address this question. The purpose of this project is to further the understanding of the behavior of reinforced concrete (RC), high-performance reinforced concrete (HPFRC), and ultra-high performance fiber-reinforced concrete (UHP-FRC) moment frames under the collapse-level seismic events. This has been accomplished through the testing of full-scale columns and slab-beam-column sub-assemblage frames subject to collapse-inducing loading protocols using NEES@Minnesota's MAST facility. Due to the current knowledge of such behaviors being so limited, the improvement of collapse simulation models from these test results will be influential to the future design of buildings in high seismic risk areas. In addition to developing knowledge on the general behavior of collapse-driven behavior, the testing also utilizes innovative ultrasonic internal imaging technology to track the progression of internal damage in RC members. The testing also uses Digital Image Correlation (DIC) technique to monitor the full field strain distribution in the highly deformed regions of the specimens.

The first phase of the project completed eight full-scale reinforced concrete columns in 2013. The rectangular RC columns were designed based on ACI 318-11 and subjected to a constant axial load and various lateral loading. The loading protocols were designed to attain story drift ratios exceeding 10%, causing the specimens to lose most of their lateral loading capacity. The specimens were representative of actual columns in the ground floor of a 20-story modern moment frame building located in a high seismic region. The two different cross-sectional dimensions (36×28 in. and 28×28 in) are larger than all flexure-critical columns previously tested. One of the columns used the emerging innovative material, Ultra-High-Performance Fiber-Reinforced-Concrete (UHP-FRC), to enhance seismic performance of columns.

The second phase of this project was completed during Q4 of FY 2014. This phase included tests of three full-scale slab-beam-column subassemblages. Each of these specimens represented a modern RC exterior moment frame with post-tensioned slabs. Each beam was 42 inches deep and 32 inches wide. The overhanging slabs were 8 inches thick. Except for the HPFRC specimen-in which the majority of the hoops and ties were eliminated-the subassemblies were designed according to ACI 318-11 requirements. The testing was carried out by using both near-collapse and symmetrical fully reversed cyclic loading protocols which displaced the specimen up to severe damage and obvious strength degradation (about 8% story drift).



Above: One of the full-scale slab-beam-column subassemblages after testing.