Durability and Intelligence of Civil Engineering Structures

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Abstract

Basic research in durability, smart materials and intelligent structural systems as well as their development have demonstrated great potential for enhancing the functionality, serviceability and life-cycle performance of civil infrastructure systems and as a result, offer the potential for significant contributions to the improvement of productivity, efficiency and quality of life. The intelligent design/construction of new structures and the renewal of aging and deteriorating civil infrastructure systems include efficient and innovative use of high performance sensors, actuators, materials, and structural systems. In this paper some examples of National Science Foundation (NSF) funded projects and research needs as well as some initiatives are presented.

Introduction

Recently NSF launched a collaborative research initiative on the long-term durability of materials, machines and structures (Chong, et al, 1998). The focus is on innovative accelerated tests and modeling of deterioration behavior, which will enable reliable prediction of long-term performance from short-term tests. A goal of the initiative is to provide close links between basic research and engineering applications in the field of deterioration science by coordinating research efforts and combining resources from a number of agencies.

This initiative is aimed at developing innovative short-term laboratory or in-situ tests, which allow accurate, reliable prediction of long-term performance of materials, machines and structures. To accomplish this goal it is necessary to better understand the fundamental nature of the deterioration and damage processes in materials and to develop innovative ways to model the behavior of these processes as they affect the life and long-term performance of components, machines and structures. Size effects in scaling up from laboratory specimens to actual structures need to be addressed. Accelerated testing and durability modeling techniques developed will need to be validated by comparing their results with performance under actual operating conditions. The results of the initiative will lead to improved durability, life cycle performance, safety, reduced maintenance and lower cost which in turn should lead to superior structures.

On the other hand, researchers from diverse disciplines have been drawn into vigorous efforts to develop smart or intelligent structures that can monitor their own condition, detect impending failure, control or heal damage, and adapt to changing environments. The potential applications of such smart materials/systems are abundant -- ranging from design of smart aircraft skin embedded with fiber optic sensors to detect structural flaws; bridges with both sensor and actuating elements to counter violent vibrations; flying MEMS with remote control for surveying and rescue missions; and stealth submarine vehicles with swimming muscles made of special polymers. Such a multidisciplinary civil infrastructure systems research front [NSF 93-5, 1993], represented by material scientists, physicists, chemists, biologists, and engineers of diverse fields--mechanical, electrical, civil, control, computer, aeronautical, etc.--has collectively created a new entity at the interface of these individual research elements. Smart structures/materials are generally created through synthesis; by not only combining sensors, processing, and actuators but through their integration with conventional structural materials such as steel, concrete, or composites. Some of the structures and materials currently being researched or that are in use (as summarized in Chong *et al.*, 1994; Liu *et al.*, 1994) include:

- piezoelectric composites, which convert electric current to (or from) mechanical forces;
- shape memory alloys, which can generate force through changing the temperature across a transition state;
- electro-rheological (ER) and magneto-rheological (MR) fluids, which can change from liquid to solid (or the reverse) in an electric and magnetic field respectively, altering basic material properties dramatically.

Current research activities aim at understanding, synthesizing, and processing material systems which behave like biological systems (Rogers and Rogers, 1992). Smart structures/materials basically possess their own sensors (nervous system), processor (brain system), and actuators (muscular systems)--thus mimicking biological systems. Sensors used in smart structures/materials include optical fibers, corrosion sensors, and other environmental sensors and sensing particles [e.g. smart dust]. Examples of actuators include shape memory alloys that would return to a desired shape when heated, electro- and magneto-rheologic hydraulic systems, and piezoelectric, ferroelectric and magnetostrictive composites. The processor or control aspects of smart structures/materials are based on microchip, computer software and hardware systems, and increasing real time mechatronic-like control implementation becomes transparent to the user of the smart structural system.

In a bigger framework, the Civil Infrastructure Systems (CIS) initiative (Chong and Liu, 1993) call for efforts in:

- deterioration science
- assessment technologies
- renewal engineering
- institutional effectiveness and productivity at the system level.

These are in addition to the implied needs (Chong, et al, 1994) in:

- Reliable accelerated tests for long term durability behavior
- improved computers, microprocessors and the information highway
- more accurate/complete modeling of lifetime predictions
- new sensors and control systems; NDT; new materials
- electro - rheological fluids.....shape memory alloys, etc.
- understanding corrosion better at the detail level life-cycle performance and costs.

Traditionally engineers and material scientists have been involved extensively with the characterization of materials. Within the past decade, technological advances in the understanding of materials have lead to the advent of many so-called smart materials. For example, at the nanoscale, material scientists have demonstrated the ability to design entirely new materials molecule by molecule. The impact of this ability to tailor and optimize material attributes is increasingly being realized in structural systems. With the availability of advanced computing capabilities and new developments in the material sciences, researchers can now characterize processes, design, model, and manufacture materials with desirable performance and properties. In particular, new applications for shape memory materials, electro- and magneto-rheologic fluids, piezoelectrics, ferroelectrics, magnetostrictives, and electro-active polymers are being realized. One of the challenges is to model short term micro-scale material behavior through the meso-scale and macro-scale behavior into long term structural system performance (Fig. 1). Supercomputers and/or workstations used in parallel are useful tools to solve this scaling problem by allowing the development of models that take into account the large number of variables and unknowns needed to project micro-behavior into infrastructure systems performance.

Materials		Structures		Infrastructure
Nano/micro-level	*meso-level*		*macro-level*	*systems integration level*
Molecular scale	**Microns**		**Meters**	**Up to km scale**
~micro-mechanics	~meso-mechanics		~beams	~bridge systems
~nanotechnology	~interfacial		~columns	~lifelines, machines
smart materials		*smart structures*		*smart systems*

Fig. 1. Scales in Materials and Structures [from Boresi and Chong, 2000; Chong and Davis, 2000]

Similarly, the "astonishing" increases in the speed and data handling capacities of computational hardware realized in the past two decades offer vast extensions to the tools available to the structural engineer. For example, moving to the systems integration level, in the 1980's and early '90's The Boeing Company implemented the ability to assemble their 777 aircraft computationally, through the use of computer aided design and manufacture. This allowed them to go straight to build without the need for costly intermediate-stage mock-up fabrication and assembly, with the accompanying tremendous cost savings on re-engineering of parts associated with unanticipated interference and the accompanying favorable impact on rollout timeline. The opportunities growth in the use of the power of improved computation capabilities for simulation and for real time modeling and control in what is being recognized as the information technology is just starting to be realized. A model-based simulation initiative (NSF 00-26, 2000) has been launched by NSF this year.

At the micro-level, research to address the need for accelerated tests [Chong and Larsen-Basse, 1998] to simulate various environmental forces and impacts has been greatly advanced with computational models that aid in the extrapolation of short term test results into long term lifecycle behavior. A joint NSF-Sandia National Laboratory initiative on model based simulation and life cycle engineering [NSF 00-31, 2000; also in www.nsf.gov] offers support to researchers who are developing new computational tools in support of bridging these material and structural systems scales. Additional NSF engineering initiatives in this area include NSF 00-36, 2000 on Nanoscale Modeling and Simulation and NSF 00-31, 2000 which offers smaller grants (up to 18 months of support) for Exploratory Research on Model-Based Simulation.

Durability And Accelerated Tests

The initiative aims to support fundamental research by individual investigators and small groups on new concepts and methods for accurately assessing the durability of materials, machines and structures, with an emphasis on high-risk/high-payoff research. The nation's annual expenditures to replace deteriorated equipment, machines, and components of the infrastructure are enormous. Most machines, structures and facilities deteriorate over a period of years or decades and eventually wear out, break down, or become unproductive or unsafe. Understanding when to replace them or how to prolong their useful lifetime is becoming increasingly important. In some cases, a whole unit or system must be replaced when a single critical component fails. Once it becomes possible to accurately predict, measure, and control the rate of deterioration it becomes possible to closely determine the life-cycle of these critical components. That, in turn, makes it feasible to develop design methodology and/or inspection, monitoring, and replacement strategies, which allow significant extension of the life of the complete system, thus resulting in significant savings to society. Progress has already been made in several areas. For example, in the case of metallic creep, we have time-temperature correlation parameters that permit results of short duration tests at elevated temperatures to be used reliably to predict long term behavior at lower temperatures.

Much of the deterioration of concern here is due to environmental effects and/or exposure to loads, speeds and other operating conditions that are not fully anticipated in the original design. There are many forms of deterioration to consider, such as fatigue, overload, and ultraviolet damage for composites, corrosion, and wear. The loss due to corrosion alone amounts to $100 billions per year in the U. S. Materials of interest in this initiative include the full spectrum of construction materials, metals, ceramics, polymers, composites, and coatings. Application areas include, but are not limited to, units of the constructed infrastructure such as structures (above and below ground), transportation systems and units, and manufacturing machinery. Some possible research topics could be

- multiple interactive effects and deterioration mechanisms
- accelerated techniques, related instrumentation and model validation to long-term field data
- determination of service life from wear tests and modeling
- deterioration of structural materials and protective coatings (e.g. polymeric coatings on bridges) as a function of environment
- failure mechanisms of composite materials
- corrosion protection systems
- size effects in testing, instrumentation and modeling
- relevant statistical methods and reliability
- comparison of models with long term field data.

Twenty five awards totaling $7m were made under this initiative. A grantees' workshop will be held in October, 2000 at UC – Berkeley, organized by P. Monteiro, et al. Proceedings will be published by Elsevier.

Research In Smart Structures And Materials

One of the challenges is to achieve optimal performance of the total system rather than just in the individual components. Among the topics requiring study are innovative energy sources for wireless sensors, energy - absorbing and variable damping structural properties as well as those having a stiffness that varies with changes in stress, temperature or acceleration. The National Materials Advisory Board has published [National Acad. of Sciences, 1993] a good perspective on the materials problems associated with a high performance car and a civilian aircraft which develops the "values" associated with these applications. These are also applicable to civil structures. Among the characteristics sought in smart structures/materials are self healing when cracks develop and in-situ repair of damage to structures such as bridges and water systems in order that their useful life can be significantly extended. There is the associated problem of simply being able to detect (predict) when repair is needed and when it has been satisfactorily accomplished. The use of smart materials as sensors may make future improvements possible in this area. The concept of adaptive behavior has been an underlying theme of active control of structures that are subjected to earthquake and other environmental type loads. Through feedback control and using the measured structural response, the structure adapts its dynamic characteristics to meet the performance objectives at any instant.

Fig. 2 is a sketch of a futuristic smart composite bridge system, illustrating some new concepts: including advanced composite materials with protective coating to mitigate ultraviolet damage, wireless sensors, optical fiber sensors, data acquisition and processing systems, advanced composite materials, structural controls, dampers, and geothermal energy bridge deck de-icing. Since a composite bridge is very much lighter (up to five times lighter) than a conventional concrete or steel bridge, excessive vibration and the resulting fatigue damages can be minimized and durability maximized by elaborate structural control systems (Liu, Chong and Singh, 1994; Rogers and Rogers, 1992). An artist rendition of this bridge appeared in *USA Today*, 3/3/97.

electro-rheological (ER) fluids for the vibration control of structures. ER fluids stiffen up very rapidly (changing elastic and damping properties) in an electric field. Other NSF supported researchers are studying shape memory alloys (University of Texas, Virginia Tech, and MIT); surface superelastic microalloying as sensors and microactuators (Michigan State); and magnetostrictive actuators (Iowa State, University of California at Los Angeles); etc. Photoelastic experiments at Virginia Tech demonstrated that NiTiNOL shape memory alloy wires could be used to decrease the stress intensity factor by generating a compressive force at a crack tip.

Other examples include:

- Semi-Active Vibration Absorbers (SAVA),W. N. Patten, et al,(Univ. of Oklahoma). This is part of a 5-year NSF Structural Control Initiative with Prof. Larry T. T. Soong as the grantees coordinator. A smart micro-controller coupled with hydraulic systems reduces large vibration amplitudes over 50% produced by heavy trucks passing through a highway bridge, adding 15% more load capacity and extending bridge life over 20 years. Figs. 3 (a,b) show the SAVA setup and the stress reduction respectively.

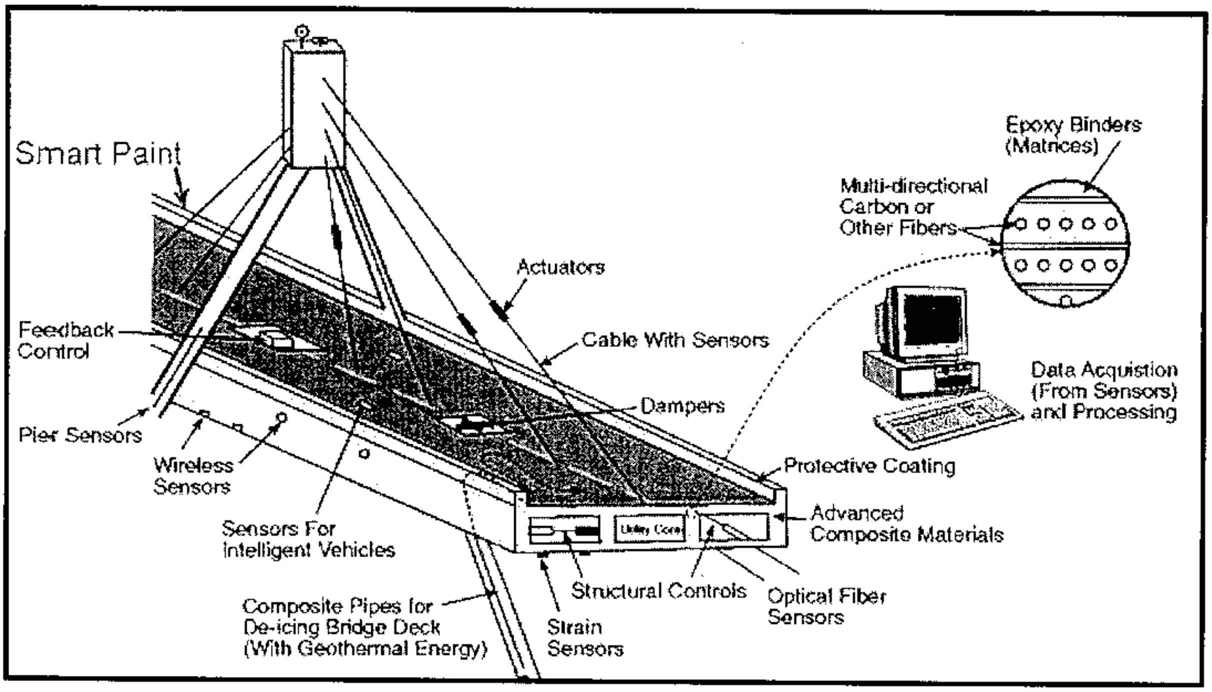

Fig. 2. An Intelligent Bridge System.

Examples Of Smart Structures And Materials

Smart structures and materials may heal themselves when cracked. NSF grantees have been developing self-healing concrete. One idea is to place hollow fibers filled with crack-sealing material into concrete, which if cracked would break the fiber releasing the sealant, according to Surendra Shah, Director of the NSF Science and Technology (S&T) Center at Northwestern. Lehigh researchers at ATLSS, a NSF Engineering Research Center, are looking into smart paints, which will release red dye (contained in capsules) when cracked. Optical fibers which change in light transmission due to stress are useful sensors. They can be embedded in concrete or attached to existing structures. NSF-supported researchers at Rutgers University studied optical fiber sensor systems for on-line and real-time monitoring of critical components of structural systems (such as bridges) for detection and warning of imminent structural systems failure. NSF grantees at Brown University and the University of Rhode Island investigated the fundamentals and dynamics of embedded optical fibers in concrete. Japanese researchers recently developed glass and carbon fiber reinforced concrete which provides the stress data by measuring the changes in electrical resistance in carbon fibers. Under a NSF Small Grants for Exploratory Research Programs, researchers at the University of California-Berkeley recently completed a study of the application of

• Fiber-optic Sensors in Bridges, R. Idriss (New Mexico State University). Fiberoptic cables are etched by laser with 5 mm long internal gauges, spaced about 2 m apart. These cables, strung under the bridge with epoxy, will be able to detect the stresses by sending light beams down the cable at regular intervals and by measuring the bending of the light beams. These gauges can also be used to monitor general traffic patterns. The sensors serve as a data collector as well as a wireless transmitter.

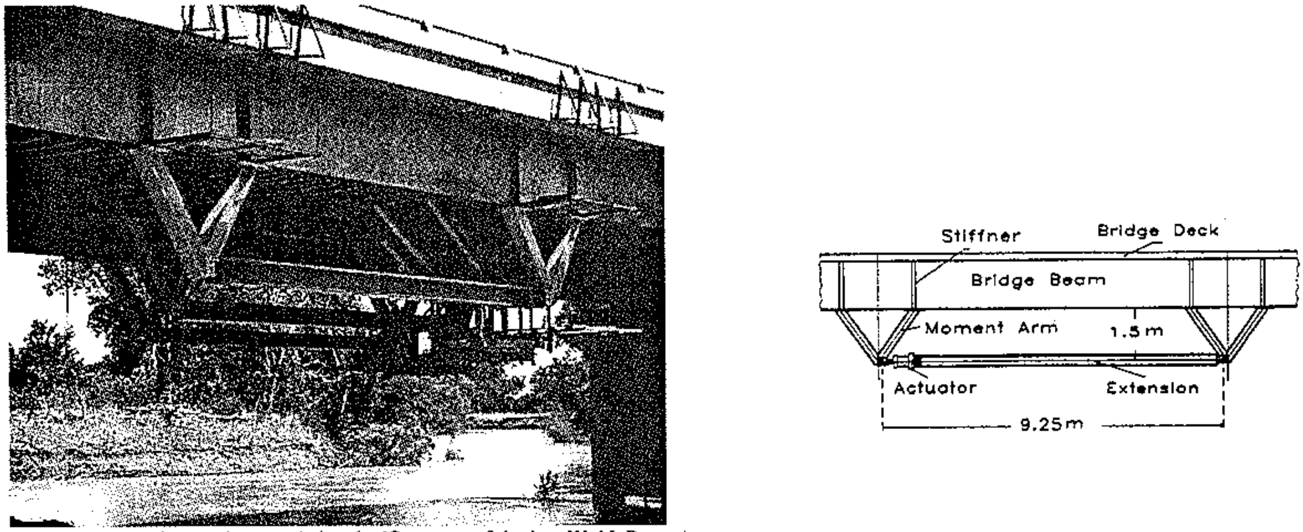

Fig.3(a). SAVA Setup photo and sketch. (Courtesy of the late W. N. Patten).

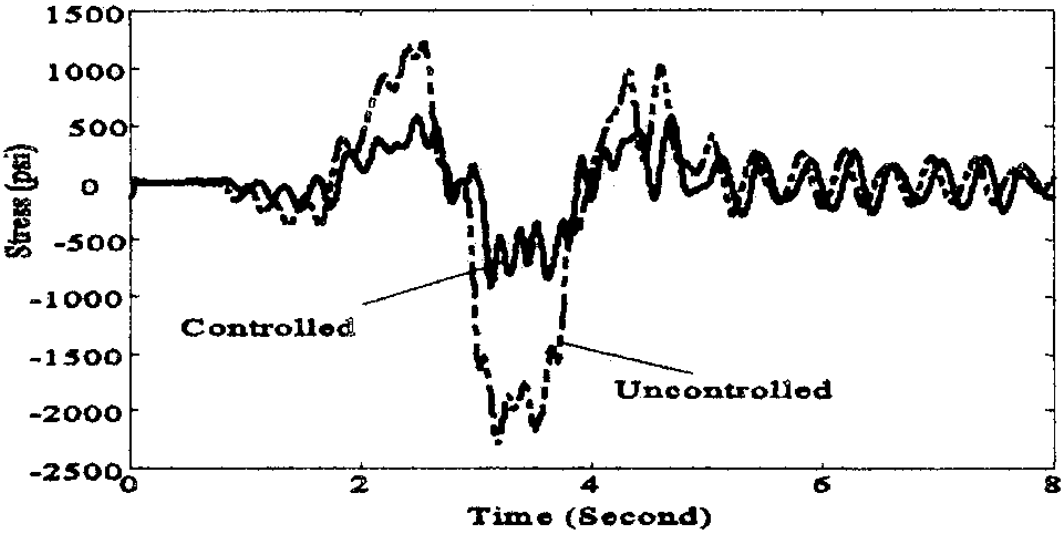

Fig. 3(b). Reduction of Stresses at Critical Locations, Controlled vs. Uncontrolled Conditions (Courtesy of the late W. N. Patten).

• Reliability and Safety of Structures using Stability-based Hybrid Controls, Prof. B.F. Spencer (University of Notre Dame). Magnetorheological (MR) fluid dampers are one of the most promising smart damping intelligent isolation systems according to Prof. B.F. Spencer, Jr. due to proven technology - reliable and robust; low cost; insensitivity to temperature; low power; and scalable to full-scale civil engineering applications.

• Passive and Active Damping Control for Large Civil Structures, N. M. Wereley (University of Maryland). The objective of the research activities is to augment damping in large civil structures applications via both passive and active means, to reduce structural response. The research program has entailed development, analysis, and experimental demonstration of passive, semi-active, and active structural damping control for civil structures using smart materials and structures technology. The research includes consideration of stability augmentation, shock, and vibration control using electrorheological (ER) and magnetorheological (MR) dampers. Damping strategies are being tested on dynamically scaled three story civil structures building model using dampers such as depicted in Figure 4.

• Synthesis of Smart Material Actuator Systems for Low and High Frequency Macro Motion: An Analytical and Experimental Investigation, G. Naganathan (University of Toledo). This project is to demonstrate that motions of a few centimeters can be performed by smart material actuator system. A program that combines theoretical investigations and experimental demonstrations is being conducted. Potential configurations made of piezoceramic and electrostrictive materials are being evaluated for providing larger motions at reasonable force levels for applications.

• Design, Modeling, and Development of Active Aperture Antennas, G. N. Washington (The Ohio State University). The primary goal of this work is the development of a novel class of aperture antennas capable of variable directivity (beam steering) and power density (variable focusing or beam shaping). The actuation for these antennas is employed using a distinct mechanism. The mechanism employs Polyvinylidene Fluoride (PVDF) film bonded to a lightweight metalized mylar structure. Since the film is piezoelectric, any electrical voltage drop across the film will cause the film to lengthen in its stretch direction. The resulting lateral deflection from a length change causes the production of a moment which causes the antenna surface deflection. This is illustrated in Figure 5.

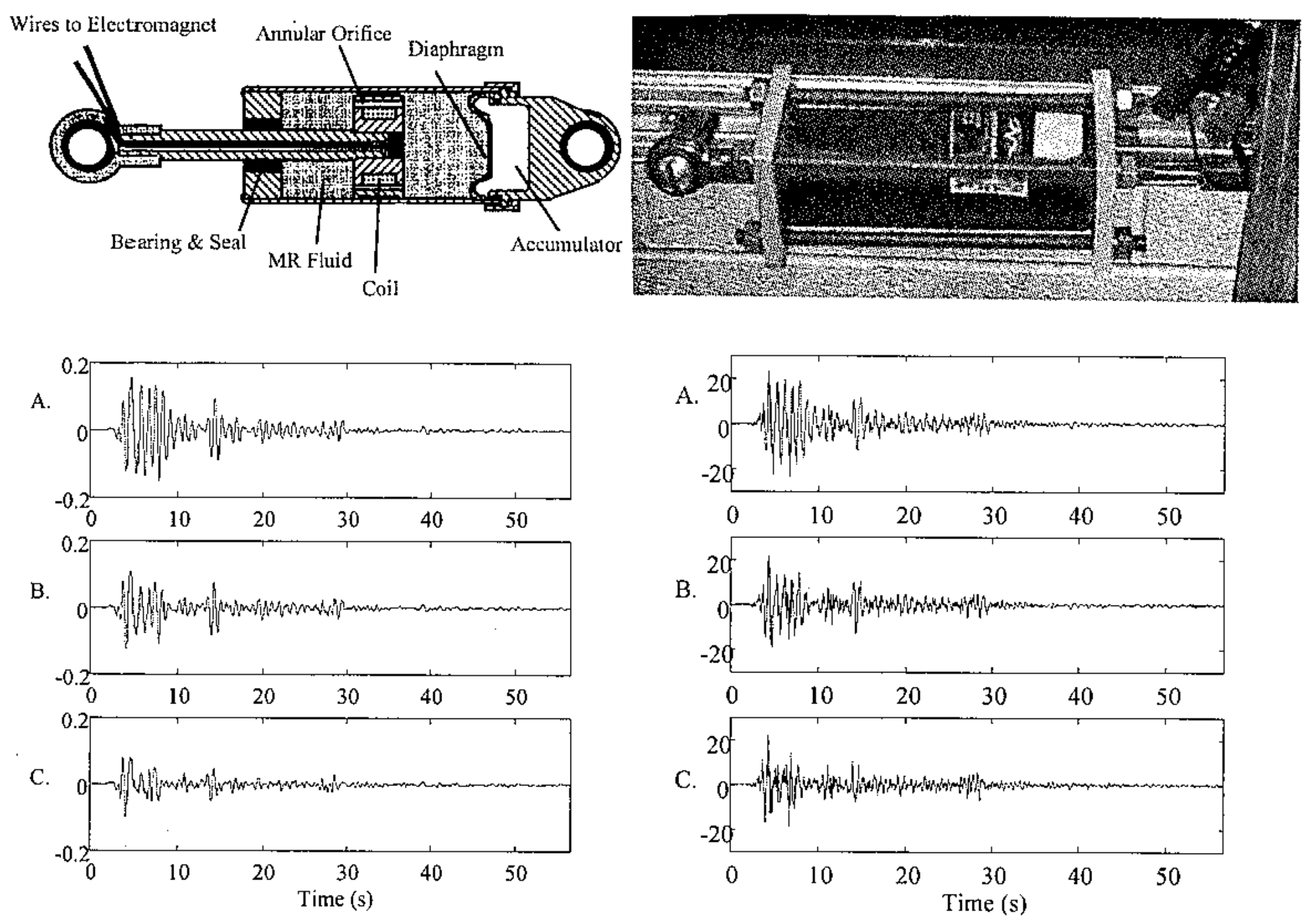

Figure 4. Upper schematic and photo depict MR damper used in 3 story scale model building simulation of response to 3x El Centro earthquake. Lower plots show displacement (left) and acceleration (right) responses to: A) no control, B) Skyhook controller, and C) Continuous Sliding Mode controller. (Courtesy of N. M. Wereley, University of Maryland.)

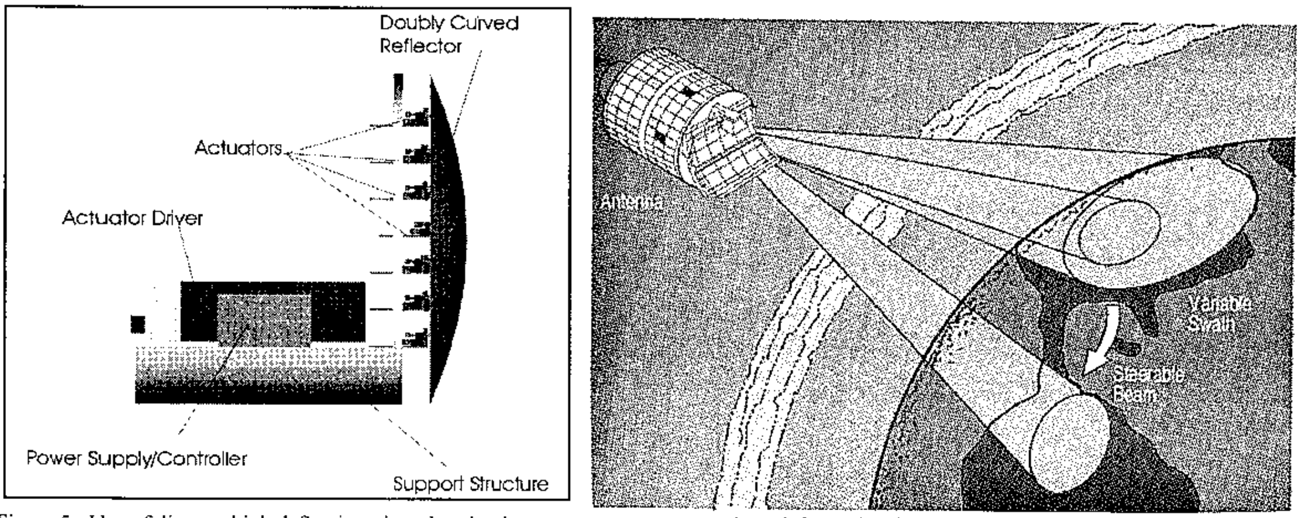

Figure 5. Use of discrete high deflection piezoelectric picomotor actuators to produce deformation for an active aperture antenna, allowing expanded ground coverage through beam steering. (Courtesy of G. N. Washington, The Ohio State University.)

- Other NSF supported researchers are studying shape memory alloys (e.g. University of Texas-Austin, VPI, and MIT); surface superelastic microalloying as sensors and microactuators (Michigan State); and Magnetostrictive active vibration control (Iowa State and UCLA).

As smart materials research progresses, newspapers, journals, and government programs are beginning to focus on this multidisciplinary research endeavor. A New York Times article (July 2, 1991) entitled "Smart Buildings" highlighted several NSF supported projects. In 1991, the Journal of Intelligent Material Systems and Structures published a special issue called "Intelligent Civil Engineering Structures," edited by the author. Through these efforts a solid technological base is being built enabling engineers and others to prevent and/or minimize damage and deterioration from both predictable and unpredictable hazards and events.

Structural control involves sensing, data processing feedback, and structural actuating (control). The NSF Structural Control Initiative [NSF 91-62, 1991 was launched in FY 1992 as a five-year, $5 M program. The NRC/Transportation Research Board - SHRP program co-funded some of the projects during the initial phase of the program. Some 50 projects supported in FY 92 to FY 97. Results are available from the principal investigators or from the coordinator of the initiative, Professor Larry T. Soong, Department of Civil Engineering, SUNY Buffalo [Soong and Singh, 1995].

Summary And Conclusions

An overview of the state of the art and engineering research in durability, intelligent structures and materials are presented. The author hopes that this paper will act as a catalyst, sparking interest and further research in these areas. This paper reflects the personal views of the author, not necessarily those of the National Science Foundation.

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