A VERSATILE HIGH PERFORMANCE TESTING FACILITY TOWARDS REAL-TIME DYNAMIC HYBRID TESTING

A.M. Reinhorn[1], M. Bruneau[1], A.S. Whittaker[1], M.C. Constantinou[1],
S. Thevanayagam[1], S. Chu[2], M.C. Pitman[3], K. Winter[4]

ABSTRACT

The University at Buffalo (UB) 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 40 m (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, to include an expanded strong floor, reactions 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.

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 size specimens and entire structures might even be counter-productive, making it difficult to study localized or specific problems within the

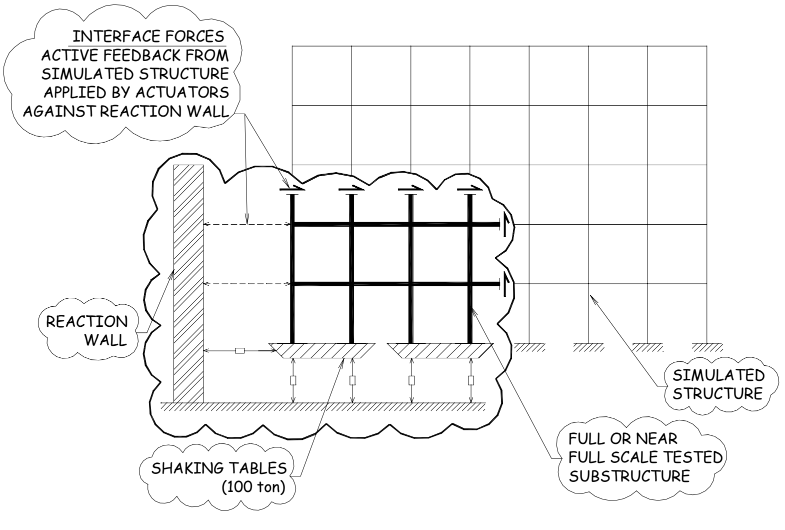

Fig.1. Real-Time Hybrid Seismic Testing System (Substructure Dynamic Testing)

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[1] Professor, [2] Postdoctoral Associate, [3] Lab Manager, [4] Project Manager, Dept. of Civil, Structural and Environmental Engineering, University at Buffalo (SUNY), Buffalo, NY 14260. *Ph: (716) 645-2114 x2400*

complex system. Powerful and damaging 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 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 whole 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 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 virtual 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 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, to tackle increasingly complex problems and accelerate 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 to allow broad inclusive cross-disciplinary and multi-disciplinary teams of researchers to collectively contribute toward the same goal.

The motivation underlying the development of the above *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 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 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.

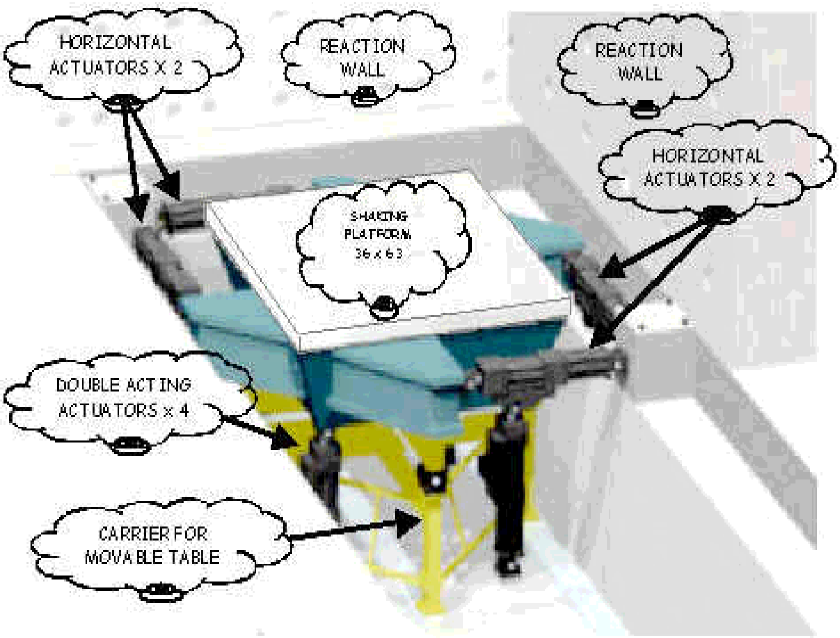

Fig. 2: Schematic of New Shake Table in Trench

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.

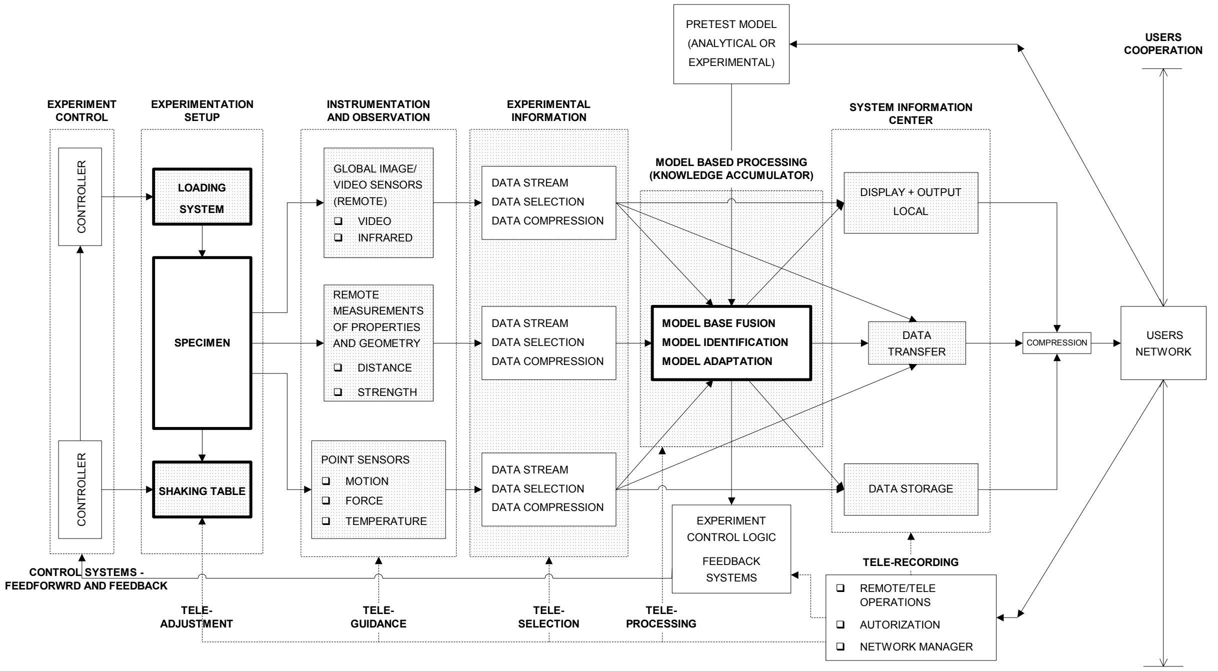

Fig.3. Functional diagram of SEESL – Model based adaptation through hybrid testing and computing (shadowed areas indicate new equipments or components)

Local Network for Testing and Analysis: 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 collection from experiments, and computational model adaptation that serves as the center and gateway for tele-observation, -processing, and -control, and interfaces with the advanced experimental equipment described in the previous appendix. The system includes a basic numerical computational center (*knowledge accumulator*) with parallel processing capabilities for real-time data processing and control. It receives data from an experiment through advanced sensors, namely digital video cameras, point and remote measuring devices, distance/motion detectors (on the left hand side of the figure), and from remote users and operators through the network interface (on the right hand side of the figure). The *integrated* system takes advantage of digital video, with compression and IP transmission, to actively involve remote users in operation, observation, and data processing. Tele-experimentation equipment (computer interfaces) enables tele-observation, tele-guidance, tele-processing and tele-transmission of data (as shown in the figure) through local software for real-time communication with the various components in the local experimentation network. In particular, local users (i.e. on the Intranet) or remote users (on NEES GRID through a NEES-POP) can provide before or during testing basic initial reference models prepared from computer simulations. Local users (i.e., within the UB Intranet) or remote users (on NEES GRID) can interact before, during and following a test. During a test, users will be able to issue commands to activate system feedback, operate sensors and transducers, stream selected data, access and operate model-based simulators to generate performance estimates and feedback. Security protocols that are being developed by the Investigators in conjunction with the NEES System Integrator will limit access to the various control levels.

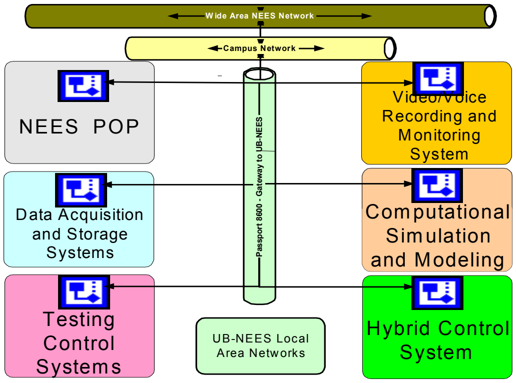

Figure 4: Block diagram of LAN and WAN connectivity

The implementation of the above concept requires the development and deployment of a local-area network (LAN) with connection to the UB wide-area network (WAN). The block diagram in Figure 4 below shows the components of the LAN. Figure 5 shows details of the subnets and components of the LAN. The LAN, which is being designed and implemented at this time as part of the NEES Phase I to UB includes five basic components (subnet) for (1) basic testing control; (2) real time simulation and control; (3) data acquisition; (4) audio/video information interface; and (5) numerical simulation. The LAN has an interface to the WAN and to the NEES GRID through a NEES-POP, which is being developed by the NEES System Integrator (SI). The network is developed locally around a Gigabit Master Switch (passport 8800 or equivalent) that can accommodate connections to the subnets with either Gigabit or 10/100 Megabit switches.

The *test control* subnet includes a layered network of computer clusters that control the individual earthquake simulators, experimentation stations (including ATTS), individual actuators and internal data transfer. The testing network has (a) an internal non-routable subnet ensuring proper interconnection of instruments, (b) direct memory network sharing (ScramNet^{TM}), and (c) an addressable subnet for running experiments. The subnet uses Windows 2000 for basic operations and security control, while some of the components are connected with proprietary operating services developed by MTS Systems Corporation and UB research staff .

The *real-time hybrid simulation and control* subnet includes a cluster of computers running Windows 2000 and real-time operating software from Matlab (Real-Time Workshop and Simulink), and stations for structural simulations, control reference generation and high-speed data acquisition. Similar to the test control subnet, the real-time hybrid subnet uses a shared memory network and an internal non-routable subnet. Remote access to this subnet will be achieved through Application Sharing (NetMeeting or equivalent).

The *data acquisition* subnet includes clusters of IP-addressable Optim/Megadac multi-channel stations (300 channels) and PC-based workstations using industry standard A/D and D/A interfaces connected directly to the data acquisition (DAC) subnet in the existing SEESL FAULTLINE domain. Data is acquired through distributed workstations, located on the laboratory floor, running Megadac/TCS proprietary software. Remote operation is achieved by a locally residing application interface (API) or by Application Sharing.

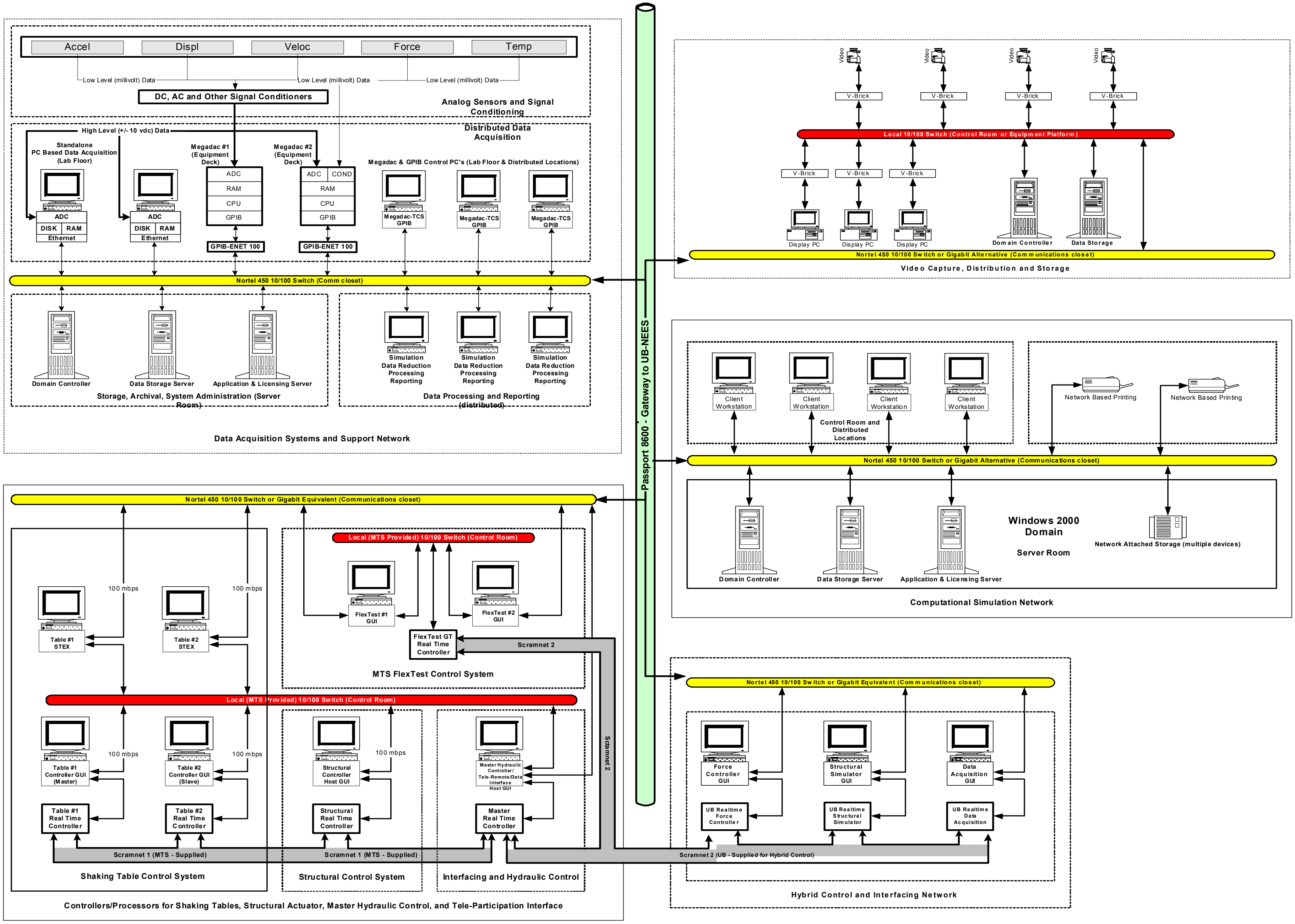

Figure 5: Local Area Network components

The latter approach is advantageous because it does not require an API or TCS license on the remote computer. Integration and remote operations of this system was successfully demonstrated to NSF in December 2001. The SEESL DAC subnet currently includes computational platforms for data interpretation, data management, analysis and control. SEESL has licenses for platforms including Labtech Notebook, DaDisp (a graphical spreadsheet), MatLab, Maple, WorkBench and several instrument-simulation programs.

The plan for the *video/audio* subnet includes four remotely operable digital video cameras and recorders for digital data storage with data streaming and MPEG compression. An additional high resolution and high speed digital video camera (Kodak-Ektapro or equivalent) with a dedicated recording system for data storage and compression will be used to develop methods for measuring displacements and deformations through image processing and pattern recognition. The subnet connects several workstations for two-way communication and one-way data streaming. The network uses industry-standard video and audio protocols that have already been implemented in a video tele-conference unit in SEESL.

Video-data processing permits real-time observation of damage and post-experiment quantification of responses. The technology exists in other fields (e.g., remote sensing, handwriting pattern recognition, medical testing) but must be adapted for structural engineering use. Displacement-measuring sensors based on laser technology will be used to investigate and then calibrate displacement estimates based on image processing. Point sensors, which include piezoelectric force/pressure detectors, fiber optic stress bands and more conventional accelerometers, velocity, and displacement transducers, will also be used to calibrate image-based measurements. The video/audio subnet uses conventional processors based on Windows 2000, with high bandwidth USB2.0 and Fire-Wire (IEEE 1394) connections, and scalable servers that provide for substantial expansion. Video-equipment purchases will be delayed as long as reasonable to ensure that the equipment is state-of-the-art in September 2004.

The *computational simulation and modeling* subnet (or *knowledge accumulator*) is a cluster of workstations running various operating systems (Windows, Unix, Linux, or Solaris) that are networked to provide the computational power required for test preparation/simulation, data interpretation, test visualization, analytical-model development, computational-platform development, and model and platform validation. Although this is the traditional computational environment at a research institution such as UB, development, visualization and simulation tools in the proposed installation will be interfaced with the experimentation subnets for integrated *model-based* research. The *model-base* is a unique model for simulation and testing that is adjusted through experimentation and the use of computational tools. The model-base is the learning tool for all users linked by the NEES Collaboratory. Users could also contribute to improving or expanding the model-base using knowledge from experimental or computational endeavors. Each new experiment will contribute information to the model-base; information that will then be transformed into computational tools for industry. Platforms such as IDARC, OpenSees, and 3D-BASIS, either as stand-alone packages or integrated into commercial programs such as LARSA, SAP2000, and ABAQUS would become vehicles for improved tools for the evaluation of structures

The interface to the UB WAN is illustrated in Figure 6. The LAN that is described above will be part of the new Ketter Hall laboratory but will be linked to the existing LAN in Ketter Hall. The current LAN is connected through Gigabit fiberoptics cables, connections and switches to the UB backbone that has OC3- (155Mb) switched connections. The new LAN will be also connected to the backbone with a clean connection. The UB backbone is connected to the

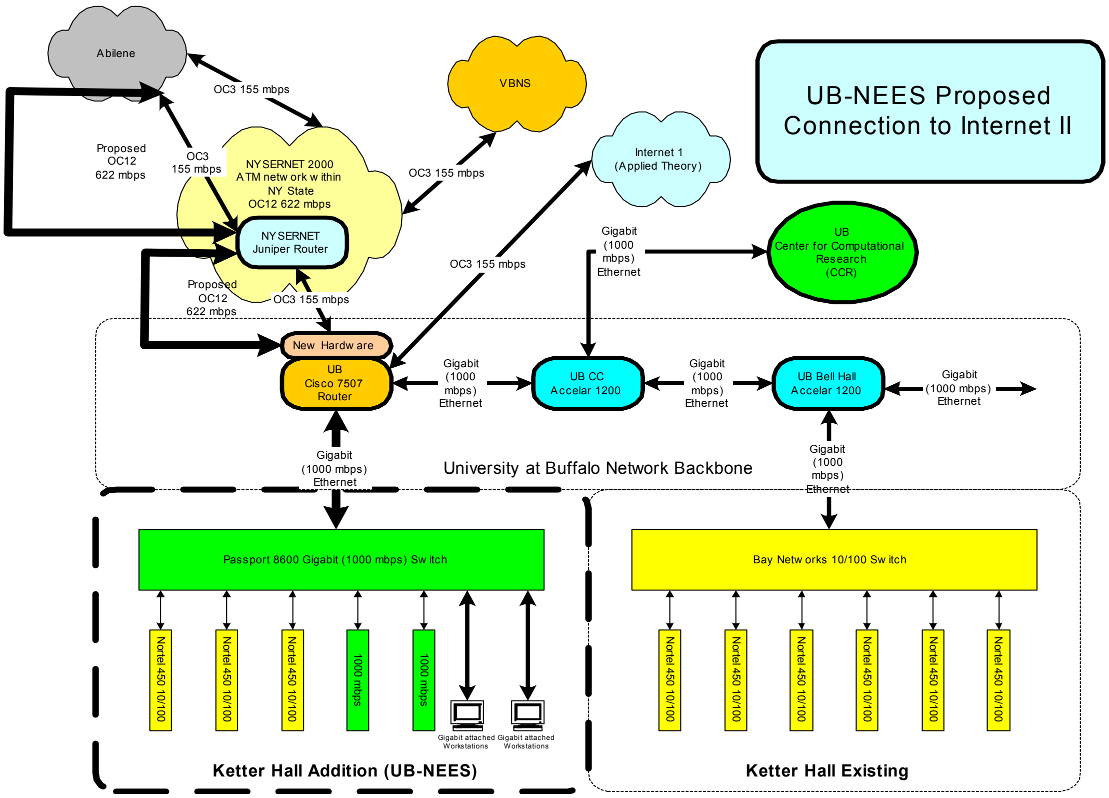

Figure 6: UB – SUNY and SEESL connectivity to the wide-band Gi-

NYSERNet system via OC3, which provides connections to wide band networks, including vBNS and Abilene. Although NYSERNet is a OC12 (622MB) system, the connections to UB and Abilene are OC3. However, UB plans to work with NYSERNet and upgrade the connections to OC12 prior to September 2004.

EXAMPLE OF RESEARCH PROJECT

This project is illustrated in Figure 7. 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 RTDHTS 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). 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

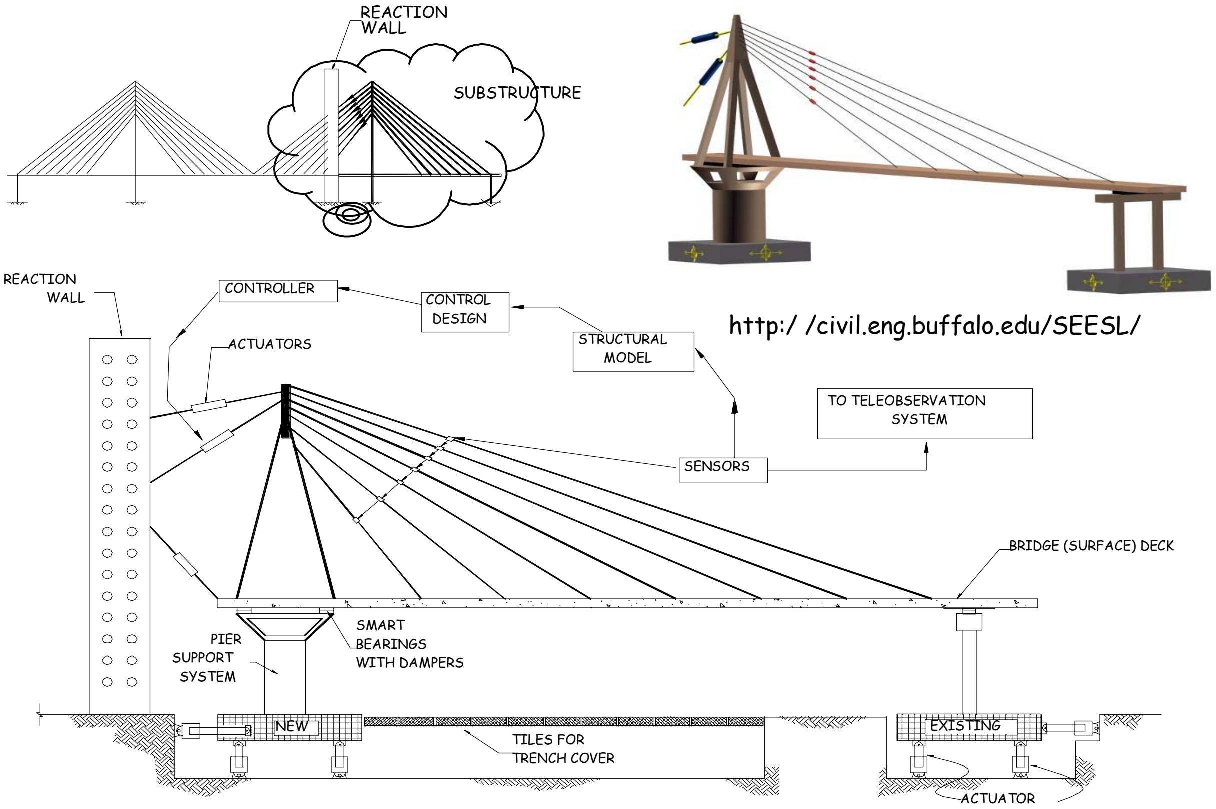

Fig. 7 - Cable stayed bridge segment with RTDHTS with two shake tables, reaction wall, actuators and controllers.-

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 strategy could be modified to investigate the seismic behavior of such bridges having variable soil conditions at each support. Again, through teleoperation with 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.

REMARKS ON FURTHER NEES DEVELOPEMNTS

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:

- 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.
- 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.
- 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.
- 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.

ACKNOWLEDGMENTS

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