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Smart Technology as Applied to Bridges

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Abstract

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FINAL REPORT

SMART TECHNOLOGY AS APPLIED TO BRIDGES

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Faculty Research Scientist

Virginia Transportation Research Council
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the University of Virginia)

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BRIDGE RESEARCH ADVISORY COMMITTEE

ABSTRACT

A smart bridge is one that senses some significant condition of its environment or behavior and then automatically reacts to that condition. This report presents an overview of the subject, describing how emerging technologies are making it possible for bridges to be smart in a variety of ways. Special attention is paid to sensors, materials, and control systems, the applications of which are important for smart bridges.

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INTRODUCTION

A smart bridge is capable of sensing one or more aspects of its environment or behavior and then automatically providing a useful response. Two categories of smart bridges are identified and described in this report. A Level I system is one that senses some critical condition of a bridge and then automatically transmits some form of alert or warning for appropriate action to be taken. A Level II system not only senses some critical condition of a bridge but also takes action to correct that condition. Such a bridge would, for example, sound a warning to its users when it is overloaded, and it would also strengthen itself.

To most observers, bridges are thought to be purely static or passive structures, except for an occasional moveable bridge over a waterway. In reality, bridges are only static at the macro level. At the micro level they are indeed active and dynamic. Bridges expand and contract with changes in ambient temperature. They deflect and vibrate under the passage of a vehicle. Bridge materials such as concrete have a tendency to crack, spall, and otherwise deteriorate. Metal components often corrode. Traditional passive methods of treating these problems do help, but they generally only delay subsequent problems.

PURPOSE AND SCOPE

The purpose of smart bridges is to deal with changing and dynamic problems in an active rather than passive way. Such an approach represents a historical departure from previous bridge building. In our time, active (smart) control systems are indeed indispensable for such things as aircraft, space vehicles, robots, and automated machine tools. It is the purpose of this study to explore how smart systems can be used in future bridge design, construction, and operation. It is not the purpose of this report to discuss specific reliability, economic, or legal issues associated with the application of smart technology on bridges.

METHODS

In this project, investigations were conducted in several areas. A study of recent literature constituted the major portion of the methodology. In particular, the literature related to smart or potentially smart materials, structures, and controls was examined. A number of researchers active in this area were also contacted to gain updated information on the subject. Several laboratories were also visited: the Center for Intelligent Material Systems and Structures, the Fiber Electro-Optics Research Center at the Virginia Polytechnic Institute and State University, and the University of Virginia's Intelligent Processing of Materials Laboratory. Summaries of the laboratory visits are found in the Appendix of this report.

RESULTS

Bridge Problems Potentially Amenable to Smart Systems

The vast majority of problems with bridges arise in connection with deterioration of the deck, which is usually constructed of concrete. Traffic wear, cracks, spalls, scaling, and corrosion of the reinforcing steel are common problems. Passive solutions, such as the use of additives in the concrete and overlays on the riding surface, are only partially effective. Coating the steel with epoxy only delays corrosion to some degree. Nonetheless, when serious trouble develops, expensive patching or redecking is required. New forms of active or smart systems may provide even better solutions.

The corrosion of steel in bridges is a persistent problem. Protection by paint is the most common remedy, but labor intensive repainting every several years is required. Alternative long-lasting, active, corrosion-preventing methods may be possible.

Bridge piers located in water are commonly subject to foundation scouring or deterioration at the water line. On navigable waterways, impact damage by vessels is also possible. Passive preventative or deflection systems have only limited success. Active systems could prove more effective.

In seismic zones, severe damage or the total collapse of bridges often occurs. Passive modifications at joints where failure generally occurs can reduce the severity of the damage, but smart systems could do even more to prevent such damage.

Frequent damage occurs to bridge structures as a result of overload, particularly old bridges. Retrofitting with a smart system could be a cost-effective solution to this problem.

From time to time, cracks develop in steel bridges for a variety of reasons. Such potentially dangerous cracks may go undetected for long periods of time especially when they are small. Smart systems would be able to detect these cracks before they cause serious harm.

A potential problem for motorists crossing bridges is the danger of going over the side in the event of an impact with the guard rail or parapet. If such impacts could be avoided by an active system, distress to the bridge, to vehicles, and to motorists could all be eliminated.

Level I Systems

Level I smart systems are those in which one or more critical attributes or conditions of a bridge are sensed and then responded to by the signaling of some kind of alert or warning. The smart systems described here are those that either exist or are currently being researched. Most of these have arisen as a result of modern electronics and information technology. Level I systems are dependent on four basic components: sensors, data processors, communications systems, and signaling devices. All of them must work together.

Various kinds of sensors that could be useful for smart bridges are listed below; of particular importance is their capability to transmit the sensed information electronically:

- accelerometers (used to sense vibration, impact, and seismic activity)
- acoustic sensors (used to sense vibration and defects in materials)
- air pollution detectors (used to sense the presence of harmful air pollution or smoke in the air)
- air speed gages (used to measure wind velocity)
- capacitance sensors (used to sense the formation of ice on a surface)
- corrosion sensors (used to detect corrosion in metals)
- electromagnetic transducers (used to measure physical displacements, such as deflection, settlement, and end movement)

- fatigue gages (used to sense the onset and progress of cracking in metals)
- flow meters (used to measure water velocity near bridge structures)
- inclinometers (used to detect movements of a structure)
- infrared sensors (used to sense surface or near surface temperatures remotely)
- lasers (used to determine physical displacements of solid objects remotely)
- magnetic resonators/sensors (used to detect cracks, flaws, and fatigue in metals)
- moisture probes (used to sense moisture in materials)
- optical fibers (used to sense strain, stress, and dislocations)
- photoelectric sensors (used to sense the presence of moving objects remotely)
- potentiometers (used to measure physical displacements, such as deflection, settlement, and end movements)
- pressure sensors (used to sense the presence of objects passing over the sensor)
- radars (used to determine distances to objects or changes in density of objects in air and in some solids)
- sonars (used to determine distances to solid objects or certain irregularities in water)
- strain gages (used to measure strains through the electrical resistance of metal or carbon filaments from which stress, force, and deformation of materials may be determined)
- thermocouples (used to sense temperatures in substances)
- video cameras (used to monitor and record anything visible or audible)
- water-level gages (used to determine the level of water, as in a stream or river).

Data processors are needed in Level I systems to process the data collected by the sensor or sensors. Processors can be simple or highly complex. A simple processor can be nothing more than an electrical on-off switch, which cuts in or out. Complex microprocessors, such as modern digital or analog computers, can deal with more variable and sophisticated control functions; they can output fully evaluated information.

Communication systems take the output of the data processor and transmit such information to whatever location is desired. Over short distances, conventional electrical wires can be used. Over longer distances, telephone lines can often be used. Fiber optic cables, if available, allow even faster transmission of large quantities of information. Where transmission that is independent of physical connections is required, such methods as conventional radio or even satellite transmissions are possible. Depending on the circumstances, the power for such transmissions can be supplied by public utilities, electrical generators, batteries, solar cells (backed up by batteries), or newly developed fuel cells.

The signaling devices by which people are alerted to a particular condition of a bridge that requires special attention constitute the end point of Level I smart systems. Signaling devices are usually visual or acoustic devices, although tactile devices are also possible. Common visual devices are lights (steady or flashing) of various colors (most often red) and changeable message signs. Common acoustic devices are buzzers, bells, horns, and sirens. An example of a tactile device is a vibrator that induces a high frequency vibration in a hands-on control stick or wheel. Such signaling devices may be bridge mounted or installed as part of in-vehicle information systems.

The following is a listing of some possible applications of Level I systems for bridges.

1. *Impact warning systems.* These systems generally use a radar detection device mounted on the bridge to sense whether an impact will occur between the top of a moving vehicle (such as a truck) and the underside of a bridge. A flashing warning light (sometimes with a warning sound) at the approach alerts the driver of such a vehicle. A similar radar warning signal is used on navigable waterways to alert the pilot of a boat or ship to a possible collision with the underside of a bridge or with a bridge pier.

2. *Overload warning systems.* Electronic strain gages possibly along with electronic deflection sensors can be programmed to indicate when a bridge is overstressed or overloaded as a result of the presence of a vehicle or group of vehicles. This situation is particularly important for old posted bridges for which strict load limits are required. A warning horn on the bridge could alert motorists to stop or proceed with caution. Warning lights at the bridge approaches could warn other motorists not to proceed onto the bridge until the lights go off.

Such information could also be transmitted to an appropriate field engineer so that an immediate damage inspection could be made on the bridge.

Under study in Japan is a novel form of strain or stress sensor used as an integral part of the reinforcement in concrete.[1] Conventional reinforcing steel is replaced with a composite glass and carbon fiber reinforcement. The carbon fibers are so designed that as the stress level in the reinforcing increases, more and more of the fibers break. By measuring the change in electrical resistance caused by the rupturing fibers, a good correlation can be had of the stress level in the reinforcement (or concrete). The glass component of the reinforcement continues to carry the load unaffected.

3. *High-water warning systems.* High water poses a danger not only to motorists but to bridges themselves. A water-level gage, possibly with a flow meter, strategically positioned on a bridge crossing a flowing body of water would detect dangerous water conditions and alert motorists of such danger by means of warning lights. Field personnel could also be alerted to take appropriate action.

4. *High-wind warning systems.* At certain bridge locations, frequent high cross winds pose dangerous driving conditions for motorists (especially trucks). High winds on flexible bridge structures (e.g., suspension and cable-stayed ones) can also be damaging to the bridge by inducing excess vibration. Air-speed indicators and accelerometers mounted on the bridge would sense unsafe conditions and alert both motorists and field engineers of the situation.

5. *Scour warning systems.* Bridge foundations located in flowing water are often weakened (and sometimes destroyed) by scour caused by fast moving water. Using flow meters to measure water velocity and sonar or radar devices to detect scour depth, a warning system could be devised to warn both motorists and field personnel of possible danger.[2, 3]

6. *Ice warning systems for decks.* During cold weather, bridge decks often become covered with ice before pavements do as a result of cold air and wind exposure from the bottom as well as the top. Such a condition can be very hazardous to motorists. A warning system could be created by the installation of an icing sensor installed in the deck. Such a sensor is still under development by the aircraft industry for wing icing problems. It is based on the difference between the electrical capacitance of water and ice; thus, when ice formation is sensed on the deck, warning lights would be turned on.

7. *Seismic warning systems.* Accelerometers installed on bridges in areas of high seismic potential can be programmed to trigger an alert when shocks reach a condition severe enough to possibly damage the structure. An alert of this nature would advise motorists either to stop before crossing such

bridges or at least to proceed with caution. Similar alerts could be transmitted to field engineers for appropriate action.

8. *Crack warning systems.* Both metal and concrete structural members crack on occasion. If the cracks are small and generally stable, they may not pose a threat to safety. On the other hand, if they grow, they are likely to be serious. New acoustic sensors using piezoelectric crystals are able to detect changes in crack conditions in structural members.[4] Rapid and significant changes in the acoustic pattern could be instantly relayed to field engineers for their attention. An immediate field inspection could thus be undertaken to ascertain the seriousness of the problem.

Still another crack detection method for concrete is under development.[5] Although it is primarily a visual method, it is noted here as an interesting new technique. In principle, hollow sealed carbon fibers filled with a colored dye are placed in the concrete as part of the reinforcing (as described in No. 2). When a crack develops in the concrete across the reinforcing, the fibers rupture and release the dye. Capillarity draws the dye to the surface, which would allow for early and easy visual detection of the crack or cracks. Electronic color scanners could be used to detect the dye on the surface, which would allow for automatic monitoring.

9. *Fatigue warning systems.* Metal fatigue often results in the sudden failure of bridges. Certain metal members that are repeatedly highly stressed are vulnerable to metal separation because of fatigue. A newly developed fatigue gage mounted on a member gives warning when the fatigue limit of that member is soon to be reached. The principle of the gage is based on its having several small notched metal reeds attached to the metal bridge in such a way that when each reed reaches its prescribed stress history (matching that of the bridge at the gage's location), the reed snaps off at the notch. Such information could potentially be transmitted electronically to a field engineer for appropriate action, thereby possibly preventing a disaster.

10. *Deck delamination warning systems.* Delamination of bridge decks (either with or without bituminous overlays) is generally a slow process, although sometimes it does result in sudden failure in its later stages. Instrumentation in the form of infrared thermography or ground-penetrating radar can remotely detect this process even in its early stages.[6, 7] Such an early warning system could be used to advise field engineers of impending problems. Permanently mounted instrumentation on a bridge is possible for continuous monitoring.

11. *Corrosion warning systems.* Metal corrosion is generally a slow process, which may gradually weaken bridges to the point of failure. Normally, corrosion is detected by visual examination, but not all corrosion is exposed enough to be visible to an inspector. In steel-reinforced concrete, sensors detect-

ing current between the steel (acting as an anode) and a noble metal cathode buried in the concrete correlates with corrosion activity.[8] Modified versions of this cathodic detection sensor could possibly be used to monitor corrosion in other critical locations in bridges as well. Such calibrated sensors would inform field engineers of the onset of corrosion that could be harmful to the strength and safety of a bridge.

Level II Systems

Level II systems are those in which one or more critical conditions of a bridge are sensed and then the structure responds by rectifying that condition or conditions. Such a system is generally more technologically advanced than the Level I systems previously described. Some Level II systems already exist and are in use, others are currently being researched, and still others are awaiting future exploration.

1. *Cathodic Protection (already existing, although research is continuing).* Cathodic protection as used in bridges is cited as a smart system in that it is an active system that inhibits the corrosion of reinforcing steel in concrete bridge decks contaminated with chlorides (salt).[9] In this system, a direct current is passed through electrical anodes (usually wires or wire mesh) buried in the surface of the deck. The current then flows through the concrete to the grounded reinforcing steel in the deck; thus, it functions as a cathode. The resulting polarization halts and prevents corrosion caused by the chloride ions. Combined with the previously cited corrosion warning system, a cathodic protection system can function as a Level II system. To date, this manner of controlling corrosion in metal in bridges has been limited to reinforcing steel in concrete, but its theoretical application for other situations is also possible. It has the potential for eliminating metal corrosion in all vulnerable locations in bridges.

2. *Smart materials being researched.* Most materials considered smart are still under development.[10, 11] One such emerging material is a concrete that seals its own cracks. Researchers at the University of Illinois at Urbana-Champaign are currently exploring this form of self-healing concrete.[12] In principle, hollow brittle fibers (such as fiberglass) are filled with a fluid crack-repair adhesive and then sealed off at the ends. These fibers are then mixed in with the concrete. Should cracks develop in the concrete, the fibers across the cracks would rupture and release the adhesive to seal such cracks. Such a concrete would have obvious benefits in virtually any bridge using concrete.

A number of other smart materials are also being studied in various laboratories. Even though their applications in bridges are less obvious than those of weathering steel and self-healing concrete, a brief description of them here will indicate the growing activity in the area of smart materials.

One interesting application is to have fibers made from shape memory materials mixed in with concrete.[4] Such fibers not only inhibit the formation of cracks by virtue of their normal reinforcing effects; but they also can be used to close cracks that do develop. For example, when cracks open up, the embedded fibers at the cracks would be stretched, but when heat is applied, the fibers will contract and tend to close these cracks.

Electroheological fluids represent a class of materials that stiffen with the passage of electrical current.[4] These fluids contain a suspension of fine polarizable particles. When subjected to an electrical current, the particles polarize and link up to form strong chains. If this unique fluid were sandwiched between thin metal or plastic plates, such a laminate could change its overall stiffness on command.

Certain forms of ceramics and polymers can also be smart in that when sensing a change in pressure, temperature, or electrical current, they respond by changing shape.[4, 13] Of special interest is a ceramic containing lead, titanium, and zirconium that, when subject to pressure, generates a piezoelectric voltage, which in turn causes the ceramic to expand. By laminating the ceramics appropriately, a rather large and rapid expansion can be generated. The general behavior of these piezoelectric materials is exactly the opposite of most other materials, which tend to compress when subjected to pressure. This smart material tends to expand under the same conditions. This material could be used to negate reflective sound on a surface (as noise attenuator walls) and eliminate compression strains in critical compression elements.

Plastics can now be custom designed with multidirectional strengths, that is, having different strengths in different directions.[13] In structures, it is common for stresses to be higher in one direction than another. Thus, a material that is tailored to these different conditions would be more efficient than a homogeneous material. Such tailored composite materials are already in use in aerospace structures. Experiments with semi-crystalline or liquid-crystalline polymers are being conducted so as to make these smart materials self-assemble or rearrange their complex molecular structure to best resist any stresses that might be imposed upon them. Examples found in nature indicate that such restructuring is possible.

Still another emerging smart material is glass.[13] Several kinds of glass are under development. One of these is a glass laminate that changes its transparency from cloudy to clear when a small electrical current is passed through it. It is made by sandwiching a polymer film encapsulating minute spheres of liquid crystal between plates of clear glass. In an unstimulated state, the crystals are unaligned and scatter any incoming light, thereby making the laminate cloudy. Under an electrical field, the crystals align themselves and let light pass through. A similar kind of glass laminate (which is called *electrochromic*) can be made that changes its color when subject to an electrical current. Sandwiched between two sheets of clear glass is an electrochemically active polymer film. With varying amounts of current, the glass changes from being colorless to blue-gray. At any desired tint, the current can be cut off, and the glass remains at that tint until current is reapplied. Another kind of glass laminate, which uses a photosensitive inner layer, changes its tint depending on the amount of light it receives. Under strong sunlight, the glass darkens, thereby transmitting less light. With less sunlight, the laminate clears. Laminates of this nature are already in use in many eyeglasses and sunglasses. Whereas, smart glass is not likely to be used in bridges themselves, they could well have applications in signs and lighting systems related to bridges.

3. *Active structural controls (being researched).* An active structural control system is one that senses certain attributes of a structure (strain, deformation, or vibration), analyzes this data, and then responds as needed to modify or nullify undesirable aspects of these attributes.

One application of active structural control is for bridge piers that may be subject to large or unpredictable settlement such as is caused by poor underlying soil.[14] Mechanical screw or hydraulic piston jacks would be permanently positioned under the bearings. Sensors located at the bearings would detect any settlement and signal a control device of this movement. The control unit would then actuate the jacks to automatically bring the bridge superstructure back into proper position.

Somewhat more complex than self-leveling jacks are active control systems that keep bridge decks from experiencing excessive deflection or vibration. Seismically induced dynamic behavior can also be mitigated. Although potentially applicable for any bridge, their best applications are for long-span, cable-stayed, and suspension bridges. They would operate by employing an integrated system of sensors, microprocessors, and actuators.[15] A bank of motion sensors such as inclinometers (for static measurement) and accelerometers (for dynamic measurement) positioned along the length of the deck would be required. They could be supplemented with an array of strain sensors attached to critical structural members. Data from these sensors would be transmitted to a programmed microprocessor to analyze the structure's behavior and activate and control the actuators as needed. The actuators could be of various kinds. Most direct kinds of actuators would be hydraulic jacks attached to the ends of a representative number of the diagonal cables sustaining the deck. A convenient location of the jacks would be at the point of attachment of the cables and the deck structure. This actuator-tendon system would act much like muscles in one's body, which also act in tension pulling as much or as little as commanded by the brain. Mathematical studies of this manner of active control have shown that properly programmed actuators do indeed greatly reduce the severity of both static and dynamic movements in bridge decks. With enough sensors and actuators attached to a bridge, undesirable movements could virtually be eliminated.

An alternate form of actuator is the tunable damper. Structural dampers are usually located at the juncture of two or more members subject to articulation. Their purpose is to absorb some of the dynamic energy of the structure. Whereas, conventional passive dampers can be used for bridges, active or tunable ones are more effective because the amount of damping can be adjusted to the degree needed to control the dynamic movement of the structure. Tunable dampers can be fluid, gas, or even electroheological. The control of fluid and gas damping is accomplished by varying the size of the discharge orifice. Electroheological damping control is done by changing the viscosity of the material by means of the passage of electrical current through it. By locating adjustable dampers throughout a bridge's structure and by dynamic control of their damping characteristics, unwanted vibration and seismic activity can be appreciably suppressed.

Another way to suppress dynamic movements is by the use of mass dampers. A smart system would involve hanging a series of masses along the length of the deck. They would be attached to the superstructure with tunable dampers. When the deck oscillated, the suspended masses would react through the programmed dampers against the structure to suppress the oscillations.

Aerodynamic appendages can also be used as actuators to control the dynamic behavior of bridges. Similar to the various control flaps used on aircraft, aerodynamic flaps can be attached to bridge superstructures as well. Automatically adjustable flaps or appendages would help to reduce undesirable motions created by wind.

Active structural systems replace the extra material (steel, concrete, etc.) that would be needed in a bridge to achieve stiffness. In long-span bridges, such replacements are highly desirable to reduce the dead-to-live-load ratio.

4. *Collision Avoidance (being studied.)* A vehicle colliding with a bridge not only does harm to the vehicle and occupant, but it damages the bridge as well. Current research associated with Intelligent Vehicle Highway Systems holds out promise that collision avoidance is possible.[16-19] The technology to keep a vehicle from striking a bridge could be incorporated wholly within the vehicle itself or it could be partially incorporated in the bridge. To implement this technology solely to avoid bridge collisions is probably not warranted, but should highway systems that have this capability be developed, smart bridge collision avoidance would be a natural addition.

5. *Deck deicing (concept).* Ice and snow on bridge decks constitute a serious safety problem. The most common method of deicing is by spreading some form of salt to lower the freezing point of ice, but such salts are deleterious to the deck. Thermal deicing is a more direct and a harmless way to counteract the problem. Heating wires or mesh embedded near the surface of a concrete deck is probably the most direct way to heat such a deck. Capacitance-based sensors

designed to detect the formation of ice would activate an electrical energy source to melt the ice or snow. Commercial electricity is a possible source of the electricity required, but it could be expensive and inconvenient to supply. Solar cells (with storage back-up) would have to be large and cumbersome for the output required. Self-contained chemical fuel cells, however, might be the answer, but such fuel cells await further development at this time.

6. *Automatic Bridge Actuation (concept)*. Many low bridges over navigable waterways are designed to open and close for ship traffic. Currently, their opening and closing is controlled by human operators. Coded remote electronic signaling devices (similar to automatic garage door openers or railroad crossing gates) could be used to automatically actuate such bridges. Associated safety barriers, lights, bells, and the like for motorists approaching the bridge could also be automatically actuated. As an additional safety feature, a radar scanner could observe whether any person or vehicle is on the bridge prior to opening. Numerous other automatic controls could be incorporated so as to achieve a proper balance of water and vehicular traffic flow (not unlike automatically controlled traffic lights at a street intersection).

DISCUSSION

The focus of this report has been on the technology of smart bridges and its possible applications. This new concept generally involves thinking of bridges as active or dynamic systems rather than as passive or static systems.

The reliability of the systems, legal and liability issues, possible required back-up systems or redundancies, maintenance and operations requirements, and cost-effectiveness are not discussed in this report. Before many of the smart systems for bridges are implemented, these issues have to be addressed. None the less, there is sufficient reason to believe that for many situations, smart bridges will provide the traveling public with safer bridges and will provide transportation agencies with structurally better bridges.

CONCLUSIONS

The main conclusion to be drawn from this study is that numerous technologies are emerging that enable bridges to be smart in a variety of ways. Indeed, in a few instances, smart systems have already been applied for use on bridges. Most other applications, however, are still in their research-and-development phase.

RECOMMENDATIONS

It is recommended that ongoing developments in the general areas of smart materials, smart structures, and electronic control systems continue to be monitored. It is also recommended that at least one of the more promising areas of application be intensively researched so as to bring it to a level of actual application. A good candidate from Level I systems for development is an overload warning system; from Level II systems, an active structural control system, such as a tunable damper, would be a good candidate.

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Virginia Polytechnic Institute & State University, Blacksburg, Virginia (Center for Intelligent Material Systems and Structures and the Fiber and Electro-Optics Research Center).

APPENDIX

Presented here is a summary of research activities related to smart bridges being conducted at the University of Virginia and the Virginia Polytechnic Institute and State University.

University of Virginia at Charlottesville

Located in the School of Engineering and Applied Science is an Intelligent Processing of Materials Laboratory, which is directed by Dr. Hayden Wadley. The principle activity of this lab, begun in 1988, focuses on the processing of metal powder composites using a hot isostatic press (called HIP). To monitor this fabrication process, various special sensors are being developed. Two of these could have application for smart bridges. One is an acoustic sensor to detect crack formation, and the other is a luminescence sensor to measure internal strain in materials.

When a crack forms in a material, it releases a certain amount of stored elastic energy, thereby propagating a strain wave in the material. By means of a piezoelectric crystal mounted on the material, such strain waves are detected and converted into minute electrical signals. After amplification, these signals reveal when a crack has occurred or propagated further. When an array of piezoelectric sensors is mounted on the material, it can be determined both when and where a crack has formed. This is done by measuring the time difference of the strain wave between several crystals.

Luminescence sensing is a relatively new way to measure strain in a material and thereby determine stress. As used in this lab, thin fibers of chromium dopant are embedded in a composite matrix produced by HIP. Such fibers are used since they are capable of withstanding the high temperatures developed in the HIP process. The exposed ends of the fibers are excited by an argon ion laser, and this results in a small amount of luminescence. This luminescence is captured by liquid-nitrogen-cooled charged couple detectors and compared against the luminescence of chromium dopant fibers not in the matrix. Since the level of luminescence varies with the degree of strain of the fibers, stresses induced in the matrix can be discerned.

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Within the electrical engineering department, there is a Fiber and Electro-Optics Research Center (FEORC) started in 1986 and directed by Dr. Richard Claus. Numerous research projects resulting in the development of several innovative sensors of particular importance for smart bridges have been undertaken in this center. The sensors are all based on electro-optic fibers technology and can be used in structures to measure such things as strain (general or local), vibration, temperature, corrosion, and acoustic waves.

In principle, silica fibers, when excited by a beam of laser light, change their luminescence whenever their dimensional properties are changed, for example, by stretching, bending, and the like. When compared to commercially available electrical strain gages, optical fibers are many times more sensitive in detecting strain and, in addition, are less prone to pick up stray or random background noise. In a bridge, such fibers could be either embedded in the mass of the member or bonded by epoxy adhesives to the surface of the member. For localized sensing, a Fabry-Perot optical sensor can be used. Essentially, a Fabry-Perot sensor uses two optical fibers whose ends are separated by a small gap. When light waves are transmitted through the fibers, the reflected light waves across the gap change with changes in the width of the gap; thus, strain at the location of the gap can be determined extremely precisely. In September of 1991, a 30-foot reinforced concrete bridge in Roanoke's Garden City was instrumented by the FEORC with Fabry-Perot sensors. Two pairs of these sensors were bonded to the underside of the bridge across an open surface crack. The bridge was then dynamically loaded by driving an 8.2-ton van across the bridge. The output data from the sensors is being evaluated to ascertain the behavior of this bridge. Currently, other fiber optic bridge-related applications are being studied at the University of Southern California under the supervision of Dr. Claus of FEORC.

Within the mechanical engineering department there is a Center for Intelligent Materials Systems and Structures (CIMSS), which was started in 1987 and directed by Dr. Craig Rogers. At CIMSS, research generally focuses on the investigation of new materials that possess unusual mechanical or electrical properties and the application of these materials to sensing or controlling the behavior of various kinds of structures. Only a few relevant ones are selected for this report.

One of the materials being investigated is called a shape memory alloy (SMA). When deformed beyond its elastic limit, this metal remains deformed. However, when heated, it reverts back to its original shape. Studies at CIMSS are being conducted using fibers or platelets of this alloy to reduce stress concentrations in a host object, for example, around holes or cracks. This is done by strategically locating fibers or platelets so that the shape memory nature of the alloy applies stress-relieving counter forces on the object when heated. A direct way to heat these shape-memory alloys is by resistance heating using electrical current.

Under development is a time domain reflectometer (TDR) sensor that has a variety of possible applications. In smart bridges, it could locate regions of high strain and indicate the type of strain (caused by shear, tension, or compression). It could also detect areas where corrosion may be occurring or where there may be pressure-point loading. The principle on which the TDR is based is that there is a change in electrical impedance between the inner and outer wires in a coaxial cable when the gap between these wires is changed. When an electrical pulse is sent down the cable, a pulse is reflected wherever there is an impedance change, thereby indicating those locations along the length of cable where there could be problems.

Another technique being studied to monitor the health of a structure is that of active tagging using ferro-magnetic particles embedded in an object. When such particles are excited by a magnetic field, it is possible to determine where cracks or delaminations have occurred.

Still another sensor makes use of a transformation-induced plasticity steel that undergoes a martensitic phase transformation when strained. This transformation alters it magnetic properties, so that by using a magnetometer, strain (or stress) conditions of the material to which the TRIP sensor is attached or embedded can be determined.