Smart and designer structural material systems†

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Summary

An efficient civil infrastructure system is essential to every country's productivity, security, and quality of life. Basic research and development in smart structures and designer materials have shown great potential for enhancing the functionality, serviceability, and increased lifespan of civil infrastructure systems. New construction and the intelligent renewal of ageing and deteriorating civil infrastructure systems include efficient and innovative use of high-performance designer materials, sensors, actuators, and mechanical and structural systems. High-performance designer materials, in particular, require new methods of computational materials science, some of which are described herein. In this paper, some examples of National Science Foundation (NSF) funded awards, some examples of National Institute of Standards and Technology (NIST) 'designer material' projects, and future research needs, as well as new research initiatives on nanotechnology, are presented.

Key words: composites; computational materials science; concrete; designer materials; smart materials; smart structures; solid mechanics; structural control

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Introduction

Traditionally, engineers and material scientists have been involved extensively with the characterization of existing materials. Characterization is necessary in order to be able to use a material in a rational manner. Within the past two decades, technological advances in the understanding of materials, as well as in computational capabilities, have led to the advent of many so-called *designer* materials. For example, at the nanoscale, material scientists have demonstrated the ability to design entirely new materials with desirable properties, molecule by molecule. In part to facilitate the application of this technology to civil infrastructure systems, the National Science Foundation (NSF) has begun broad research initiatives in nanotechnology, which will be further described in this paper. The designer material process can also be carried out in the composite building process where the relevant length scales are micrometres and millimetres, and the building components are not molecules, but chemically and morphologically distinct phases. The impact of this ability to tailor and optimize material attributes, thus manufacturing designer materials, is increasingly being realized in structural systems[1–3]. Computational materials science is necessary to optimize the design of complex materials. With the increasing availability of advanced computing capabilities, both in hardware and software[4], and new developments in the materials sciences, researchers can now characterize processes, and design, model, and manufacture materials with desirable performance and properties. This is often a multi-scale process. Fig. 1 displays these length scales and their important properties, and how they fit together for civil infrastructure materials.

Of course, one crucial aspect of the performance of any material, but especially materials for the civil infrastructure, is durability—how long a material can perform its required task. This can be assessed in three ways: experiments that last as long as the material does in practice, accelerated degradation experiments, and computer model simulations. The first is impractical in most cases for civil infrastructure materials. From the macro- to the micro-level, research to address the need for accelerated tests to simulate various environmental forces and impacts has been greatly advanced,

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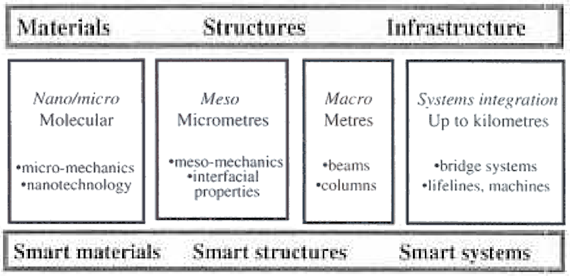


Fig. 1 Scales in materials and structures[4]

along with computational models that aid in the extrapolation of short-term test results into long-term life-cycle behaviour. Research in this area has been supported by the NSF Durability Initiative[5]. A joint NSF–Sandia National Laboratory initiative on model-based simulation and life-cycle engineering[6] emphasizes development of new computational tools in support of bridging length scales in material and structural systems. Additional NSF engineering initiatives in these areas include the Nanoscale Modeling and Simulation Initiative[7] and the Exploratory Research on Model-Based Simulation Initiative[8].

In the specific area of cement-based materials, NIST has well-established programmes for both making concrete into a designer material, on length scales ranging from nanometres to metres, as well as for quantitatively predicting durability and service life, using computer model simulations. This programme involves a synergistic combination of experimental and computational materials science to understand and control cement-based materials (concrete) in a multi-scale approach. The experimental results are used to help build the necessary models, and the results of the models help predict, design and control the experiments needed.

Another growing trend in civil infrastructure materials and systems, which has revolutionary potential, is the use of *smart* materials and systems. These are materials and systems that often behave like biological systems. Smart structures/materials basically possess their own sensors (nervous system), their own processor (brain system), and their own actuators (muscular systems), thus mimicking biological systems. Sensors used in smart structures/materials include optical fibres, corrosion sensors, and other environmental sensors and sensing particles. Examples of actuators include shape memory alloys that return to their original shape when heated, hydraulic systems, and piezoelectric ceramic polymer composites. The processor or control aspects of smart structures/materials are based on microchip, computer software and hardware systems.

Each of these three areas, nanotechnology, designer materials, and smart materials and systems, will be further described and illustrated in the rest of this paper.

Nanotechnology research initiatives

Initiated by one of the authors (K. P. Chong), with the organization and help of researchers from Brown (K. S. Kim, *et al.*), Stanford, Princeton and other universities, a NSF Workshop on Nano- and Micro-Mechanics of Solids for Emerging Science and Technology was held at Stanford in October, 1999 (http://en732c.engin.brown.edu/nsfreport.html). The following two paragraphs have been freely adapted from the Executive Summary of this workshop.

Recent developments in science have advanced capabilities to fabricate and control material systems on the scale of nanometres, bringing problems of material behaviour on the nanometre scale into the domain of engineering. Immediate applications of nanostructures and nano-devices include quantum electronic devices, bio-surgical instruments, micro-electrical sensors, and functionally graded materials. The branch of mechanics research in this emerging field can be termed nano- and micro-mechanics of materials. A particularly challenging aspect of fostering research in the nano- and micro-mechanics of materials is its highly cross-disciplinary character. Important studies of relevance to the area have been initiated in many different branches of science and engineering. A subset of these, which is both scientifically rich and technologically significant, has mechanics of solids as a distinct and unifying theme.

Recognizing that this area of nanotechnology is in its infancy, substantial basic research, which needs to capitalize on the progress made in other disciplines, must be done to establish an engineering science base. This link between the discoveries of basic science and the design of commercial devices must be completed to realize the potential of this area. Such a commitment to nano- and micro-mechanics, based on capabilities in modelling and experiment embodying a high degree of rigour, will lead to a strong foundation of understanding and confidence underlying this area of nanotechnology. The potential of various concepts in nanotechnology will be enhanced, in particular, by exploring the nano- and micro-mechanics of coupled phenomena and of multi-scale phenomena. Examples of coupled phenomena include modification of quantum states of materials caused by mechanical strains, ferroelectric transformations induced by electric fields and mechanical stresses, chemical reaction processes biased by mechanical stresses, and change of bio-molecular conformality of proteins caused by environmental mechanical strain rates. Multi-scale phenomena arise in situations where properties of materials to be exploited in applications at a certain size scale are controlled by physical processes occurring on a size scale that is orders of magnitude smaller. Important problems of this kind arise, for example, in thermomechanical behaviour of thin-film nano-structures, evolution of surface as well as bulk nano-structures caused by various material defects, nano-indentation, nano-tribological response of solids, and failure processes of micro-electro-mechanical systems (MEMS).

Coordinated by M. Roco, NSF recently announced a programme (NSF 02-148, http://www.nsf.gov) on collaborative research in the area of nanoscale science and engineering. The goal of this programme is to catalyse synergistic science and engineering research in emerging areas of nanoscale science and technology, including: biosystems at nanoscale; nanoscale structures, novel phenomena, and quantum control; device and system architecture; design tools and nanosystems specific software; nanoscale processes in the environment; multi-scale, multi-phenomena modelling and simulation at the nanoscale; and studies on societal implications of nanoscale science and engineering. This initiative provides support for: Nanoscale Interdisciplinary Research Teams (NIRT), Nanoscale Science and Engineering Centers (NSEC), Nanoscale Exploratory Research (NER), and Nanotechnology Undergraduate Education (NUE). Key research areas have been identified in advanced materials, nanobiotechnology (e.g. nano-photosynthesis), nanoelectronics, advanced healthcare, environmental improvement, efficient energy conversion and storage, space exploration, economical transportation, and bionanosensors. The National Nanotechnology Initiative (NNI), described on www.nano.gov, will ensure that investments in this area are made in a coordinated and timely manner (including participating federal agencies—NSF, DOD, DOE, NIST, EPA and others). In addition, individual investigator research in nanoscale science and engineering will continue to be supported in the relevant programmes and divisions outside this initiative.

Designer materials

In the old, but still valid, materials science triad, material properties depend on microstructure, which in turn depends on processing. To make designer materials available, that is, materials whose microstructure is tailored, via controlled processing, to perform a certain way, requires, at the least, an ability to predict properties on the basis of microstructure. This involves more than just some kind of empirical relation between porosity and elastic moduli, for example, but also a quantitative calculation of the properties that a certain microstructure will give. Most real materials are not simple enough, except for crystals, to allow analytical calculation of their properties from their structure. Mathematically characterizing their microstructure may be a very difficult task by itself, let alone calculating anything from it. Computational materials science carries much promise for solving this problem, where computers are used to characterize the structure as well as to compute the properties. This can take place on the micrometre and millimetre length scales, as well as on the nanoscale. An example, from work on cement-based materials performed mainly at NIST, is described below[9]. However, the complex structure of concrete is discussed first, to further justify the need for a computational materials science approach.

Concrete—a structural material

The name concrete comes from the Latin *'concretus'* (to grow together[10]), which mainly occurs over the time scale of hours and days, as the hydration process causes the cement/aggregate suspension to develop from a viscoelastic, moldable fluid into a hard, rigid solid. More than five trillion kilograms of concrete are used around the world each year.

It is important to remember that cement is the powder that reacts with water to form cement paste, a hard, solid material that forms the matrix for the concrete composite[11]. The starting point for cement paste, cement powder, is obtained by simultaneously grinding cement clinker and gypsum. The cement clinker is manufactured by firing carefully proportioned and finely ground mixtures of limestone and clay. After grinding, the cement powder consists of multi-size, multi-phase, irregularly shaped particles, generally ranging in size from less than 1 μm to about 100 μm, with an average diameter of about 15–20 μm. Fig. 2 shows a grey-scale image of such a powder, taken in back-scattered mode in a scanning electron microscope.

The addition to cement paste of sand (fine aggregates) up to a few millimetres in diameter makes mortar, and the addition of rocks (coarse aggregates) up to a few centimetres in diameter makes concrete. Fig. 3 displays a piece of concrete, showing sand and rock-type aggregates. Concrete is a porous material, with many different kinds of pores, ranging from the air voids that are entrapped in the mixing process, which can be quite large, up to a few millimetres in diameter, to the capillary pores, which are essentially the space occupied by the water left over from mixing, down to the nanometre-scale pores that exist in some of the hydration products produced by the cement–water chemical reaction. Since these nanoscale pores control the properties of the calcium–silicate–hydrate hydration product, which is the main 'glue' that holds concrete together, concrete is in some ways a nanoscale material.

Until recent years, the overwhelming technical emphasis on concrete has been compressive strength, which perhaps has led to the idea that concrete is simply a commodity material, with nothing needed to

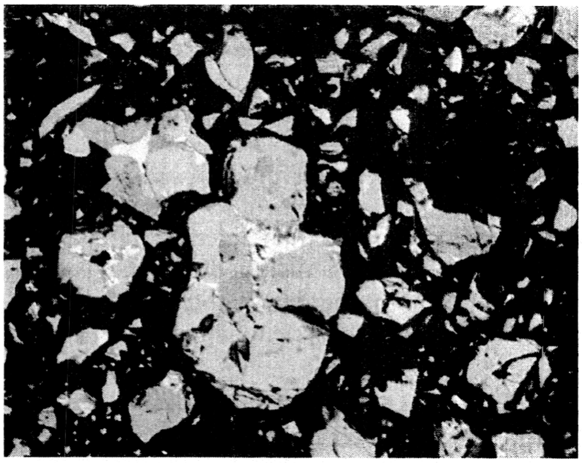


Fig. 2 A picture of a cement powder dispersed in epoxy, and taken in back-scattered mode by a scanning electron microscope. The larger particles are about 50 µm wide. The multi-phase nature of the individual particles can be clearly seen by the different grey scales

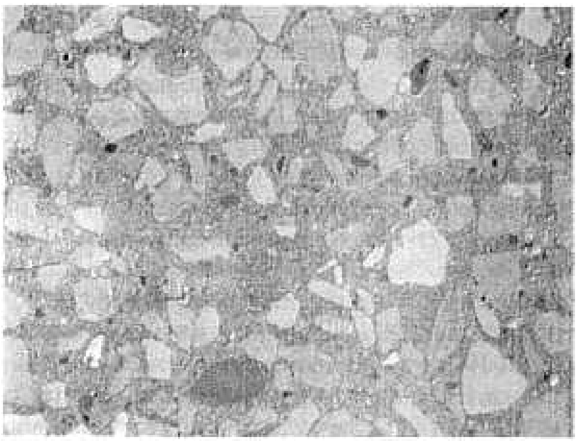


Fig. 3 Image of a concrete specimen, approximately 100 mm long, showing some of the different shapes and sizes of aggregates possible

be understood about the microstructure. However, more recently, it has been recognized that much of the concrete in the infrastructure in the US and Europe and elsewhere has been deteriorating faster than expected, with much of this deterioration due to the corrosion of reinforcing steel coming from the ingress of chloride and other ions from road salts, marine environments, and ground soils[12]. This has led to new attention being paid to the microstructure of concrete, with the realization that concrete is a complex composite, whose improvement and control requires the usual materials science approach of processing, microstructure, and properties. The range of the random microstructure of concrete, from nanometres to micrometres to millimetres to the final end use of metres or more, covers nine orders of magnitude in size! It is then a large and difficult task to try to theoretically relate the microstructure and the properties of concrete. This has led to the use of computer simulations, coupled with modern experimental probes[13].

Within the Building and Fire Research Laboratory at the National Institute of Standards and Technology (NIST), the HYPERCON High Performance Concrete Technology project (see http://ciks.cbt.nist.gov/phpct/) is working to develop the materials science knowledge necessary for making high-performance concrete (HPC) a usable, well-understood, and durable material, thus enabling the reliable application of HPC in buildings and the civil infrastructure. HPC is defined[14] as 'concrete having desired properties and uniformity which cannot be obtained routinely using only conventional constituents and normal mixing, placing, and curing practices'. These properties include, among others: high strength, high toughness, durability, enhanced workability, and freeze-thaw durability. This development is one of the main drivers for the materials science of concrete research, as concrete technologists have realized that concrete structure and properties can be tailored to meet various needs. National programmes on HPC exist in the United States, China, Japan, Canada, Norway, and France. In the US, besides the basic concrete research at NIST and that sponsored by the NSF, other federal programs, such as the Federal Highway Administration (FHWA), the Strategic Highway Research Program (SHRP), and Ideas Deserving Exploratory Analysis (IDEA) support HPC and concrete research[15,16].

The work of the HYPERCON project at NIST involves the combination of experimental and computational materials science research, which is needed to address the complex nature of concrete. The delivery of the output of this research is focused on developing computer-integrated knowledge systems (CIKS), which are a synergistic combination of databases, models, and computational tools. The topics currently addressed by HYPERCON are:

1. *Processing of HPC* is addressing methods for selecting and proportioning ingredients, determining the rheological properties, and selecting the mixing, placing, and consolidation procedures and the curing conditions to assure a product of the desired performance and uniformity.
2. *Characterization of HPC* aims at providing techniques needed for characterizing the composition and properties of concrete materials, including the composition, structure, and uniformity of an HPC produced by any process or from any source.
3. *Performance Prediction of HPC* is developing a suite of models for simulating and predicting transport and other durability-related properties of HPC.

4. *Economics of HPC* is building models for calculating the life-cycle costs of HPC in infrastructure applications.

Virtual testing

There are two main microstructural models that have been developed for the cement paste length scale (micrometres) and the concrete length scale (millimetres). For the cement paste scale, a cellular automaton-type model is used, operating on a three dimensional digital image of the multi-phase cement particles[13]. The information for the particles is obtained from back-scattered scanning electron microscopy and X-ray microprobe analysis. Fig. 4 shows several spatial distributions for (a) calcium, (b) silicon, and (c) aluminium, where the lighter the grey scale, the more of that element is present. Notice that the aluminium appears only in the interstitial material connecting the primarily calcium-silicon main grains. This kind of information has to be captured for any model of cement hydration to work well. This X-ray microprobe information is added to that shown in Fig. 2, and used to identify the standard cement chemical compound spatial distribution in a cement powder at the particle level. This experimental information, obtained in two dimensions, then enables the generation of three-dimensional particles containing all the multi-phase experimental information. The various phases are dissolved and reacted computationally, and a three-dimensional digital image representation of the microstructure at the micrometre length scale is formed (colour images of cement microstructure are available at http://ciks.cbt.nist.gov/monograph and http://vcctl.cbt.nist.gov). Various algorithms are used to compute properties such as electrical conductivity, ionic diffusivity, fluid permeability, and elastic moduli of the simulated structure.

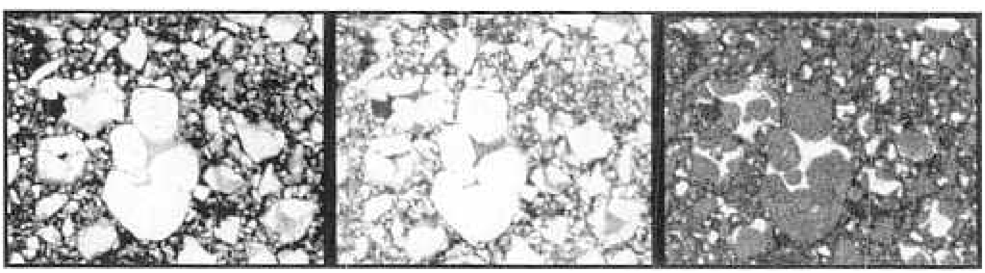
Some of the complex chemistry of cement hydration is illustrated in Fig. 5, where the principal reactions between the silicate, aluminate, ferrite, and sulfate phases and water are shown, using standard cement chemistry notation: C = CaO, S = SiO_2, F = FeO_2, A = Al_2O_3, H = H_2O, and $\bar{S}$ = SO_3. The cellular automaton rules of the cement hydration model are set up to mimic this chemistry[11].

At the millimetre length scale, a hard-core soft-shell model has been used to successfully predict the diffusivity of ions in the pore space of concrete[17,18]. The particle size distribution of the aggregates is taken from experiment. The hard-core particles, which do not overlap, are taken to be the aggregates. The soft shells, which can overlap and which form a third phase beside the matrix, are taken to be interfacial transition zone material, which is cement paste matrix material altered by the presence of the aggregates and which is generally more porous than the rest of the bulk cement paste matrix. This model uses spherical particles, which are adequate for some properties like ionic diffusion, where the aggregates have zero properties compared with the cement paste matrix. In this case, it has been shown that shape makes very little difference[19].

However, many other properties, such as the rheology of concrete in the fluid state and the elasticity of solid concrete, have a rather sensitive dependence on aggregate shape. Recent work on mathematically describing the shape of real aggregates, as taken from an X-ray tomograph, uses a

$$C_3S + 5.3H \rightarrow C_{1.7}SH_4 + 1.3CH$$
$$C_2S + 4.3H \rightarrow C_{1.7}SH_4 + 0.3CH$$
$$C_3A + 6H \rightarrow C_3AH_6$$
$$C_3A + 3C\bar{S}H_2 + 26H \rightarrow C_6A\bar{S}_3H_{32}$$
$$2C_3A + C_6A\bar{S}_3H_{32} + 4H \rightarrow 3C_4A\bar{S}H_{12}$$
$$C_4AF + 3C\bar{S}H_2 + 30H \rightarrow C_6A\bar{S}_3H_{32} + CH + FH_3$$
$$2C_4AF + C_6A\bar{S}_3H_{32} + 12H \rightarrow 3C_4A\bar{S}H_{12} + 2CH + 2FH_3$$
$$C_4AF + 10H \rightarrow C_3AH_6 + CH + FH_3$$

Fig. 5 Cement model reactions, using cement chemistry notation discussed in text[11]



(b)

Fig. 4 Different chemical maps of the same cement particles, using X-ray microprobe analysis on a scanning electron microscope. It is interesting how different chemical species correlate with different locations in the microstructure, even for cement powder: (a) calcium image; (b) silicon image; and (c) aluminium image. The grey scale is darker where there is less of the element of interest present. Note that the aluminium is almost entirely in the interstitial regions between clumps of calcium-silicate compounds shape expansion in terms of spherical harmonics:

$$r(\theta, \varphi) = \sum_{n=0}^{N} \sum_{m=-n}^{n} a_{nm} Y_n^m(\theta, \varphi)$$

where Y_n^m is a spherical harmonic function, usually found in quantum mechanics[20], the a_{nm} are complex constants, and $r(\theta, \varphi)$ is the length from the centre of mass of the particle to the surface along the direction indicated by the two angles[21,22]. Fig. 6 shows six two-dimensional images of a three-dimensional aggregate particle extracted from an X-ray tomograph (light grey) along with an image of the same particle as constructed from its spherical harmonic expansion (dark grey), at different rotation angles. In all cases, the two images are nearly identical, showing the power of the expansion for characterizing real three-dimensional shape. Using mathematical techniques from quantum mechanics for characterizing concrete aggregate shape is an example of the kind of interdisciplinary research that was described earlier in the paper, and which is needed to truly exploit the power of designer materials in civil infrastructure systems.

At the nanometre scale of concrete, there has been some modelling work done along with experimental probes, with an encouraging degree of agreement between model predictions and experimental results, but much more needs to be done[23]. An exciting new development in this area has been the use of molecular dynamics techniques for analysing the interactions of various ions with cement hydration product surfaces[24–26]. This new application should lead the way to atomic and nanometre-scale understanding and control of concrete structure, thus completing the format laid out in Fig. 1.

The development of modelling and simulation tools for cement and concrete at the micrometre and millimetre length scales has allowed the development of a virtual testing laboratory. Fig. 7 shows a schematic view of the structure of the Virtual Cement and Concrete Testing Laboratory (VCCTL), which is a computer-based 'virtual laboratory' the goal of which is to reduce the number of physical concrete tests, whether for quality assurance or for expediting the research and development process. Many of the models developed at NIST over the last 10 years are at the stage where their predictions are quantitative and accurate. Many standard tests can be replaced by computer models right now, and many more will be able to be replaced in the future, so that, for example, a cement company that develops a new cement will be able to immediately predict many facets of the performance of concrete made from this cement. Models now available can handle the effects of: (1) different kinds of curing, which involves cement particle size distribution and composition, mineral admixtures, and temperature and moisture conditions; and (2) aggregates, which include the

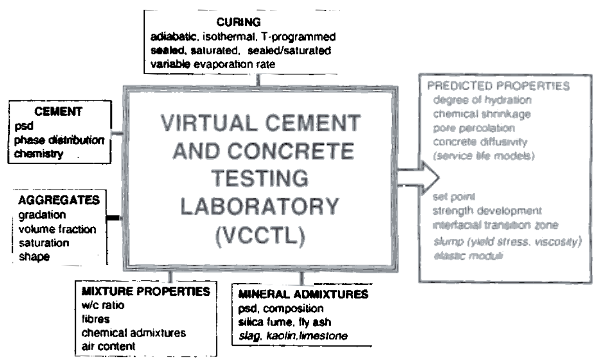


Fig. 7 Schematic overview of the structure of the Virtual Cement and Concrete Testing Laboratory. Italics indicate a capacity that is planned, but not currently available

Fig. 6 Six views of an aggregate, at six different rotation angles, taken from an X-ray tomograph of a real piece of concrete. The aggregate images taken from the tomograph are dark grey, and the images made from the spherical harmonic expansion are light grey

particle size distribution (as given by a sieve analysis), volume fraction, degree of saturation, and shape. These models can now, or will soon be able to, predict: degree of hydration, chemical shrinkage, heat release, diffusivity, set point, strength development, elastic properties, and rheological properties such as slump, yield stress, and plastic viscosity. Databases are also becoming available for using the cement hydration model for various cements, which are an important component of the VCCTL (see http://ciks.cbt.nist.gov/phpct/database.html).

Version 1.0 of the VCCTL is now available (see http://vcctl.cbt.nist.gov). A consortium of industrial companies has been formed to participate in the computational and experimental research needed to improve and extend the VCCTL in order to make it more powerful and usable. It is this kind of approach that is making, and will continue to make, concrete into a true designer material.

In order to be able to use the VCCTL as more than a 'black box,' there must be a strong educational component available to any user. This component is the Electronic Monograph[27–29], which is a website set up like an electronic book, with chapters and sections, organized by a linked table of contents, and with an electronic index (search engine). Right now, the text in this monograph is the equivalent of over 2000 pages of single-spaced, 12-point printed text. The monograph covers most of the computer modelling work on concrete carried out at NIST over the last 10 years and some of the experimental work, and could be classified as a virtual textbook on the computational materials science of concrete[30].

NIST is trying to extend these computational materials science techniques to others in the cement and concrete materials field and to other material fields. Training in the use of these computational tools, and in how they work, is provided in the annual ACBM/NIST (Center for Advanced Cement-Based Materials) Computer Modeling Workshop. The announcement for the 2002 workshop can be found at the monograph web page given above. The workshop is a four-day tutorial that provides intensive lectures on the materials science behind these models. These lectures are accessible to both experimentalists and modellers. Support for this workshop series was originally provided by NSF via ACBM. It is now continuing to be supported by ACBM in its post-NSF phase (see below).

NSF-supported work in cement-based materials

The National Science Foundation, through its engineering programmes in the Civil and Mechanical Systems Division, in addition to the Engineering Research Centers (at Lehigh University) and the Science and Technology Centers (at Northwestern University) programmes, has supported research in concrete materials and structures. This work can feed into the concrete materials science problem as described above, supplying basic information for testing computational materials science predictions at several length scales, which ultimately will support the continued transformation of concrete into a designer material.

Some of the NSF supported general topics are:

- durability of concrete;
- low temperature behaviour;
- mathematical modelling of concrete creep and shrinkage;
- self-healing concrete, smart concrete;
- research needs for concrete masonry;
- rehabilitation, renovation and reconstruction of buildings;
- new rib geometries for reinforcing bars;
- high-strength and/or high-performance concrete;
- fibre-reinforced concrete;
- fracture toughness and behaviour;
- size effects;
- micro-mechanics of concrete;
- shear in reinforced concrete;
- physics and chemistry of cement-based materials;
- behaviour of concrete in cold climates;
- fibre optics (sensors) in concrete;
- continuous lightly reinforced concrete joint systems;
- highway bridges;
- construction methods;
- automation/robotics;
- non-destructive evaluation;
- seismic precast concrete structures;
- structural controls;
- international cooperative initiatives;
- full-scale seismic pseudo-dynamic testing of reinforced concrete.

One of the largest NSF commitments to basic research on concrete, from 1989 to 2000, has been the NSF Center for Advanced Cement-based Materials (ACBM), started by Professor S. Shah of Northwestern University in 1989 as one of the original NSF Science and Technology Centers (http://www.civil.nwu.edu/ACBM). After the 11-year NSF funding was completed in 2000, ACBM continued with strong support from industry. In addition to the industrial funding members, who also participate in the research, ACBM is composed of: Northwestern University, University of Michigan, University of Illinois, Purdue University, and NIST. ACBM's original areas of investigation included processing procedures (control of initial/final structure), microstructure (porosity, damage, interfaces), bulk properties (fracture mechanics, durability, fiber-reinforced concrete, modelling;

(generic, interfacing, simulation), and design of new materials (improved properties through materials science). The research thrust today builds on the expertise developed in these areas, and focuses on waste reduction and utilization (blended cements), service life prediction, and design for performance (optimization, designer materials).

In addition to the 11-year ACBM program, NSF has supported research in concrete via individual investigator grants. The following, taken from the list of general topics given above, is a list of examples of current NSF research projects in concrete (for details see: www.nsf.gov, search by principal investigators' names under *awards*), more than half of which are related to HPC.

- R. Zoughi, University of Missouri Rolla; Detection and Profiling of Accelerated Chloride Penetration in Concrete Using Near-field Microwave Techniques;
- S. Shah, Northwestern University; Development of Non-Clinker Based Cement for Hazard Reduction;
- K. Kurtis, Georgia Tech; POWRE: Examination of the Mechanisms of ASR Gel Expansion Control by Lithium Additive in Concrete;
- J. Morton, CSC Palatine, IL; SBIR Phase II: Non-corroding Steel Reinforced Concrete;
- S. Bang , V. Ramakrishnan, South Dakota School of Mines; Application of a Microbial Immobilization Technique in Remediation of Concrete Cracks;
- G. Scherer, Princeton University; Novel Method for Measuring Permeability of Concrete;
- R. Berliner and M. Conradi, University of Missouri Columbia; The Durability of Concrete: The Crystal Chemistry of the Calcium Aluminosulfate Hydrates and Related Compounds;
- H. Jennings, Northwestern University; The Effect of Composition on the Colloid Structure of Calcium Silicate Hydrate: Implications for Concrete Durability and a Basis for a Fundamental Understanding of Cement;
- L. Schwarz, University of Arkansas; CAREER: Roles of Rheology, Chemical and Mechanical Filtration, and Applied Gradient on Injectability of Cement Grouts, Morphology of Grouted Soil, and Improvement in Soil Properties.

Smart structures and materials

In recent years, 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 damage, and adapt to changing environments. The potential applications of such smart materials/systems are abundant, ranging from design of smart aircraft skins embedded with fibre optic sensors to detect structural flaws; bridges with sensoring/actuating elements to counter violent vibrations; flying MEMS with remote control for surveying and rescue missions; to stealth submarine vehicles with swimming muscles made of special polymers. Such a multidisciplinary civil infrastructure systems (CIS)[31] research front, represented by material scientists, physicists, chemists, biologists, and engineers in diverse fields (mechanical, electrical, civil, control, computer, and aeronautical) has collectively created a new entity defined by the interface of these research elements. Smart structures/materials are generally created through synthesis by combining sensoring, processing, and actuating elements integrated with conventional structural materials such as steel, concrete, or composites[1,2,32]. Some of these structures/materials currently being researched or in use are[33,34]:

- 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 electric and magnetic fields, respectively, dramatically altering basic material properties.

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 fibres filled with crack-sealing material into concrete, which if cracked would break the fibre, releasing the sealant, according to S. Shah, Director of ACBM. Lehigh researchers at Advanced Technology in Large Structural Systems (ATLSS), a former NSF Engineering Research Center, have developed smart paints, which will release red dye (contained in capsules) when cracked.

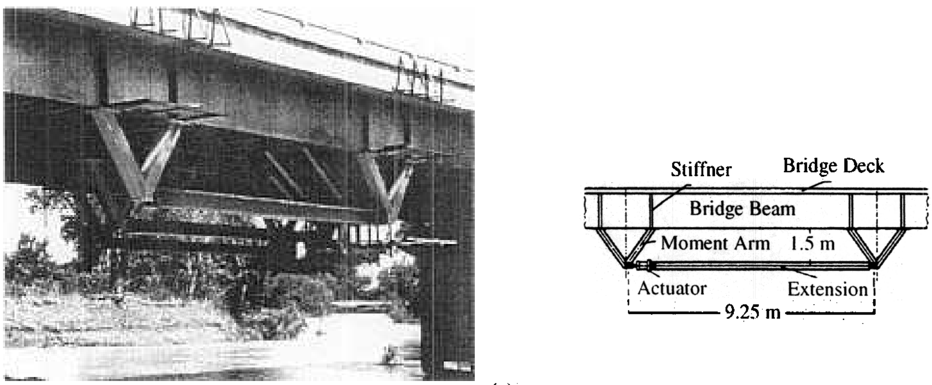
Optical fibres that change in light transmission properties due to stress are useful sensors. They can be embedded in concrete or attached to existing structures. NSF-supported researchers at Rutgers University studied optical fibre sensor systems for on-line and real-time monitoring of critical components 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 have investigated the fundamentals and dynamics of embedded optical fibres in concrete. Japanese researchers have recently developed glass- and carbon-fibre-reinforced concrete that provides stress data by measuring the changes in electrical resistance in carbon fibres.

Under a NSF Small Grants for Exploratory Research programme, researchers at the University of

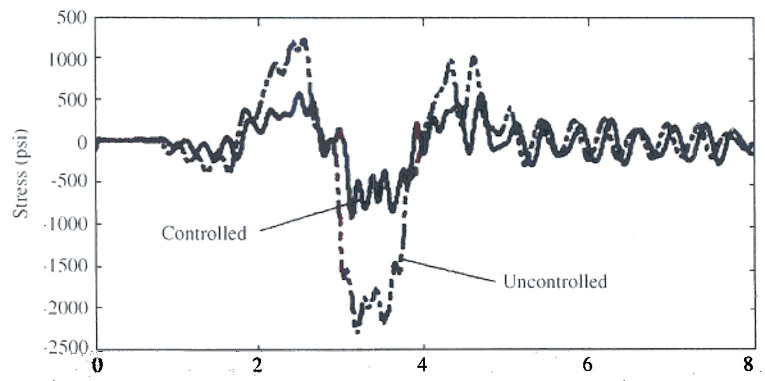
California at Berkeley recently completed a study of the application of electro-rheological (ER) fluids for the vibration control of structures. ER fluids stiffen very rapidly in an electric field, changing their elastic and damping properties. Other NSF-supported researchers are studying shape memory alloys (University of Texas, Virginia Tech, and MIT), surface superelastic microalloying as sensors and microactuators (Michigan State), and magnetostrictive active vibration control (Iowa State, Virginia Tech). 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*, (University of Oklahoma). This is part of a 5-year NSF Structural Control Initiative with Professor Larry T. T. Soong as the grantees' coordinator (the project was originally started by R. Sack and W. N. Patten). A smart micro-controller, coupled with hydraulic systems, reduces large vibration amplitudes produced by heavy trucks passing over a highway bridge by more than 50%, adding 15% more load capacity and extending bridge life over 20 years. Fig. 8 (a,b) shows the SAVA setup and the stress reduction, respectively.
- Fibre-optic Sensors in Bridges, R. Idriss (New Mexico State University). Fibre optic cables are laser-etched with 5-mm-long internal gauges, spaced about 2 m apart. These cables, adhered to the underside of the bridge with epoxy, will be able to detect stresses by sending light beams down the cable at regular intervals and 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.
- Intelligent Structures and Materials, C. A. Rogers (University of South Carolina). Specifically, this Presidential Young Investigator (PYI) project[35] includes: distributed sensing and health monitoring of civil engineering structures, active buckling control structures; and active damage control of composites. Micrometre-size magnetostrictive particles are mixed with the composite for health monitoring. Proof-of-concept experiments have demonstrated that delaminations could be located by active magnetostrictive tagging, and low-velocity impact damage resistance of composites could be improved by hybridizing them with shape memory alloy material (SMA).
- Research conducted by M. Taya (University of Washington, Seattle) explored the use of TiNi shape



(a)



(b)

Fig. 8 (a) SAVA setup photo (left) and sketch (right); (b) reduction of stresses at critical locations, controlled and uncontrolled conditions (courtesy of the late W. N. Patten) memory alloy fibres and reinforcements in aluminum and epoxy matrix composites to induce desirable stress states. The use of a shape memory alloy for fibre reinforcement can result in the production of compressive residual stresses in the matrix phase of the composite. This can result in increases in flow stress and toughness of the composite compared with these properties in the same composites when the TiNi was not treated to produce a shape memory effect in the composite. The induced compressive stress in the matrix is responsible for the enhancement of the tensile properties and toughness of the composite.

- W. Sharpe and K. Hemker (Johns Hopkins University) developed new test methods to measure the Poisson's ratio and the fracture toughness of MEMS. While engineers are able to design MEMS and predict their overall response, they cannot yet optimize the design to predict the allowable load and life of a component because the mechanical properties of the material are not available. This research is attempting to measure and provide such data. Further, they are performing comprehensive microstructural studies of MEMS materials which, together with the mechanical testing, will enable a fundamental understanding of the micromechanical response of these materials. There is currently a trend toward thicker materials (of the order of hundreds of micrometres) in MEMS because a larger aspect ratio is needed for a mechanical device to be able to transmit usable forces and torques. The mechanical testing techniques are also being extended for such applications. MEMS have great potential in smart structures as well.
- 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 centimetres can be performed by a smart material actuator system. A programme that combines theoretical investigations and experimental demonstrations were conducted. Potential configurations made of piezoceramic and electrostrictive materials were evaluated for providing larger motions at reasonable force levels for applications.
- Reliability and Safety of Structures Using Stability-based Hybrid Controls, B. F. Spencer (University of Notre Dame). MR fluid dampers are one of the most promising smart damping intelligent isolation systems, according to B. F. Spencer, owing to proven technology—reliability and robustness, low cost, insensitivity to temperature, low power requirements, and scalability to full-scale civil engineering applications. Fig. 9 depicts the effectiveness of MR dampers in suppressing earthquake excitation in the laboratory.
- Passive and Active Damping Control for Large Civil Structures, N. M. Wereley (University of Maryland). The objective is to augment damping in large civil structural applications via both passive and active means, to reduce structural response. The research programme 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

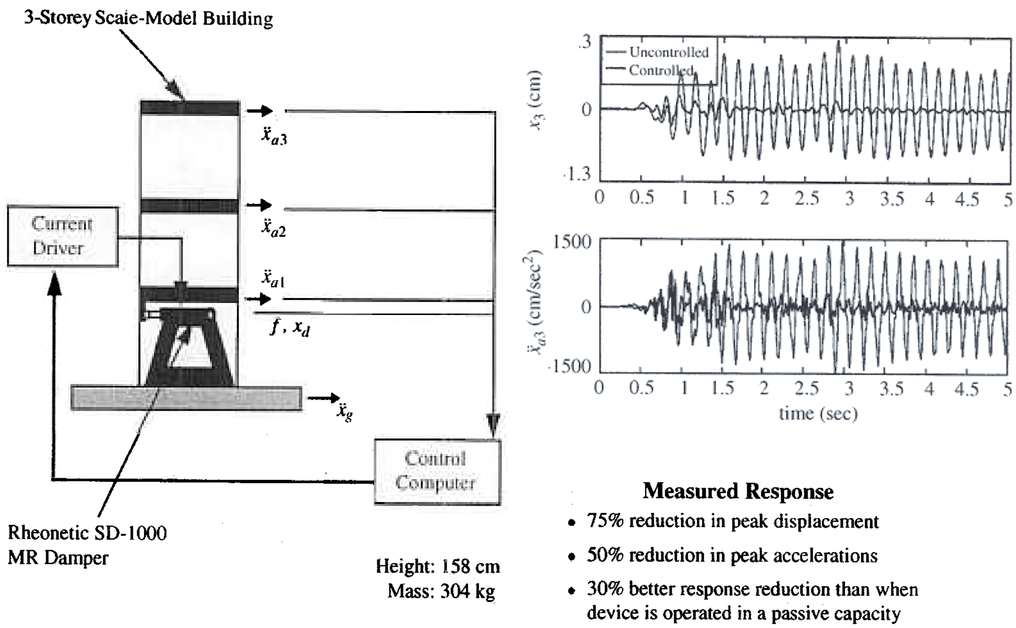


Fig. 9 Response of a three-storey scale model building (displacement and acceleration) to an excitation 120% of that of the El Centro earthquake (Courtesy of B. F. Spencer, Notre Dame University)

ER and MR dampers. Damping strategies are being tested on a dynamically scaled three story civil structure building model using dampers such as those depicted in Fig. 10.
- Remote Sensing of Damage in Large Civil Structures Using Embedded Sensors for Hazard Mitigation, D. J. Pines (University of Maryland). The project involves integrating research and education to advance the technology of smart materials and structures and techniques to remotely monitor damage in, or the 'health' of, large civil structures. The research focuses on the development of a smart civil structure with embedded piezoelectric sensors for inferring structural damage. A laboratory setup is shown in Fig. 11. The research will emphasize the integration of embedded sensors, actuators and processors into load-carrying members of large civil structures for the purpose of remote damage detection.
- Magnetostrictive Actuator Development for Vibration Control in Structures, A. B. Flatau (Iowa State University). This research seeks to design, develop and implement a system of magnetostrictive actuators for sensing and control of structural vibrations. Investigations supporting the design and implementation of magnetostrictive transducers include device quasi-static performance and frequency response studies, and modelling of system nonlinearities and hysteresis effects. The effort is motivated in part by the availability of magnetostrictive materials that can provide higher counter-forces and strains as compared with piezoelectric materials.

Research challenges in smart structures and materials

An important research challenge in smart structures and materials is to achieve optimal performance of the total system rather than just in the individual components. Among the topics requiring study are energy-absorbing and variable damping properties, as well as those materials having a stiffness that varies with changes in stress, temperature or acceleration. The National Materials Advisory Board has published[36] a good perspective on the materials problems associated with a high-performance car and a civil aircraft that develops the 'values' associated with these applications. Among the characteristics sought in smart structures/materials are the self-healing of developing cracks and *in situ* repair of damage to structures such as bridges and water

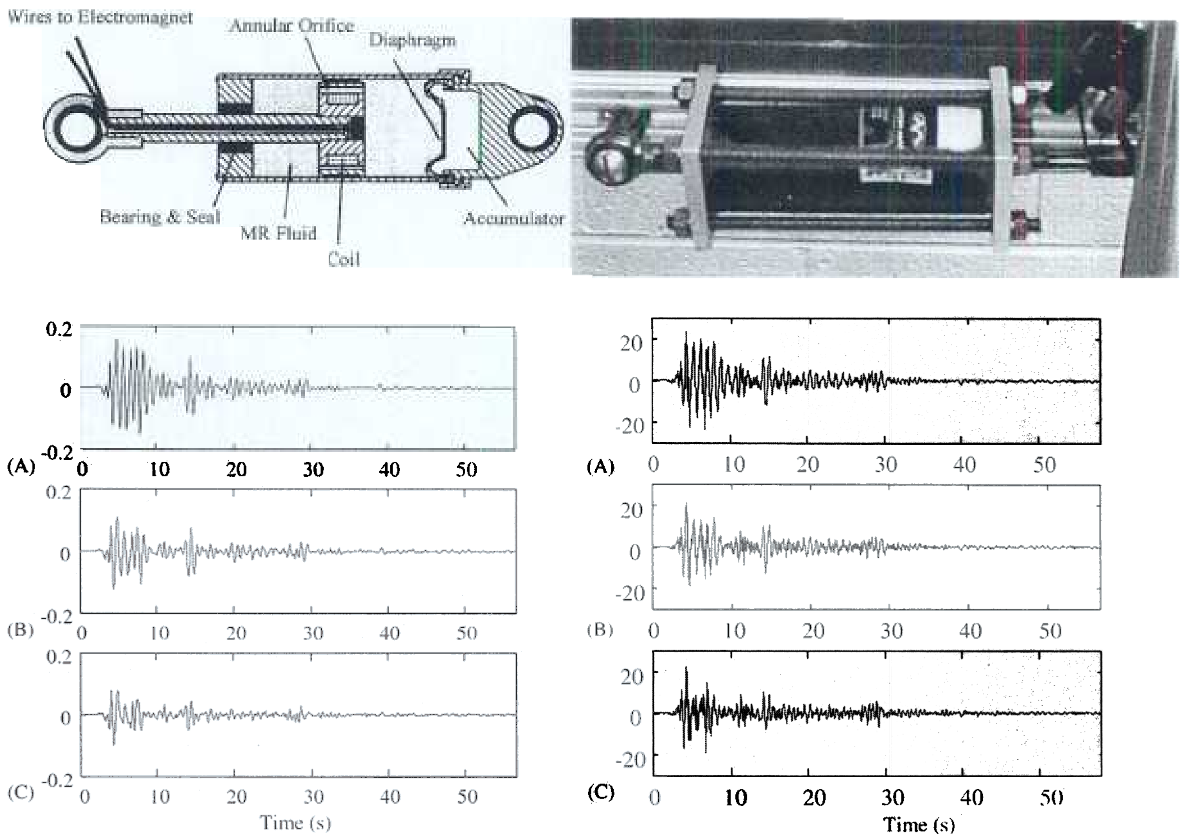


Fig. 10 Upper schematic and photo depict MR damper used in three story scale model building simulation of response to three times the El Centro earthquake. Lower plots (in arbitrary units) show displacement (left) and acceleration (right) responses to: (A) no control; (B) Skyhook controller; and (C) continuous sliding mode controller (Courtesy of N. M. Wereley, University of Maryland)

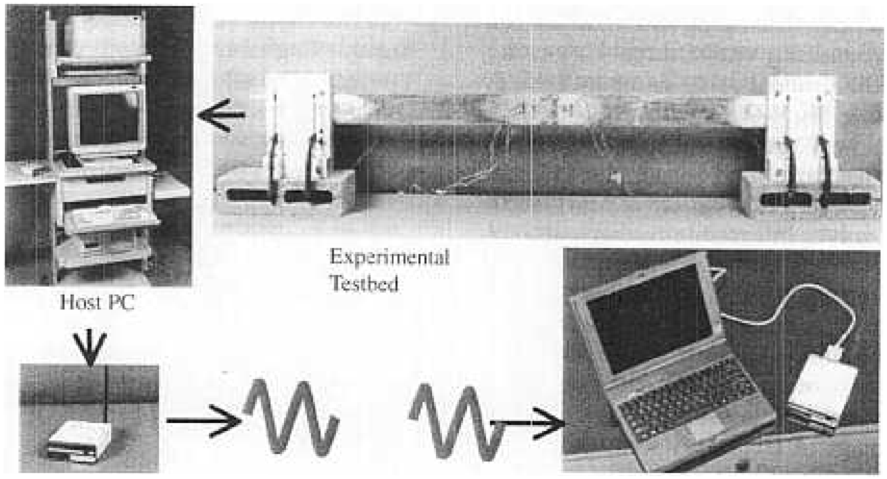


Fig. 11 Laboratory demonstration of remote 'health' monitoring and damage detection (Courtesy of D. J. Pines, University of Maryland)

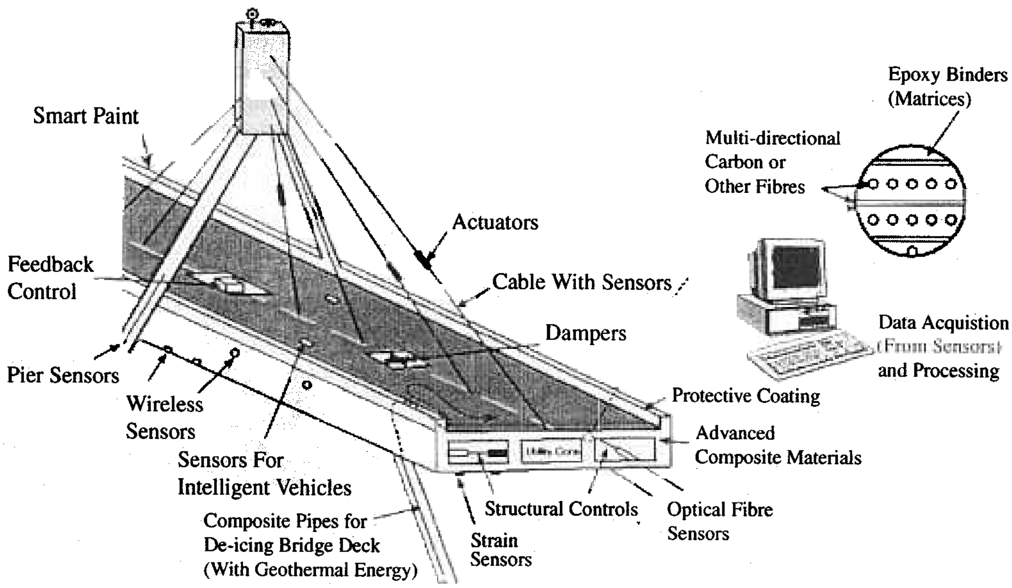


Fig. 12 A futuristic smart bridge system[3]

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 behaviour has been an underlying theme of active control of structures that are subjected to earthquake and other environmental 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. 12 is a sketch by the senior author (KPC) of a futuristic smart bridge system, illustrating some new concepts: wireless sensors, optical fibre sensors, data acquisition and processing systems, advanced composite materials, structural controls, dampers, and geothermal energy bridge deck de-icing. An artist's rendition of this bridge appeared in *USA Today*, 3 March 1997[37].

Discussion and conclusions

Structural materials and systems for the civil infrastructure are changing rapidly, owing to the driving forces of nanotechnology, designer materials, and smart materials. Behind all of these, however, lies the power of the computer in the information technology explosion of the last few decades. This growth in both computer power and computer connectivity is reshaping relationships among people and organizations, and transforming the processes of discovery, learning, and communication[38]. It is resulting in unprecedented opportunities for providing rapid and efficient access to enormous amounts of knowledge, data, including real-time data for smart structures, and information. The new information technology makes it possible to study vastly more complex systems than was hitherto possible, which is the key to advancing, in fundamental ways, our understanding of learning and intelligence in complex living and engineered systems.

An overview of the state of the art and of NSF-supported, as well as NIST-conducted, engineering research in smart structures and designer materials has been presented. New NSF research initiatives to encourage and support nanotechnology have also been described. The authors hope this paper will act as a catalyst, stimulating interest and further research in these areas. This paper reflects the personal views of the authors, not necessarily those of the National Science Foundation and the National Institute of Standards and Technology.

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Disclaimer

Certain commercial equipment and entities are identified in this paper in order to adequately specify experimental procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology.

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