

Grid Based Distributed Hybrid Testing

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Abstract

Due to a growing requirement for state-of-the-art research facilities for conducting sophisticated and large scale structural dynamic experiments, there is a paramount need to have a network for collaborative experiments and to create the computational infrastructure. United Kingdom Network for Earthquake Engineering Simulation (UK-NEES) aims to collaborate to build such a network for the United Kingdom. It will use grid technologies to enable a smooth interface with other similar network systems both in the UK and overseas, potentially allowing Oxford researchers to collaborate with other leading researchers across the world to further the understanding of seismic design through integrated experimentation, computation and simulation. This paper describes the current status and capabilities of the Oxford UK-NEES node in distributed hybrid (combined numerical and physical) testing. An architecture for carrying out distributed hybrid tests is proposed and developed and an example of this in the context of earthquake engineering is made.

1. Introduction

Earthquakes and the resulting destruction and loss of life are well documented. Major seismic events are truly tragedies affecting the community for years after an event, with significant human and economic losses hampering the physical and social infrastructure. These disasters are a global problem with the Sumatra Earthquake and Tsunami of 2004 where damages totalling \$20bn and with over 200,000 deaths a recent warning of the devastating potential of earthquakes.

Earthquake engineers study the effects of ground motion through seismic loading on structures in an effort to increase survivability and to ensure immediate occupancy post event. This is often done through computer simulations or by performing physical experiments. This paper discusses the current and ongoing development of a relatively new earthquake engineering analysis method: distributed hybrid testing.

Distributed Hybrid testing at a large-scale involves sharing of heterogeneous resources which are owned and operated by different institutions, and for collaborative experiments to

be performed successfully, a flexible integration of these resources is required. A grid based framework would suit the needs of distributed hybrid testing as it provides an infrastructure where heterogeneous resources can be integrated.

The National Science Foundation (NSF) in the United States launched a major research initiative in 1999 and established the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) [1]. The main aims of the U.S. NEES network are to provide a grid based infrastructure to provide central, unparalleled experimental facilities which can be accessible for researchers locally or remotely. The initiative potentially allows for collaboration in conducting advanced research through integrated experiments to further understanding in earthquake engineering.

The United Kingdom Network for Earthquake Engineering Simulation (UK-NEES) has been recently started, and creates an opportunity for the United Kingdom to become a leader in hybrid testing and to join in the new international collaborative effort to link research labs to allow globally distributed large scale hybrid testing. It consists of three nodes one at Bristol University, one at Cambridge University

and one at Oxford University that are currently working together to enable distributed hybrid testing to be carried out in the UK and to set up UK-NEES as part of a larger global NEES framework. Collaboration at this scale will open opportunities for UK researchers to have access to advanced research facilities which may normally not be available to their host institutions. Smaller UK centres, most of which lack experimental facilities, stand to benefit significantly from the data-sharing and tele-participation aspects of the NEES system, including the opportunity to strengthen collaborative links both within the UK and worldwide. The UK practitioner community will also have better access to UK and worldwide research.

In section 2, the necessary background to understand distributed hybrid testing and the proposed architecture that is described in section 3 is presented. Current, related and future work is discussed in sections 4, 5 and 6 respectively. Finally, the conclusions of this paper can be found in section 7.

2. Background

2.1 Distributed hybrid testing

As has been mentioned, earthquake engineering analysis is often done through numerical simulations or physical tests. While purely numerical simulations and physical tests have their benefits each has significant short falls. Numerical simulations can be difficult to perform accurately when there are poorly understood or unknown nonlinear properties which have to be modelled, while physical testing often has to be carried out at large or full scale to fully capture the dynamic response of the structure which can be quite expensive for civil engineering structures. Hybrid testing combines numerical and physical testing, in an attempt to make use of the advantages of both. In such testing the structure is split into numerical and physical parts where parts of interest can be tested physically with the rest of the structure treated numerically. A test is run through both parts simultaneously with the interaction between these parts or sub-structures controlled over the duration of a test through the use of software controllers, physical actuators and sensors. During testing, seismic loads or displacements are generally applied from the numerical model to the instrumented physical model at a regular time step and the results of these applied forces are measured and fed back to the numerical model to await processing for

the next time step. Hybrid experiments are often performed with only a single physical part tested at full or large scale, although multiple physical parts may also be tested depending on the capabilities of any one lab. In order to run these tests there are significant control issues to overcome mostly dealing with the time delays associated with the connected physical and numerical sub-structures largely, due to the use of hydraulic actuators. Hybrid tests were originally carried out pseudo-dynamically, that is with the time period of the loading 'slowed down', this is useful in some cases such as investigating crack propagation. However, with tests involving physical components whose properties are greatly time dependent, tests must be run in fast or what is termed, 'real time.' This means live testing, where the test duration is equal to the actual earthquake duration. This term is subjective, for successful tests care has to be taken that the highest natural frequency of the system is taken into account when choosing the time step for loading. Such real time hybrid testing has been developing for a number of years now [2] and recent advances allow more complicated computational models [3]. The advantage of sub-structuring in hybrid testing is that the computational and physical parts do not necessarily have to be located on the same site. The experiment may be performed across geographically distributed sites, requiring coupling of sites. This allows the potential for carrying out much larger tests than any one lab could do on its own.

2.2 Network for Earthquake Engineering Simulation (NEES)

The main objective of NEES is to develop a network of integrated and interconnected facilities to transform earthquake engineering research through collaborative experimentation, computation, databases and model-based simulation. The interconnection enables the operation of distributed experimental research equipment, including tele-observation and tele-operation, which complement and facilitate distributed testing. Figure 1 illustrates the proposed NEES connectivity with each NEES grid node providing unique experimental or simulation capability and resources to the grid.

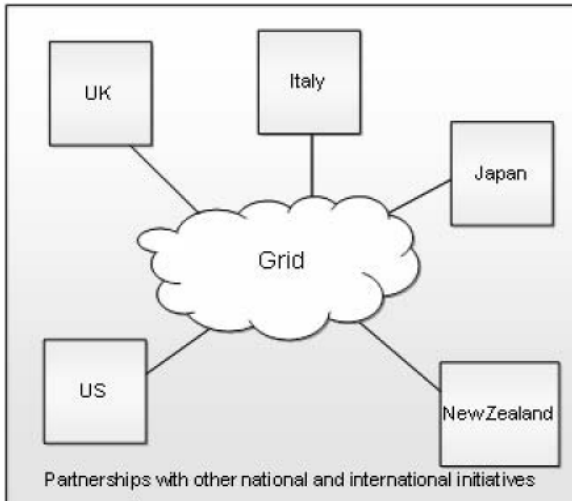


Figure 1. NEES framework

2.3 UK-NEES

The UK Network for Earthquake Engineering Simulation (UK-NEES) is initially comprised of research laboratories at Bristol, Oxford and Cambridge universities, but there is the potential for expansion to other laboratories. The fundamental aim of the UK-NEES grid node coincides with those of the U.S. NEES programme. The main objective is to make UK-NEES the primary vehicle for collaborative earthquake engineering research within and beyond United Kingdom, with active contribution from universities, research centres and from the broader engineering community. The grid node in the UK aims to provide the following functionalities which are shown in figure 2:

- *Tele-observation*: Remote viewing of the tests.
- *Tele-participation*: Remote viewing and participation in the tests.
- *Tele-operation*: Remote operation of the tests.
- *Distributed hybrid testing*: Structure is tested with components split into physical and numerical parts which are tested simultaneously in geographically distributed labs.
- *On-line data access*: On-line access to test data.

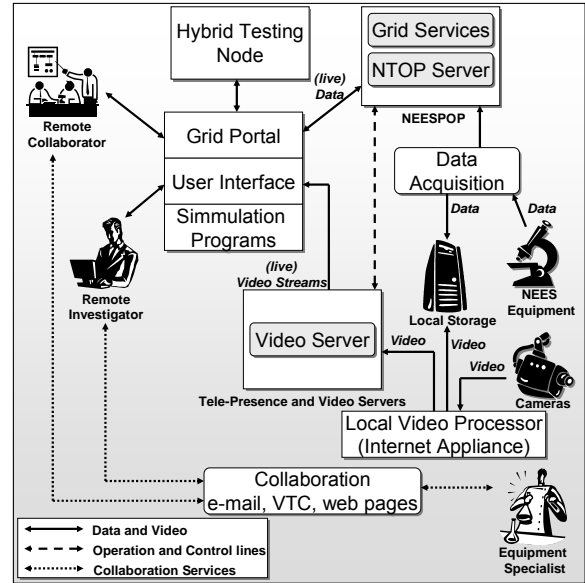


Figure 2. UK node architecture

The remote participants or investigators communicate with the equipment specialist in advance to set up the equipment with which they want to perform tests. This advance information ensures smooth running of the experiment and also allows the specialist to be available for demonstration. These are the some of the key components of the system:

- *NEES Equipment*: Test Specimen, actuators, sensors, hydraulic controls, etc.
- *Data Acquisition System (DAQ)*: Acquires data from research Equipment.
- *NEES "Point of Presence" (NEES POP)*: Provides a home for NEES grid services at the equipment site.
- *Hybrid Testing Node*: Synchronizes and runs the geographically distributed hybrid tests.

The remote user who wants to run the experiment would log on to the portal and can perform distributed hybrid tests. From the portal, users can view live streaming videos captured by network cameras using a web browser via the FlexTPS application. Users can also play back video and view data in real time using the Real-Time Data Viewer via the Data Turbine application [4]. The grid architecture will allow integration of heterogeneous hardware and software platforms and simpler extension of the grid. Improved data reliability or redundancy may also be achieved through storage of data at multiple sites.

3. Grid Architecture: hybrid testing nodes

Hybrid tests are composed of two types of component: physical and software. The physical components are situated across multiple sites as already mentioned, and a node architecture is utilised to carryout hybrid tests. This architecture is shown in figure 3. It is composed of three types of modules: the physical model nodes, the numerical model, and the communication server.

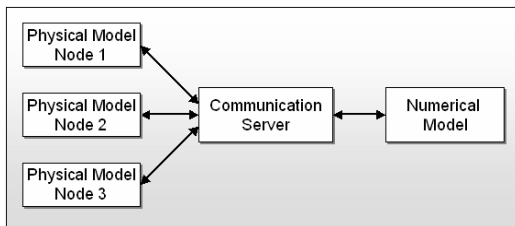


Figure 3. Distributed hybrid test architecture

3.1 Physical Model Architecture

A Physical Model Node does physical real-time tests, using actuators and real-time boards for these tests. The architecture of a physical model node is shown in figure 4.

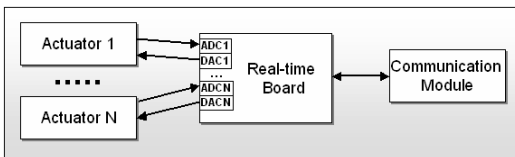


Figure 4. Physical model node architecture

- *Actuators*: Usually hydraulic devices that allow physical tests in a laboratory by allowing known loads and displacements to be applied to the physical specimen.
- *Real-time board*: Hardware component that allows data to be processed in real-time (test duration equals earthquake duration). The board has ADC (Analogue to Digital Converter) channels to receive data from the actuators, and DAC (Digital to Analogue Converter) channels to send data to the actuators.
- *Communication module*: A software component created to allow communication between the physical model nodes and the numerical model

through the communication server. This module sends data each millisecond from the ADCs to the numerical model, and the data that comes from the numerical model is sent to the DACs of the board.

3.2 Communication Server

The communication server is a software component that allows communication between the physical models and the numerical model. This is a two-way communication. On one hand, the communication server receives data from the different physical model nodes concurrently, sending them to the numerical model. On the other hand, it receives the response from the numerical model and it sends it to the physical model nodes.

3.3 Numerical Model

The numerical model executes the software simulation with the data that comes from the different physical model nodes. This model generally receives force data, processes it, and generates the displacement values that will be a feedback to the actuators.

4. Current Work

As an example a typical earthquake engineering problem is described. Shown in figure 5 is a hybrid dynamic model of a five storey, five degree of freedom steel framed building structure split into numerical and physical parts. The building is drawn in 2 dimensions however in reality it is modelled with four building columns.

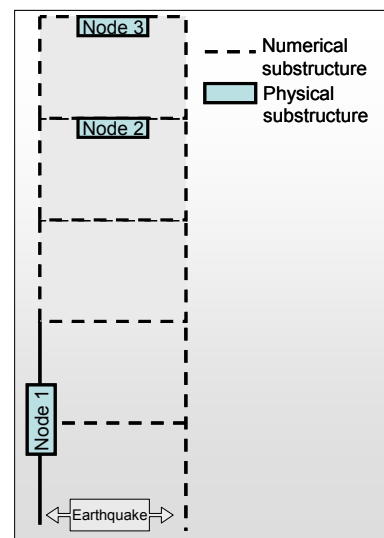


Figure 5. Structure of a 5-floor building set up for hybrid testing.

A simplified graphical representation of the test is shown in figure 6 where input forces are fed to the numerical model which in turn processes output displacements each time step and returns these to the physical parts via actuators and the physical parts return new input forces for the next time step. This is set up from a matrix equation defining the motion of the structures.

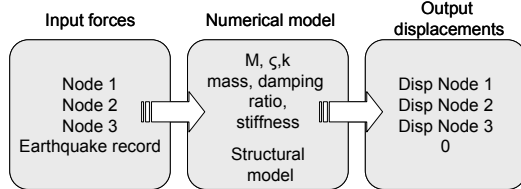


Figure 6 Graphical illustration of matrix equations.

Node 1 represents a column from the bottom 2 storeys of the building [5]. Nodes 2 and 3 represent nonlinear viscous fluid dampers. These dampers or dissipative devices are a fairly recent earthquake engineering development and are placed in buildings to absorb significant amounts of seismic energy. These devices are highly flexible and can be used in new buildings or retrofitted. Their aim is to reduce damage to buildings during an earthquake and improve chances of immediate occupancy. They are particularly utilised in public buildings such as hospitals and schools in earthquake zones.

The dampers are simulated using the following equation [6]:

$$F = c|v|^{\alpha} \text{signum}(v) \quad (1)$$

Where damper force is F , c the device damping, v the floor velocity and α is the damping exponent chosen here as 0.3. One damper is placed on floor 4 and another on floor 5. The building is at 50% scale and is excited by the El Centro NS earthquake at 100% for a 40s test.

The Oxford structural dynamics lab has developed the architecture to carry out distributed hybrid tests with several remote access points. The building hybrid test is carried out with three remote nodes, as shown in figure 7.

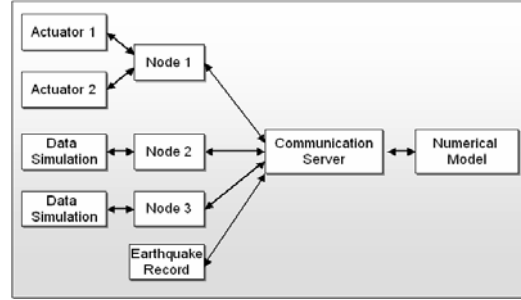


Figure 7. Hybrid Testing Architecture Developed

Each node receives the real or simulated force data every millisecond and it sends the data to the communication server. This receives all data from each node every millisecond and it sends it to the numerical model to be processed. The numerical model processes the data utilising a system of matrix equations defining the dynamic motion of the structure as has been mentioned. It accordingly, generates displacement results which are sent to the communication server. Finally, the communication server sends each node the displacement result and this is used to feedback to the actuator. This process is repeated each millisecond for the duration of the test.

Shown in figure 8 is the El Centro NS input earthquake record used to excite the building structure. Figure 9 shows the results of a simulation of the response of the fifth floor for a fifteen second period with and without the addition of dampers. It is clear that by including dampers significant reductions in interstorey drift and hence damage can be achieved.

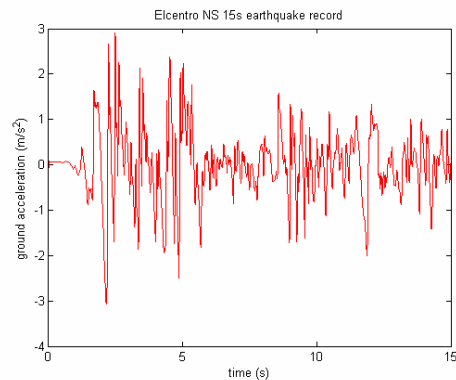


Figure 8. El Centro NS earthquake

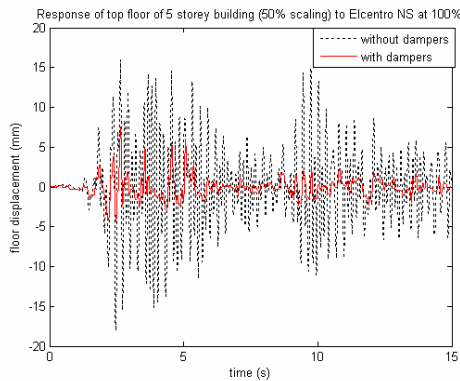


Figure 9. Response of the fifth storey with and without dampers.

5. Related Work

Grid technology enables earthquake engineering researchers to carry out distributed tests. A number of grid-related projects are currently being developed and various worldwide initiatives include:

- United States Network for Earthquake Engineering Simulation (US-NEES)* [7]: A computational infrastructure that provides the US with an integrated network for earthquake engineering research that links up the experimental facilities (shake tables, geotechnical centrifuges, and other large-scale testing equipment). They have conducted a multi-site online simulation test (MOST) [8] which combined multiple physical experiments with a numerical simulation to carry out a five hour pseudo-dynamic test in geographically distributed locations.
- The New Zealand Network for Earthquake Engineering Simulation (NZ-NEES)* [9]: This is a grid network for earthquake engineering research currently being developed in New Zealand on the lines of US-NEES. It is attempting to take advantage of the latest digital information technologies to overcome the obstacle of distance.
- Japanese Science and Technology (JST)* [10]: Joint initiatives have been agreed with US-NEES to

carryout distributed tests using the new Japanese E-defence centre.

- International Solid Earthquake Research Virtual Observatory (ISERVO)* [11, 12]: This is a research cooperation of the leading international earthquake simulation and prediction research groups including researchers based in Australia, China, Japan, and the US. ISERVO is building a grid based infrastructure for earthquake research implementing many features similar to some of the current NEES services that would potentially aid researchers to run tests and ease the use of data discovery.

6. Future Work

As the important aspect of the UK-NEES project is the development of collaboration with other sites in this country and abroad. The UK-NEES site at Oxford expects to plan a two and three sites testing programme with hybrid simulation and physical tests to be conducted at different UK-NEES nodes. The distributed hybrid tests are being developed to be migrated in an easy way to the different sites of UK-NEES.

In this way, each node as described earlier will be a remote node, and it will be working with the communication server and numerical model as shown in figure 10. Therefore, the infrastructure could be used by the different sites to carry out distributed hybrid tests.

The communication model will be improved to solve future problems of latency that will appear when it is working with a real distributed network, instead of the current local communication.

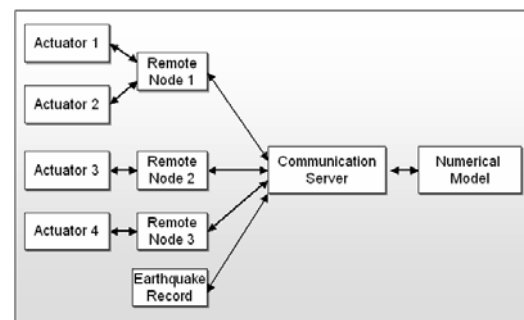


Figure 10. Distributed Hybrid Testing Architecture

7. Conclusions

A proposed distributed architecture for hybrid testing has been shown. This architecture allows expensive physical equipment located in different sites to work together to develop bigger distributed simulations, much larger than could be carried out due to cost and space limitations in any one lab. Thus, these resources can be used in a more efficient way. An example of the potential benefits of distributed hybrid testing has also been shown.

UK-NEES is the first grid network to be created in the UK to enable distributed hybrid testing. The use of grid architectures to enable connection of heterogeneous hardware platforms at different nodes and user friendly software to view and participate in testing will offer a smooth running solution for collaborative distributed testing.

The UK-NEES initiative joins together with the global initiative in forming networks for earthquake engineering research. It opens the possibility for collaborative research that can enable sharing of experimental equipment, data and knowledge. UK-NEES allows the research community to equally participate in tests in global earthquake engineering research facilities. The UK-NEES grid node at Oxford provides the architecture to develop distributed hybrid testing based on the experience it has in this area. UK-NEES will act as another tool to benefit earthquake engineering technology in a quest to relieve the devastation caused by earthquakes.

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