BLADE – BRISTOL LABORATORY FOR ADVANCED DYNAMIC ENGINEERING, DEVELOPMENT OF A NEW INTEGRATED RESEARCH FACILITY IN THE UK

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Abstract

This paper describes the development of a new integrated research facility at Bristol University. The Bristol Laboratory for Advanced Dynamic Engineering (BLADE) will provide some unique testing facilities within the UK for large scale, multi-axis, structural dynamics testing. The construction will be completed in February 2004 and it is anticipated that testing in the laboratories will commence from April 2004. A particular strength of the new facility will be the ability to develop and perform substructure testing of large systems which will be of particular benefit to the earthquake engineering community. With a strong emphasis on collaboration and international research it is hoped that in the future BLADE will play a significant role in earthquake disaster mitigation research throughout the world.

INTRODUCTION

Structural dynamics is fundamental to a vast range of engineering problems, such as the earthquake, wind and traffic response of civil engineering structures. A structure excited near resonance will always have a larger response than for a corresponding static load. It is therefore the dynamic response that governs the performance and safety of structures that are subject to significant dynamic loads. Yet despite being at the heart of these problems, structural dynamics is rarely at the heart of the design process. Instead, it is often regarded as a significant, undesirable, additional cost that must be bolted on to the end of the design process. This uninformed view misses the opportunities that proper inclusion of structural dynamics at the formative stages of a project can offer to the creative solution of the problem. For example, no amount of sophisticated computer analysis and detailed design can make significant improvements to the seismic capacity of a fundamentally badly arranged building frame. On the other hand, the application of sound structural dynamics principles at the conceptual design stage will lead to a well-configured structural frame that minimises the seismic loads applied to it and economically distributes them around itself.

The principles of elastic structural dynamics are well established, and can readily be applied to engineering problems. However, many engineering problems are concerned with controlling performance at the extremes of loading. At such extremes, non-linear structural dynamic behaviour usually dominates. Developments in the understanding of material and geometrical non-linear behaviour, and in numerical analysis, now present the engineer with opportunities to exploit non-linear structural dynamic behaviour in order to improve the dynamic performance of structures, especially at the extremes of loading. This, in turn, offers the prospect of safer, more economic and more innovative design solutions. However, unlike the elastic case, the principles of non-linear dynamics as applied to real engineering structures are still poorly understood. The combination of readily accessible powerful analytical tools and poor understanding of principles raises the real danger of inappropriate and unsafe engineering designs that attempt to exploit non-linear dynamic behaviour. This danger can only be eliminated through comprehensive, coherent theoretical and experimental research to establish principles and their sound application, accompanied by effective dissemination of the findings.

There is therefore a need to develop robust generic frameworks for non-linear structural dynamics design. The Bristol view is that a systems-orientated performance-based design philosophy provides such a framework. This philosophy recognises that all structures are complex systems of components, as well as being themselves components of a wider system. It further recognises that the performance of an individual component is not only due to its own intrinsic characteristics, but is also due to the way it interacts with the components it is connected to. This interaction may change the component's intrinsic behaviour as well as the demands, or loads, to which it is subjected. Proper understanding of these interactions is the key to successful dynamic design.

The development and implementation of such understanding relies on analysis and experiment. The relative economy and flexibility of modern numerical analysis means that it now dominates engineering design, relative to experimental observations. Many engineering industries have effectively set goals to eliminate - or at least minimise - physical testing from the design process. In earthquake engineering, which is dominated by civil engineering structures that are generally impractical to test in their entirety, it has long been common practice for structures, such as building frames, to be designed entirely by analysis. The provenance of these analytical procedures lies in reliable generic experimental research. Sadly, the succession of damaging earthquakes around the world shows graphically the limitations of this provenance, and the urgent need for more penetrative analytical and experimental research to improve it. The BLADE concept therefore aims to shift the emphasis of the structural engineering community back to investigations based on integrated experimentation, models, databases, and model-based computer simulation.

THE CONCEPT FOR BLADE

The Bristol Laboratory for Advanced Dynamic Engineering (BLADE) will be a unique, cross-disciplinary laboratory for large scale, multi-axis, structural dynamics experiments. By creating a novel, integrated research infrastructure for non-linear dynamics testing, BLADE will build on the many established international strengths of the Faculty of Engineering, and underpin its goal of enhancing the performance of all engineering systems.

At the heart of BLADE is the implementation of real-time, non-linear dynamic sub-structure test control techniques that have been developed, for example, around the EPSRC Earthquake Simulator through cross-disciplinary collaboration in the Faculty. These techniques have wide application in material specimen and structural component testing, and offer unprecedented control over the accuracy and realism of physical structural dynamics testing. BLADE will support a broad programme of research that aims to develop a unique, integrated, systems-orientated performance-based approach to structural dynamics design. It is hoped that BLADE will become an acknowledged world-leading facility for cross-disciplinary, non-linear structural dynamics research.

Fig. 1: Artists Impressions inside the two new test halls, Structural Dynamics (left) and Earthquake and Large Structures - EQUALS (right)

BLADE involves the reconfiguring and refurbishment of the Faculty of Engineering's Queen's Building, which dates from 1951, but was designed in the 1930's. In addition two new state-of-the-art 4-storey test halls are being built at the ends of the main building. One test hall, called the Structural Dynamics Laboratory (left Fig. 1), accommodates an adaptable structural dynamics test facility orientated towards smaller to medium sized testing of components ranging from aircraft wing boxes to automotive 'bodies-in-white'. The second test hall (EQUALS) is equipped with a strong floor and reaction walls for general dynamic testing of large structures, for example a typical structural frames. This second hall (right Fig. 1) also includes the Earthquake Engineering Laboratory, into which the EPSRC Earthquake Simulator (shaking table) will be relocated from its current position. Between the two test halls, reflecting its central unifying role, is the new Advanced Control and Test Laboratory (ActLab). This will supply the advanced experimental control techniques to be employed in the two test halls. Encompassing all these laboratories is the refurbished and reorganised Materials Test Laboratories (Fig. 2). The overall reorganisation integrates the current separate laboratories of the Aerospace, Civil and Mechanical Engineering departments in keeping with the growing integration of their research activities in the materials, control and structural dynamics fields. It also rationalises the supporting workshop facilities, and creates new space to accommodate cross-disciplinary research staff.

Central to the BLADE concept is the ability to test large and prototype scale components under loads that accurately simulate the in-service conditions that arise from the complete system performance. This requires the advancement and integration of the states-of-the-art in materials, component and structural assemblage testing. Using Bristol's world-class research in the adaptive control of dynamic sub-structuring experiments, BLADE will enable real engineering components, ranging, for example, from large sections of bridges, buildings, aircraft fuselages and wings, through to complete helicopter rotor assemblies, small electro-mechanical devices and material specimens, to be subjected to accurate laboratory representations of in-service dynamic loads. In essence, BLADE will be an extensive, integrated, adaptable tool-kit that the researcher can apply imaginatively to solve non-linear dynamics problems.

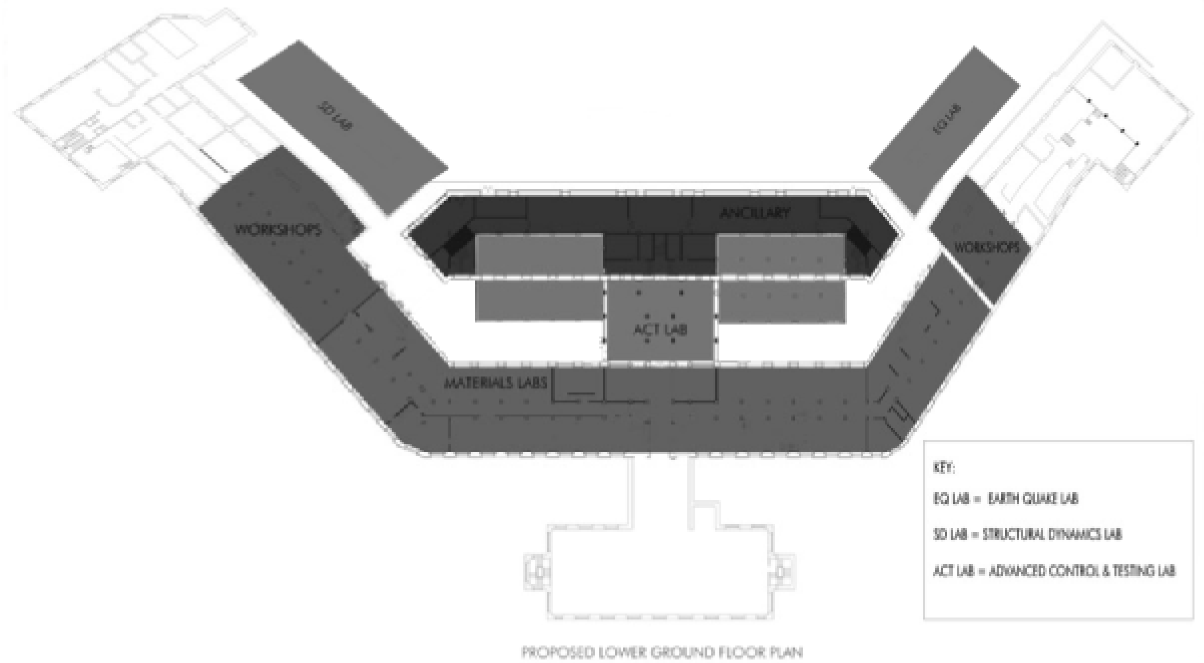

Fig. 2: Plan of the Faculty of Engineering showing the integration between the new facilities

EARTHQUAKE ENGINEERING AT BRISTOL

Earthquake Engineering has been a central research theme in the Department of Civil Engineering since 1958. Current research topics include the dynamic and seismic response of cable-stayed bridges, un-reinforced masonry, direct foundations, gravity and reinforced earth retaining walls, concrete gravity dams, dynamic model updating, experimental sub-structuring, computer vision based displacement measurements, condition and material modelling, monitoring and asset management. Underpinning all of this is the application of the principles of non-linear dynamics and chaos to the modelling of the dynamic performance of systems. The Earthquake Engineering Research Centre (EERC), formed in 1988 to promote non-disciplinary research in the Engineering Faculty, now fosters the research of many academic staff from across the Faculty of Engineering. It also has a University-owned company, BEELAB Ltd., which carries out applied research for industry.

The EERC houses the 15t capacity, six degree of freedom, Engineering and Physical Sciences Research Council (EPSRC) Earthquake Simulator (or shaking table). Opened in 1987 at a cost of nearly £1m, having been designed largely in-house, this national facility is now recognised worldwide. The shaking table expertise of the EERC has led it to become the co-ordinator of the other major European shaking table laboratories, in Italy, France, Greece and Portugal, through the EU funded European Consortium of Earthquake Shaking Tables (ECOEST) projects. In the current FP5 programme, this co-ordinating role has been extended to include other dynamics laboratories under the ECOLEADER project and the CASCADE infrastructure co-operation network, through which Bristol has helped to co-coordinate the EU's earthquake engineering research programme. More than 40 European researchers have worked at Bristol under previous EU programmes and under the current

ECOLEADER and Marie Curie Training Site programmes, a further 30 researchers are working on earthquake engineering research at Bristol.

The EERC's research philosophy is to integrate theoretical studies with laboratory experiments and observations of prototype behaviour. The three-pronged approach leads to a more balanced view of problems and ultimately to more reliable methods of analysis and design. The effectiveness of this philosophy is demonstrated by the many international projects with which the EERC has been involved. These include design studies of the 3km span Straits of Messina suspension bridge between Italy and Sicily, the design of the 120m high Victoria arch dam in Sri Lanka, seismic assessments of 12 major dams in the UK and abroad, prototype monitoring of the Second Severn Crossing cable-stayed bridge, and the development of seismic assessment methodologies for un-reinforced masonry, on behalf of the UK nuclear industry, and for dams and appurtenant works for owners in the UK.

BLADE FACILITIES FOR EARTHQUAKE ENGINEERING

The old Earthquake Engineering Laboratory afforded a very cramped site for the EPSRC Earthquake Simulator, which had limited headroom (4.5m), and only 5t overhead crane capacity. The limited space and access restricted the full utilisation of the simulator. The new Earthquake and Large Structures (EQUALS) laboratory, where the shaking table will be relocated, has 15m headroom and 20t of overhead craneage as well as plenty of adjacent space for construction of test specimens. In addition to moving the shaking table, it will be upgraded by the addition of extra servo-valves and hydraulic pump capacity to increase the platform velocity to 1.2m/s, and by the replacement of the swivels at the ends of each actuator to reduce backlash. Various control instruments and associated digital hardware in the main control panel will be upgraded to improve signal fidelity. The simulator will be adjacent to the new strong floor and reaction walls. It is worth noting that the reaction walls in the new EQUALS laboratory are somewhat unusual as they also form the walls of the new building. This has resulted in reaction walls that are 15 m high without the loss of any space within the laboratory. The use of the walls of the building has also allowed the incorporation of a 15m reaction corner, for biaxial testing, and opposing 15m walls, for testing structures such as suspension bridges, in the laboratory. The reaction walls have been designed such that a loading pattern of four 100 tonne point loads space evenly up any wall will result in deflections of less than 1mm. The reaction walls will provide an essential complementary facility for cyclic and dynamic testing of large frames and structures using new dynamic sub-structuring systems. A portfolio of 30 dynamic actuators with capacities of up to 1000kN will be available to load, for example, a full-scale multi-storey building mounted on the strong floor.

In addition to the new shaking table and reaction wall facility in the EQUALS laboratory, the BLADE philosophy of integrating all aspects of dynamics research will greatly enhance the existing capabilities of Bristol in the field of Earthquake Engineering. The positioning of the central Advanced Control and Test Laboratory (ActLab) is such that it has open access to the neighbouring engineering laboratories housing the shaking table, reaction wall, structural dynamics and materials test facilities. There is also provision within the ActLab for large-scale modular servo-hydraulic and ac/dc electro-dynamic research equipment, including a fixed/variable displacement twin pump-set, control hardware, reaction frames and cuboids, transducers and data acquisition/test hardware for the development of new control technologies. This will create an environment where important research results in control and engineering testing methodology that are being developed continuously can readily be implemented in the full-size test rigs in the EQUALS laboratory.

One example of the benefits of this integration of research areas has been the incorporation of minimal control synthesis (MCS) algorithm in the EPSRC Earthquake Simulator. MCS allows adaptive real-time control of dynamic test machines, including the capability of dynamic sub-structuring. Shaking tables have inherent dynamic problems that MCS was designed to cope with, e.g. unknown time varying parameters, non-linearities and multi-axis coupling. The impact of this research on the more general concepts of advanced engineering test facilities and methods has been enormous, and has opened up many new possibilities for enhanced testing techniques in the future. Under BLADE, the MCS control is being applied to all the dynamic experimental rigs, including existing rigs for which a retrofitting procedure has already been developed and proven. Currently we are looking to extend the existing capabilities of MCS by bringing together the non-linear passivity analysis of MCS, model reduction methods, real-time FE computation and non-linear materials testing methodology in dynamic sub-structuring. We have already developed demonstration examples of the MCS sub-structuring method, whereby a complete (emulated) system is decomposed into a real-time numerical model and a physical (substructure) experiment.

The Material Test Laboratory and the Structural Dynamics Laboratory are being set-up to allow multi-axial testing on materials such as soils or small components such as friction dampers. The equipment being installed in the laboratories will allow the specimens to be subjected to conditions similar to those seen in service, in order to develop accurate constitutive models for implementation in numerical models of complete systems. Another role of the Structural Dynamics Laboratory will be to marry together the adaptive control techniques from ActLab with the material constraints and specifications from the Materials Testing Laboratory. The outcome will be predictive tools that specify the boundaries of performance for substructure models. The benefit for the earthquake engineering research community will be the development of methods allowing an overall reduction in time – and hence cost – of experimental testing.

CONSTRUCTION OF THE NEW FACILITIES

The BLADE construction work essential involves the reconfiguring and refurbishment of the basement of the main Faculty of Engineering building as well at two new builds. The work programme started, in July 2002, with the decanting of most of the teaching and research laboratories from their existing basement locations into temporary locations on other floors in the building. To create space for this move all non-laboratory based teaching was moved into another building for the duration of the build. Once this relocation was completed, demolition of the existing infrastructure in the basement and enabling works for the two new builds started.

Of the two new buildings the EQUALS laboratory is the most unusual. The desire to incorporate 15m reaction walls and a deep pit for the relocated shaking table meant that the site of the building had to be excavated down to bedrock before construction started (left Fig 3). This then allowed the creation of a large test hall without increasing the overall height of the structure relative to the surrounding buildings. The building itself is a steel framed structure with composite floors and composite walls. The steel frame before concreting started can be seen in Fig. 3 (right). This frame is now largely hidden within the composite concrete walls that form the reaction walls for the test hall.

Fig. 3: The excavation for the new EQUALS laboratory (left) and the steel frame (right).

In order to make the 15m reaction walls as stiff as possible extra steelwork comprising 1m deep beams at 1m centres (left Fig 5) has been cast within the concrete walls. The concrete of the reaction walls is cast integrally with the 2m thick strong floor in the laboratory (Fig. 4) and the tops of the reaction walls are connected to each other via another composite slab. This means that the end of the building with the high reaction walls essentially forms five sides of a cube creating a very stiff structure without the need to resort to very thick concrete walls.

The shaking table has been positioned towards one end of the laboratory away from the 15m reaction walls but it is still surrounded by 5m reaction walls to allow simultaneous loading of a specimen on the shaking table specimen by actuators on the reaction walls. The 300t reaction block for the table can be seen right Fig. 5

Fig. 4: Reinforcement in the 2m thick strong floor showing details around the floor ducts.

The structure for the EQUALS laboratory was completed in September 2003 and the services, hydraulic supplies, air conditioning etc. are currently being installed. The upgraded shaking table will be moved to the new laboratory in February 2004.

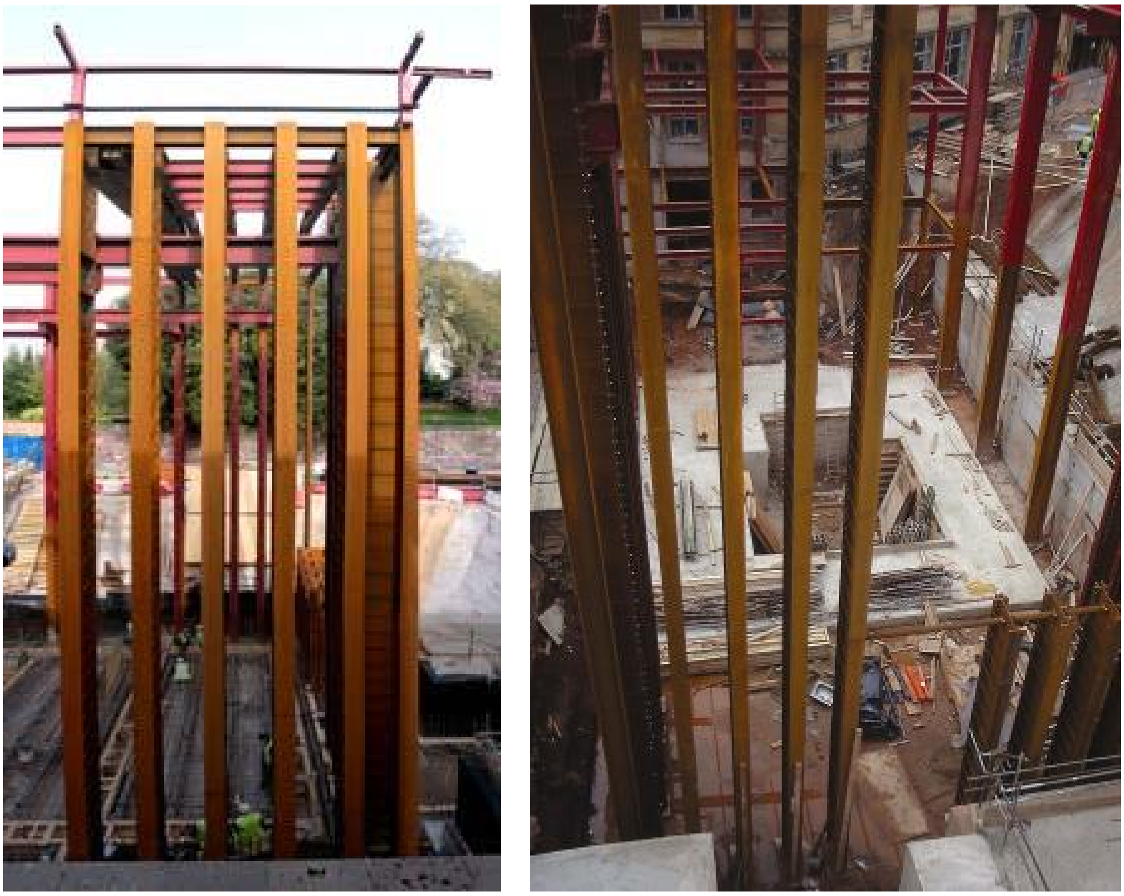

Fig. 5: Reaction wall steelwork before concreting (left) and shaking table reaction block (right).

The other new building, the Structural Dynamics laboratory, is a more conventional structure with a test hall surrounded by research offices. This building incorporates several modular test rigs for applying both static and dynamic loading to specimens across a very broad range of frequencies covering the lower seismic frequencies and higher mechanical fatigue ranges.

The BLADE construction will be completed in February 2004. This will be followed by installation and commissioning of new equipment and it is anticipated that test programmes using the new facilities will commence from April 2004.

EARTHQUAKE ENGINEERING RESEARCH PROGRAMME

Several new research projects have already started that will utilize the new test facilities and make use of the recent developments in substructuring techniques at Bristol.

Currently performance-based design concepts in earthquake engineering are being developed through the vehicle of reinforced concrete reservoir intake towers. These are, typically, hollow circular or rectangular towers, and stand in the reservoir to control the outlet of water to pipelines or hydroelectric power stations. Intake towers play a vital role in dam safety, since loss of control of the reservoir can lead to dam break and torrential flooding downstream. However, intake towers are relatively simple cantilevered structures, and lend themselves to the development of basic techniques. Non-linear behaviour occurs through cracking of the reinforced concrete in flexure, or sometimes by rocking of the tower on its foundation. A single degree of freedom model, having an assumed lateral displacement profile, can represent the dynamic response of an intake tower. The onset of cracking is controlled by the curvature strain, which is related to the assumed lateral displacement profile. Thus, by controlling the lateral displacement, the engineer can control the onset of collapse. This displacement-based design is a special case of the general systems-orientated performance-based design techniques that Bristol is trying to develop. Displacement-based design offers improved performance over conventional strength based design, since it looks at the complete behaviour of the structure, rather than just local effects.

The ultimate performance of an intake tower, or any civil engineering structure, is when it collapses. In reaching this point, the structure will have exhibited a non-linear force-deflection curve, which can be expressed, instead, as a non-linear potential well. Considerable research has been published on the problem of the dynamic escape from a non-linear potential well. The collapse condition represents the escape from the well. Of principal interest to this current research is the characterisation of the non-linear dynamic response up to collapse of a tower to a random transient load. The solution to this problem requires a strong input from the applied non-linear mathematics group and is an example of the way in which Bristol aims to engender a more collaborative approach to dynamics research. Validation of the method being developed will involve cyclic load tests of large scale models, using the newly developed dynamic sub-structuring facility to include foundation-structure interaction effects, and dynamic shaking table tests.

Another research project that will be exploiting the facilities in BLADE is a project looking at the problem of multiple support excitation of long span bridges. This project is using the latest real-time adaptive control techniques developed at Bristol to perform studies of long span cable stay bridges and long span irregular bridges. The dynamics of these types of bridges are significantly non-linear and this project aims to verify existing analysis and existing design methodologies against high quality experimental work. It is also hoped that we can develop new techniques that can simply assess the performance of these types of structures. Tests of various bridge models will be performed first on the shaking table to assess the synchronous behaviour of the bridges then a set of up to 6 actuators will be used to subject the bridge supports to different input motions. The particular difficulty with this type of testing is the significant interaction that can occur between the test specimen and the actuators typing to load the specimen. By using adaptive control techniques it is possible to adjust the control of each actuator so that it follows a prescribed motion regardless of the resistance of the specimen to the loading. This is essential when the dynamics of the specimen can change during the test.

An extension of this type of testing is the development of substructure testing which in ongoing at Bristol. Currently this research is being developed in a joint project between Oxford University and Bristol University as well as in several laboratories throughout Europe as part of on EU research programme. In essence sub-structuring will enable key parts of a structure to be modelled experimentally, whilst the remainder is modelled numerically. A key element of the sub-structuring technique is the link between the numerical and experimental parts. In Bristol we are using the MCS adaptive control algorithm to create this link because the nature of the MCS model reference is particularly suitable for sub-structuring. The initial large-scale experiments carried out on the shaking table have been very encouraging. In these tests the behavior of a series of simple systems has been successfully reproduced using the numerical-experimental sub-structuring technique in conjunction with MCS control.

Current plans to build and test a cantilever cable stayed bridge in the new EQUALS laboratory to study cable-deck interaction will give us an opportunity to test our substructuring techniques on a large scale model. In this case we hope to create a second physical model of the bridge cables but replace the bridge deck with a numerical model coupled to actuators that will excite the ends of the cables. By having two global models of the same structure, one being a complete physical model and the other with just the cables modelled physically, it will be possible to compare the various substructuring techniques being developed.

Because much of the research at Bristol is now multidisciplinary and often performed in collaboration with other laboratories both in the UK and Europe we are planning to install a grid access point within the BLADE site. This will allow the development of teleobservation and teleoperation facilities for all the laboratories which will help to engender even more cooperation between research laboratories worldwide.

The BLADE development is opening up many new areas of Earthquake Engineering research and testing and with our continuing participation in the latest EU FP6 research framework we hope that researchers from throughout Europe and further afield will soon benefit from the BLADE research facilities at Bristol.

CONCLUSION

The Bristol Laboratory for Advanced Dynamic Engineering is the natural progression of the ongoing integration of the proven engineering dynamics research at the University of Bristol. Bristol's long-term objective is to ensure world-wide recognition of BLADE as a leading centre of excellence for expertise that spans the fundamental theories of non-linear dynamics and automatic control, structural dynamics, servo-hydraulic control, ac/dc machine control, shaking table testing, reaction wall testing, materials testing, real-time sub-structuring and parameter identification. In doing so, we hope to create a resource that will play a significant role in earthquake disaster mitigation research throughout the world.

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