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THE UNIVERSITY AT BUFFALO NODE OF THE NEES NETWORK – A VERSATILE HIGH PERFORMANCE TESTING FACILITY TOWARDS REAL-TIME DYNAMIC HYBRID TESTING

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ABSTRACT

The University at Buffalo node of the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES), funded by the National Science Foundation (NSF), consists of two moveable six-degree-of-freedom shake tables, capable of accommodating specimens up to 40m (120 feet) long and weighing 100 tons (220,000 lbs), high-performance, high-capacity dynamic actuators networked to model-based data fusion processing and control systems, and a multi-million dollar laboratory expansion, which includes a greatly expanded strong floor, reaction walls, and a trench for the moveable shake tables. This equipment is fully integrated in order to achieve a *Real-Time Dynamic Hybrid Testing* (RTDHT) system.

KEYWORDS

Testing, dual shaking tables, actuators, real-time dynamic hybrid testing.

INTRODUCTION - RESEARCH VISION

Testing of very large full-scale specimens and models is currently possible in a few earthquake engineering laboratories worldwide. However, full-scale laboratory seismic testing of entire civil engineering structures (e.g., cable-stayed bridges, multi-story office buildings, industrial facilities, and pipeline distribution systems) is not likely in the near future due to the prohibitive costs that would be associated with such testing. Not only would the materials, labor, and time associated with full-scale testing exceed available research resources, but the testing of extremely large specimens and entire structures might even be counter-productive, making it difficult to study localized or specific problems within the complex system. Powerful and damaging

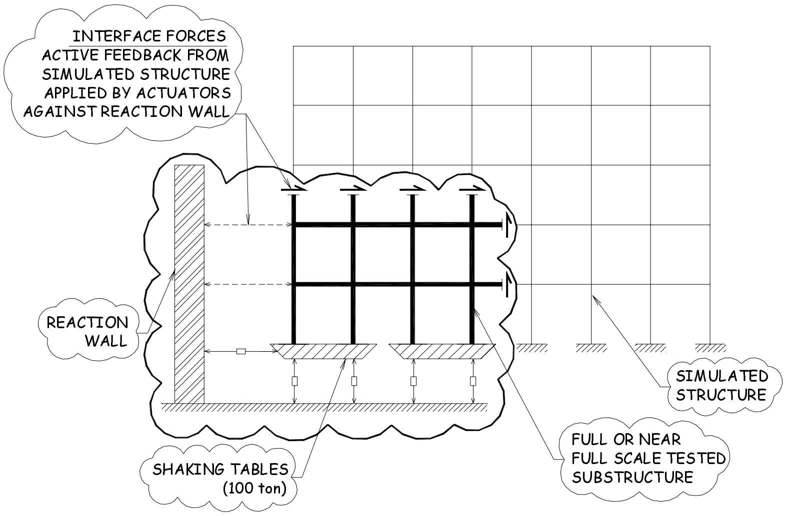

Fig.1. Real-Time Hybrid Seismic Testing System
(Substructure Dynamic Testing)

earthquakes frequently provide full-scale testing of real structures, in uncontrolled experiments of sorts, but adequately instrumenting such structures to generate the data necessary for research is also prohibitive, particularly given the unknown and often long time intervals between large earthquakes at any given site. It is believed that the best approach to experimentally generate the data needed for the development of reliable and accurate models of behavior is to compliment the testing of large-scale models with innovative testing methods that make it possible to conduct complementary tests simultaneously, and seek to supplement such experiments with real-time interactive computational analyses for better understanding of entire systems. The intent is to dynamically test large structures or substructures using shaking tables while simultaneously applying actively controlled dynamic forces at the boundary of the specimens -- forces that simulate in real time the behavior and interactions of the rest of the structure (Figure 1). Conceptually, this allows a researcher to focus on specific problems in the most realistic conditions possible, using emerging computational power in tandem with control systems. Such procedures and set-ups significantly extend the testing capabilities by integrating large-size physical components into virtually complete systems of unlimited size and configuration. Experimental capabilities must be sufficient to work at the scale necessary to ensure that credible results can be generated, but they need not be oversized. Furthermore, to ensure that new problems and needs can be addressed, and to prevent premature obsolescence of an experimental facility, a high degree of experimental flexibility is required. Finally, in order to tackle increasingly complex problems and shorten the time from research to implementation, the experimental infrastructure must be highly integrated with computational and model-based simulations (or even complementary experimental work), not only locally, but also at remote sites, in order to allow cross-disciplinary and multi-disciplinary teams of researchers to contribute.

The motivation underlying the development of *Real-Time Dynamic Hybrid Testing* (RTDHT) was *not* to build an experimental facility that would have the largest shake-tables or other associated equipment, but rather to build the *most versatile* large-scale earthquake engineering facility. This versatility is achieved by combining state-of-the-art experimental equipment, on-line experimental control methods, and the expertise of earthquake engineering researchers at the University at Buffalo (UB). This will result in the development and implementation of: (i) new experimental techniques and approaches in earthquake engineering, (ii) new earthquake-resistant design concepts and systems, (iii) analytical and computational methods supported by experimental data, and (iv) network-based collaborative research activities and sharing of data.

NEXT-GENERATION EXPERIMENTAL CAPABILITIES AND INSTRUMENTATION

Key components of the effort to implement the aforementioned capabilities include:

1. Expansion of the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at UB in order to accommodate the new NEES equipment (at a cost of $9,000,000, funded by the State of New York),
2. Installation of dual shake tables, dynamic actuators, and a high-capacity hydraulic system,
3. Development of high-performance structural control systems,
4. Development of networked tele-experimentation capabilities using modular and expandable teleobservation and teleoperation equipment.

These items combine to make possible a RTDHT facility that is modular and highly flexible, and that can test multiple configurations of full-scale components simultaneously with integrated real-time numerical simulations to investigate the seismic behavior of large structural systems in ways not currently possible.

The expansion of SEESL, housed in Ketter Hall on the Amherst Campus of UB, will include a greatly enlarged strong floor area, large reaction wall, and a trench for the moveable shake tables. A tele-participation room, equipped with high-resolution digital video and Internet2 connections is also planned as part of the laboratory expansion. This will permit broader sharing of experimental information in a setting proper to real-time observation and interaction.

As part of the equipment upgrade for SEESL, two new 6-DOF shake tables will be purchased. Both will possess the following characteristics: maximum horizontal table accelerations of 1.15g, velocities of 1.25 m/sec, and strokes of ±0.15 m (i.e. standard limits used in experimentation, and usually above the real life probable maxima, except for stroke in some instances). In addition, each table has a 50 metric tons maximum capacity, and a 20 metric tons nominal capacity at which the maximum dynamic performance can be achieved. The tables will be moveable, and located in a common trench (Figure 2). As a result, the two tables can be located directly next to each other, or anywhere up to a maximum distance of 33m (100 ft) from each other (center-to-center), accommodating test specimens up to 40m (120 ft) in length. The re-positioning of the tables within the trench can be accomplished in less than 3 days. The tables can be operated fully in-phase, or in any other way to provide correlated or fully independent multiple support excitations. Additional dynamic actuators can also be added within the trench to provide additional points of static or dynamic excitations either vertically or horizontally, depending on the needs of specific experiments. The new tables will be capable of operating at up to 100 Hz, making it possible to investigate unresolved issues relating to the seismic performance of large, stiff, non-structural types of equipment. The experience of UB researchers indicates that such

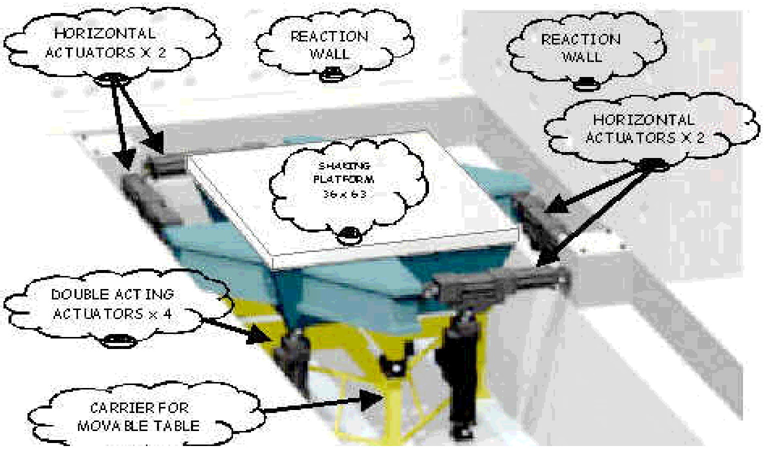

Fig. 2: Schematic of New Shake Table in Trench

performance is needed in order to generate the knowledge required for seismic qualification of equipment and systems according to emerging standard protocols. Associated controllers, an additional hydraulic power supply and distribution system, and accessories necessary to operate this equipment, are also included.

Another key element of the SEESL upgrade is the acquisition of three high-performance dynamic actuators (having ±1000 kN capacity, ±500mm stroke, 1.0 m/s max. velocity, and 800gpm servovalves), and two static ±2000 kN ±500mm stroke actuators. A flexible controller system is included with software to conduct in addition to quasi-static step-by-step testing also pseudo-dynamic testing. Source code is included such that more complex structural configurations, higher levels of sub-structuring, and other more advanced formulations of pseudo-dynamic testing can be developed and implemented. A digital control system also provide the fully flexible platform needed to develop new approaches in structural testing using real-time control, such as the RTDHT system or the effective force control technique (EFCT). High-performance hydraulic power supply and distribution system necessary to operate this equipment are also included.

The networked tele-experimentation system will use modular and expandable teleobservation and teleoperation equipment. As illustrated by Figure 3, the UB node of the NEES network is structured around an integrated system for data fusion and model adaptation that serves as the brain and gateway for teleobservation, processing, and control, and that interfaces with the advanced experimental equipment described above.

The system includes a basic computational center (knowledge accumulator) with parallel processing capabilities for real-time data processing and control. It receives data from the experiment through advanced sensors (namely digital video cameras, distance/motion detectors, and other streaming digital data to be recorded and stored), and from the remote users and operators through the tele-experimentation network interface. The system takes advantage of digital video with IP compression and transmission, to actively involve the remote users in the observation, data processing, and operation, as dictated by the needs of the experiment. Tele-experimentation equipment provides the possibilities for teleobservation, tele-guidance, teleprocessing and tele-transmission of data (Figure 3) through the general system software for real-time communication with the various components in the local experimentation network. In particular, local users (i.e. within the intranet) or remote users (in the NEES collaboratory network) can provide before or during testing basic initial reference models prepared from computer simulations. They can interact during execution of the test by issuing commands to activate system feedback, to guide sensor systems, to initiate data streaming of desired information, to access model-simulators for generation of estimated performance and feedback, and to select and direct desired information feedback. Security protocols limit access to the various control levels.

This system also requires upgrading of some of the existing digital equipment such as the advanced 196 channels data acquisition and control unit. Moreover, for the teleobservation four remotely operable digital video cameras and recorders for digital storage with data streaming and MPEG compression are planned. An additional high resolution and high speed digital video camera (KODAK-EKTAPRO or equivalent) along with a dedicated recording system for storage and compression of data is used for the development of global measurements through image processing and pattern recognition and for long term developments.

Video data processing allows real-time observation of changes of specimen envelope and permits post-experiment quantification of response. This technology exists in other fields (remote sensing, hand-writing pattern recognition, medical testing) and needs adaptation for structural engineering problems where recording of motion require much finer resolution. Additional sensors for distance measurement based on laser technology allow for remote measurements for

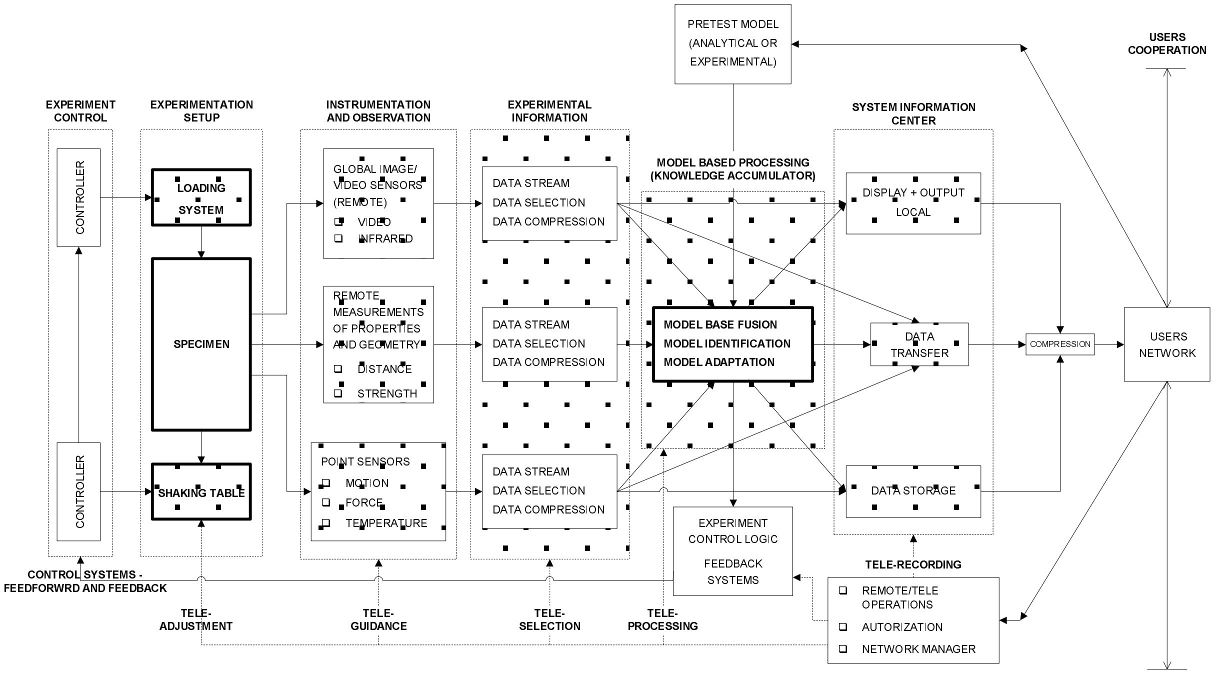

Fig.3. Functional diagram of SEESL – Model based adaptation through hybrid testing and computing (shadowed areas indicate new equipments or components)

calibration of image processing. At the same time, point sensors that include piezoelectricforce/pressure detectors, fiber optic stress bands and more conventional accelerometers, velocity, and displacement transducers, also provide for calibration of envelope image measurements. The system relies on conventional processors based on the Windows 2000/XP platform, with high bandwidth USB2.0 and FireWire (IEEE 1394), and with scalable servers that provide possibilities for growth and update. Note that purchase of all video equipment will be delayed as much as possible as it is expected that by 2004 superior HDTV equipment will be available for the same costs budgeted for the high resolution digital video equipment.

The aforementioned knowledge accumulator can also house or interface to a “model-base” developed prior to testing, and continuously refined with data and information acquired from testing. This “model-base” becomes the learning tool for all users linked through the NEES collaboratory, who can also contribute to its improvement using knowledge from past experimentation or computational efforts, or through real time parallel testing or processing anywhere on the collaboratory. It is expected that each experiment would therefore contribute to the “model-base” which then will be transformed into computational tools for the industry. Hence, platforms such as IDARC, DRAIN, 3DBASIS, stand-alone or integrated in commercial programs such as LARSA, SAP2000, ABAQUS, would become vehicles for improved modeling and overall structural evaluation [Reinhorn, 1998].

EXAMPLE OF RESEARCH PROJECT

Large cable-stayed bridges are very expensive (e.g., the new Bay Bridge East Crossing between San Francisco and Oakland will cost $1.5 billion), and there is incentive to provide experimental validation of the seismic resistance of such an investment. For example, the seismic isolation/energy dissipation system illustrated in Figure 4 has been proposed for the four cable-stayed bridges in the straits of Peloponnese in Greece, but rejected due to lack of evidence for the validity of the concept. Such experimental validation could be achieved through RTDHT using two shake tables to provide 6-dof excitation at the central pier and at the end support, thus providing experimental capabilities to model traveling wave effects (i.e. multiple support excitations). One-quarter of a bridge model would be constructed with proper dynamic characteristics. On one shake table, the seismic performance of various types of bearings could be investigated, such as types of base isolation bearings with tie-down details that could resist the uplift forces at that location. On the other shake table, particular attention would be paid to the dampers between the deck and central towers inserted to prevent pounding of the floating deck on the towers. The remaining three-quarters of the bridge would be simulated on computers, fed with data collected in real-time by sensors located on the cables and on the bridge deck. Dynamic actuators connected as shown in Figure 4 would then, using results from the analytical computations, apply the correct forces and displacements on the tower and bridge deck.

The on-line computer model in this example can also be used to model the effect of variable foundation conditions, using data from sensors and a computer model to calculate soil-structure interaction and adjust the shake tables’ signal to provide appropriate input ground motions to the specimen. Likewise, this approach could be modified to investigate the seismic behavior of such bridges having variable soil conditions at each support. Again, through teleoperation with

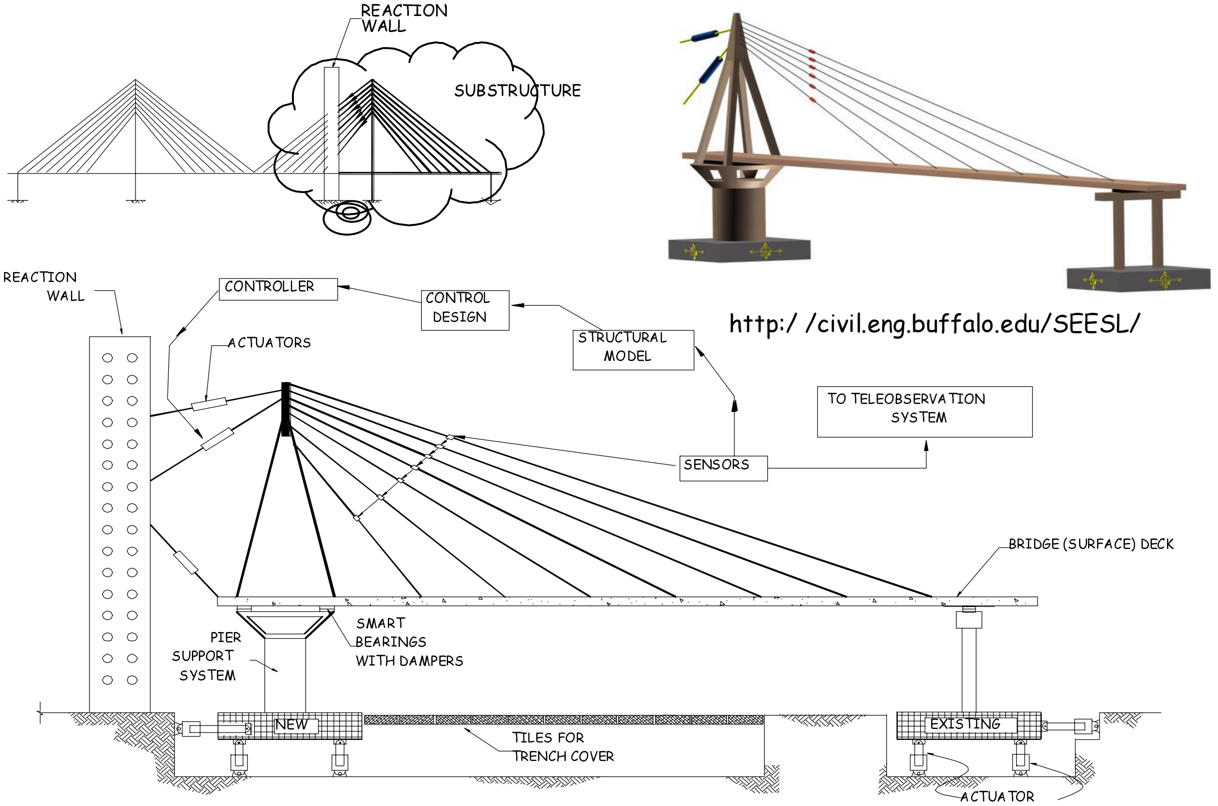

Fig.4. Cable-stayed bridge segment with RTH-STS using two shake tables, reaction walls and large-scale high performance actuators

another NEES site, this experiment could be coupled with remote large-scale tests investigating non-linear behavior of the foundations.

Although the above example illustrates how the UB-Node NEES equipment will be used to push the limits of what is currently possible in experimentation (using both tables and the dynamic actuators simultaneously, in a most complex specimen configuration), it is worthwhile to emphasize that the same equipment will also greatly enhance the existing capabilities of the SEESL, making possible many new different types of tests that cannot be described here due to space constraints.

COMMON CHALLENGES WITH OTHER NEES EQUIPMENT SITES

The greatest challenges do not lie in implementation of the interfacing technology to link the NEES nodes, but rather in the development and implementation of the advanced concepts of integrated distributed analytical and experimental capabilities. Establishment of the NEES network will resolve many access and connectivity issues and allow the earthquake engineering researchers with the appropriate expertise to focus on the development of new integrated computational, experimental, and educational platforms, equipped with visualization tools for integration and dissemination of research developments. In particular:

1. A significant outcome of the NEES collaboratory will be the integration of computational platforms developed and directly linked through the NEES network. Note that many experimentalists also have extensive analytical expertise and have successfully developed many of these relevant computational tools. This dual expertise is common, as analytical and experimental research are inseparable. The computational capabilities distributed across the NEES network could play an important role in providing part of the analytical support in RTDHT beyond the development stage. Thus NEES will not only "take" testing results, but will also "feedback" testing control capabilities for distributed RTDHT experiments, the entire network acting as a large distributed parallel computer. However, this will require significant development efforts by researchers cognizant in both experimental and analytical research.
2. It is foreseen, however, that from NEES will evolve a standard computational support framework that will make it possible for the analysts to contribute their own work without sacrificing precious time to build and maintain a program with a friendly interface. The platform may incorporate visualization features using graphical user interfaces (GUI) and virtual reality techniques, developed independently of the researcher who supplies the analysis and modeling engines.
3. It is envisioned that an expert system will be developed collectively to direct the NEES user to the appropriate type of testing or analytical platform. Similarly, it is envisioned that a *networked planning procedure* will be developed to allow for interactive pre-testing evaluation, leading to a reduction in testing time while increasing test efficiency and value of resulting data.
4. Once this is achieved, the next challenge is the use of computing in real time to interpret the information generated during dynamic testing. The challenge here lies in the integration of all components, from data collection, to data transmission, to data processing and to data visualization and animation. This challenge will be overcome when the experimentalist will be able to observe interpretation of the data simultaneously along with the test. This is analogous in concept to a computerized "radioscopy". The combination of advanced Digital Signal Processing, model-based simulation and virtual reality technologies would allow a researcher to see the interpretation along with the testing. The network system may be then used along with the real-time procedures to observe a test from a remote location, such as a classroom. Such link would provide part of the education link of the suggested network. Although this requires intense development, the benefits would be enormous.

Answering the above challenges will require resources. The UB-node of the NEES network intends to participate fully in exploring the above technologies along with the NEES collaboratory members.

CONCLUSIONS

The UB-Node of the NEES network will make possible research at a scale and complexity not possible today, and provide a platform to develop new testing capabilities that will extend the envelope of experience, validate and complement the analytical and computational design tools, and ultimately save lives, reduce property damage, and mitigate economic losses.

ACKNOWLEDGMENTS

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